Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2005

How to Obtain Copies

You can electronically download this document on the U.S. EPA's Climate Change homepage at <http://epa.gov/climatechange/emissions/usinventoryreport.html>. To request free copies of this report, call the National Service Center for Environmental Publications (NSCEP) at (800) 490–9198, or visit the NSCEP web site at <http://www.epa.gov/nscep/>.

All data tables of this document are available for the full time series 1990 through 2005, inclusive, at the internet site mentioned above.

For Further Information

Contact Mr. Leif Hockstad, Environmental Protection Agency, (202) 343–9432, hockstad.leif@epa.gov.

Or Ms. Lisa Hanle, Environmental Protection Agency, (202) 343–9434, hanle.lisa@epa.gov.

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

Released for printing: April 15, 2007

Key Categories

The photos on the front and back cover of this report depict the eight largest key categories from the 1990–2005 Inventory. 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." 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. Key category names can differ from those used elsewhere in the inventory report, due to naming conventions necessary to comply with UNFCCC reporting guidelines.

Carbon Dioxide Emissions from Non-Energy Use of Fuels

Rather than being combusted for energy, fuels consumed for non-energy purposes act as building blocks or reagents in fabricating other materials. These fossil-fuel-derived materials are important from an emissions perspective since they often provide long-term storage of the fuel's carbon. Emissions from this source have increased 21 percent since 1990.

Direct Nitrous Oxide Emissions from Agricultural Soil Management

(Photo by Lynn Betts, USDA Natural Resources Conservation Service)

Agricultural soil management is the largest single source of nitrous oxide emissions in the United States, accounting for 5 percent of U.S. greenhouse gas emissions in 2005. Direct soil nitrous oxide emissions depend on the amounts of nitrogen inputs such as fertilizer and crop residues added to soils, as well as on temperature, precipitation, and other factors. Emissions from this source fluctuate from year to year depending on weather and nitrogen inputs, and have not changed significantly since 1990.

Carbon Dioxide Emissions from Stationary Combustion: Oil

Carbon dioxide emissions from combustion of oil in stationary applications account for approximately 9 percent of U.S. greenhouse gas emissions in 2005. Stationary applications that most commonly burn oil include industrial boilers, residential and commercial furnaces, and electric power plants. Emissions from this source have increased 7 percent since 1990.

Carbon Dioxide Emissions from Stationary Combustion: Gas

Carbon dioxide emissions from combustion of natural gas in stationary applications accounted for approximately 16 percent of U.S. greenhouse gas emissions in 2005. Stationary applications that most commonly burn natural gas include residential and commercial furnaces and stoves, electric power plants, and industrial furnaces and boilers. Emissions from this source have increased 17 percent since 1990.

Methane Emissions from Landfills

Landfills are the largest single anthropogenic source of methane emissions in the United States. In an environment where the oxygen content is low or nonexistent (i.e. anaerobic), organic materials such as yard waste, household waste, food waste, and paper are decomposed by bacteria, resulting in the generation of methane. Emissions from this source have decreased 18 percent since 1990, due mostly to greater collection and combustion of landfill gas.

Carbon Dioxide Emissions from Mobile Combustion: Aviation

Fossil fuel combustion in airplanes and other aircraft resulted in approximately 3 percent of U.S. greenhouse gas emissions in 2005. The main types of fuel burned in aircraft are kerosene-type jet fuel and aviation gasoline. Kerosene jet fuel is the primary fuel used for civil aviation (i.e., most commercial aircraft) and aviation gasoline is most commonly used in general aviation (i.e., small recreational and corporate aircraft). Emissions from this source have increased 3 percent since 1990.

Carbon Dioxide Emissions from Mobile Combustion: Road & Other

Fossil fuel combustion in road and non-road vehicles accounted for approximately 23 percent of U.S. greenhouse gas emissions in 2005. Almost all of the energy consumed for transportation was supplied by petroleum-based products. Since the 1970s, the number of highway vehicles registered in the United States has increased faster than the overall population; the number of miles driven and the gallons of gasoline consumed each year in the United States have increased steadily since the 1980s. Emissions from this source have increased 33 percent since 1990.

Carbon Dioxide Emissions from Stationary Combustion: Coal

Carbon dioxide emissions from combustion of natural gas in stationary applications accounted for approximately 29 percent of U.S. greenhouse gas emissions in 2005. The vast majority of coal burned in the United States is consumed in electric power generation. Coal is also used in industrial boilers, and in small amounts in residential and commercial applications. Emissions from this source have increased 23 percent since 1990.

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

1990–2005

April 15, 2007

U.S. Environmental Protection Agency

1200 Pennsylvania Avenue, N.W.

Washington, DC 20460

U.S.A.

Acknowledgments

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

Work on fuel combustion and industrial process emissions was led by Leif Hockstad and Mausami Desai. Work on methane emissions from the energy sector was directed by Lisa Hanle. Calculations for the waste sector were led by Melissa Weitz. Tom Wirth directed work on the Agriculture chapter, and Kimberly Klunich directed work on the Land Use, Land-Use Change, and Forestry chapter. Work on emissions of HFCs, PFCs, and SF_6 was directed by Deborah Ottinger and Dave Godwin. John Davies directed the work on mobile combustion.

Within the EPA, other Offices also contributed data, analysis, and technical review for this report. The Office of Transportation and Air Quality and the Office of Air Quality Planning and Standards provided analysis and review for several of the source categories addressed in this report. The Office of Solid Waste and the Office of Research and Development also contributed analysis and research.

The Energy Information Administration and the Department of Energy contributed invaluable data and analysis on numerous energy-related topics. The U.S. Forest Service prepared the forest carbon inventory, and the Department of Agriculture's Agricultural Research Service and the Natural Resource Ecology Laboratory at Colorado State University contributed leading research on nitrous oxide and carbon fluxes from soils.

Other government agencies have contributed data as well, including 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, the Federal Aviation Administration, and the Department of Defense.

We would also like to thank Marian Martin Van Pelt, Randall Freed, and their staff at ICF International's Energy and Resources Practice, including Don Robinson, Diana Pape, Susan Asam, Michael Grant, Ravi Kantamaneni, Robert Lanza, Chris Steuer, Lauren Flinn, Kamala Jayaraman, Jeremy Scharfenberg, Mollie Averyt, Sarah Shapiro, Stacy Hetzel, Brian Gillis, Zachary Schaffer, Vineet Aggarwal, Colin McGroarty, Hemant Mallya, Lauren Pederson, Erin Fraser, Joseph Herr, Victoria Thompson, Jean Kim, Pankaj Kumar, David Berv, Allison Osborne, and Toby Krasney for synthesizing this report and preparing many of the individual analyses. Eastern Research Group, RTI International, Raven Ridge Resources, and Arcadis also provided significant analytical support.

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).[1] 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.[2] 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.

---

[1] See Article 4(1)(a) of the United Nations Framework Convention on Climate Change <http://www.unfccc.int>.

[2] See <http://epa.gov/climatechange/emissions/usinventoryreport.html>.

Table of Contents

List of Annexes (Annexes available on CD version only)

List of Tables, Figures, and Boxes

Tables

Figures

Boxes

Table of Contents

4. Industrial Processes 4-1

5. Solvent and Other Product Use 5-1

6. Agriculture 6-1

List of Annexes (Annexes available on CD version only)

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 2005. 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 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 begun 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 Intergovernmental Panel on Climate Change (IPCC) methodologies were expanded, resulting in a more comprehensive and detailed estimate of emissions.

---

[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/cop8/08.pdf>.

Box ES-1: 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 IPCC *Good Practice Guidance* (IPCC 2000), which states, regarding recalculations of the time series, "It is good practice to recalculate historic emissions when methods are changed or refined, when new source categories are included in the national inventory, or when errors in the estimates are identified and corrected." 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 2004) has been recalculated to reflect the change, per IPCC *Good Practice Guidance*. 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.

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.[5] 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 2004, concentrations of these greenhouse gases have increased globally by 35, 143, and 18 percent, respectively (IPCC 2001, Hofmann 2004).

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 HCFCs. Accordingly, atmospheric concentrations of these substitutes have been growing (IPCC 2001).

Global Warming Potentials

Gases in the atmosphere can contribute to the greenhouse effect both directly and indirectly. Direct effects occur when

---

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

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).[6] 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 of CO_2 equivalent (Tg CO_2 Eq.).[7] 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 2002,[8] 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 2005 are consistent with estimates developed prior to the publication of the IPCC Third Assessment Report (TAR). 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 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.

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).

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

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

In 2005, total U.S. greenhouse gas emissions were 7,260.4 Tg CO_2 Eq. Overall, total U.S. emissions have risen by 16.3 percent from 1990 to 2005, while the U.S. gross domestic product has increased by 55 percent over the same period (BEA 2006). Emissions rose from 2004 to 2005, increasing by 0.8 percent (56.7 Tg CO_2 Eq.). The following factors were primary contributors to this increase: (1) strong economic growth in 2005, leading to increased demand for electricity and (2) an increase in the demand for electricity due to warmer summer conditions. These factors were moderated by decreasing demand for fuels due to warmer winter conditions and higher fuel prices.

---

[6] 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.

[7] Carbon constitutes 12/44ths of carbon dioxide by weight.

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

Figure ES-1

U.S. Greenhouse Gas Emissions by Gas

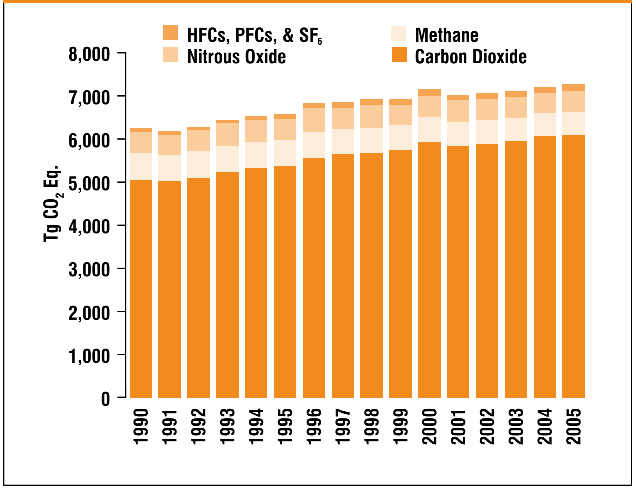


Figure ES-2

Annual Percent Change in U.S. Greenhouse Gas Emissions

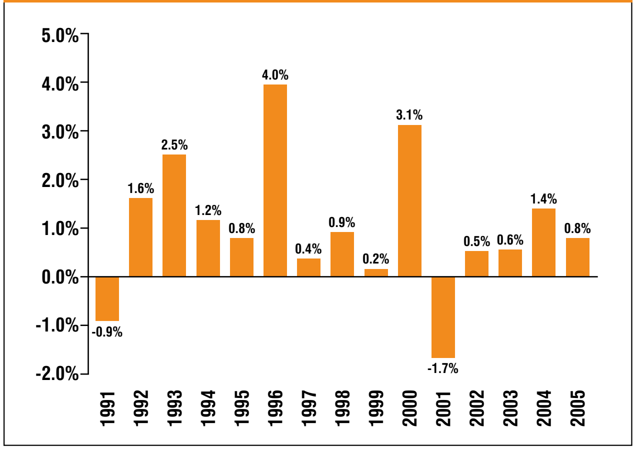


Figure ES-3

Cumulative Change in U.S. Greenhouse Gas Emissions Relative to 1990

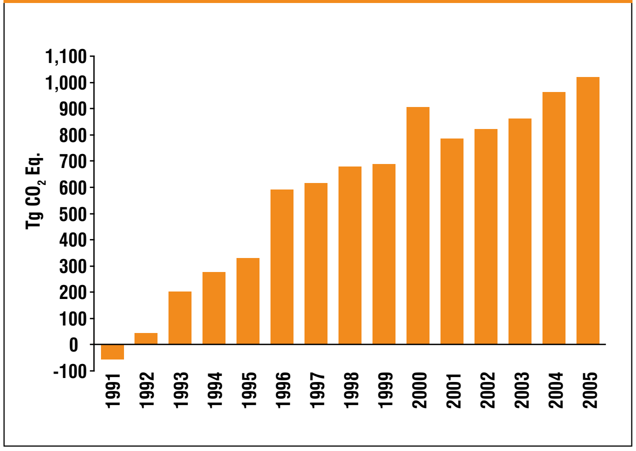


Figure ES-1 through Figure ES-3 illustrate the overall trends in total U.S. emissions by gas, annual changes, and absolute change since 1990. Table ES-2 provides a detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 2005.

Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 2005. The primary greenhouse gas emitted by human activities in the United States was CO$_2$, representing approximately 83.9 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 steadily declined since 1990, resulted primarily from decomposition of wastes in landfills, natural gas systems, and enteric fermentation associated with domestic livestock. Agricultural soil management and mobile source fossil fuel combustion were the major sources of N$_2$O emissions. The emissions of substitutes for ozone depleting substances and emissions of HFC-23 during the production of HCFC-22 were the primary contributors to aggregate HFC emissions. Electrical transmission and distribution systems accounted for most SF$_6$ emissions, while PFC emissions resulted from semiconductor manufacturing and as a by-product of primary aluminum production.

Overall, from 1990 to 2005, total emissions of CO$_2$ increased by 1,027.9 Tg CO$_2$ Eq. (20.3 percent), while CH$_4$ and N$_2$O emissions decreased by 69.8 Tg CO$_2$ Eq. (11.5 percent) and 13.4 Tg CO$_2$ Eq. (2.8 percent), respectively. During the same period, aggregate weighted emissions of HFCs, PFCs, and SF$_6$ rose by 73.7 Tg CO$_2$ Eq. (82.5

Figure ES-4

2005 Greenhouse Gas Emissions by Gas (percents based on Tg CO$_2$ Eq.)

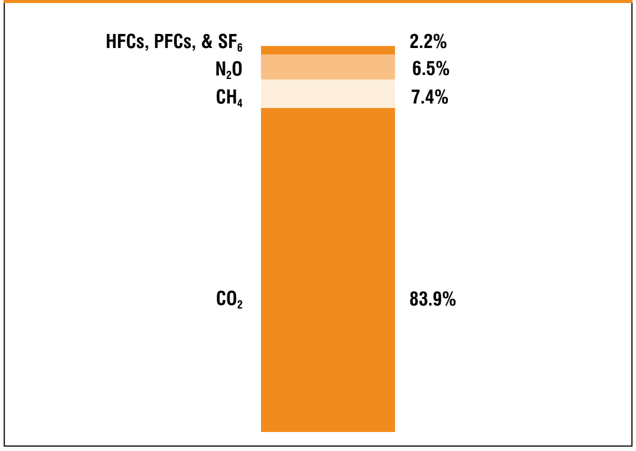


Table ES-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**5,061.6**	**5,384.6**	**5,940.0**	**5,843.0**	**5,892.7**	**5,952.5**	**6,064.3**	**6,089.5**
Fossil Fuel Combustion	4,724.1	5,030.0	5,584.9	5,511.7	5,557.2	5,624.5	5,713.0	5,751.2
Non-Energy Use of Fuels	117.3	133.2	141.0	131.4	135.3	131.3	150.2	142.4
Cement Manufacture	33.3	36.8	41.2	41.4	42.9	43.1	45.6	45.9
Iron and Steel Production	84.9	73.3	65.1	57.9	54.6	53.4	51.3	45.2
Natural Gas Systems	33.7	33.8	29.4	28.8	29.6	28.4	28.2	28.2
Municipal Solid Waste Combustion	10.9	15.7	17.9	18.3	18.5	19.5	20.1	20.9
Ammonia Manufacture and Urea Application	19.3	20.5	19.6	16.7	17.8	16.2	16.9	16.3
Lime Manufacture	11.3	12.8	13.3	12.9	12.3	13.0	13.7	13.7
Limestone and Dolomite Use	5.5	7.4	6.0	5.7	5.9	4.7	6.7	7.4
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.1	4.1	4.1	4.2	4.2
Aluminum Production	6.8	5.7	6.1	4.4	4.5	4.5	4.2	4.2
Petrochemical Production	2.2	2.8	3.0	2.8	2.9	2.8	2.9	2.9
Titanium Dioxide Production	1.3	1.7	1.9	1.9	2.0	2.0	2.3	1.9
Ferroalloy Production	2.2	2.0	1.9	1.5	1.3	1.3	1.4	1.4
Phosphoric Acid Production	1.5	1.5	1.4	1.3	1.3	1.4	1.4	1.4
Carbon Dioxide Consumption	1.4	1.4	1.4	0.8	1.0	1.3	1.2	1.3
Zinc Production	0.9	1.0	1.1	1.0	0.9	0.5	0.5	0.5
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Production and Consumption	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Land Use, Land-Use Change, and Forestry (Sink)[a]	*(712.8)*	*(828.8)*	*(756.7)*	*(767.5)*	*(811.9)*	*(811.9)*	*(824.8)*	*(828.5)*
International Bunker Fuels[b]	*113.7*	*100.6*	*101.1*	*97.6*	*89.1*	*83.7*	*97.2*	*97.2*
Wood Biomass and Ethanol Consumption[b]	*219.3*	*236.8*	*228.3*	*203.2*	*204.4*	*209.6*	*224.8*	*206.5*
CH_4	**609.1**	**598.7**	**563.7**	**547.7**	**549.7**	**549.2**	**540.3**	**539.3**
Landfills	161.0	157.1	131.9	127.6	130.4	134.9	132.1	132.0
Enteric Fermentation	115.7	120.6	113.5	112.5	112.6	113.0	110.5	112.1
Natural Gas Systems	124.5	128.1	126.6	125.4	125.0	123.7	119.0	111.1
Coal Mining	81.9	66.5	55.9	55.5	52.0	52.1	54.5	52.4
Manure Management	30.9	35.1	38.7	40.1	41.1	40.5	39.7	41.3
Petroleum Systems	34.4	31.1	27.8	27.4	26.8	25.8	25.4	28.5
Wastewater Treatment	24.8	25.1	26.4	25.9	25.8	25.6	25.7	25.4
Forest Land Remaining Forest Land	7.1	4.0	14.0	6.0	10.4	8.1	6.9	11.6
Stationary Combustion	8.0	7.8	7.4	6.8	6.8	7.0	7.1	6.9
Rice Cultivation	7.1	7.6	7.5	7.6	6.8	6.9	7.6	6.9
Abandoned Underground Coal Mines	6.0	8.2	7.3	6.7	6.1	5.9	5.8	5.5
Mobile Combustion	4.7	4.3	3.5	3.2	3.1	2.9	2.8	2.6
Petrochemical Production	0.9	1.1	1.2	1.1	1.1	1.1	1.2	1.1
Iron and Steel Production	1.3	1.3	1.2	1.1	1.0	1.0	1.0	1.0
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.8	0.7	0.8	0.9	0.9
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**482.0**	**484.2**	**499.8**	**502.5**	**479.2**	**459.8**	**445.2**	**468.6**
Agricultural Soil Management	366.9	353.4	376.8	389.0	366.1	350.2	338.8	365.1
Mobile Combustion	43.7	53.7	53.2	49.7	47.1	43.8	41.2	38.0
Nitric Acid Production	17.8	19.9	19.6	15.9	17.2	16.7	16.0	15.7
Stationary Combustion	12.3	12.8	14.0	13.5	13.4	13.7	13.9	13.8
Manure Management	8.6	9.0	9.6	9.8	9.7	9.3	9.4	9.5
Wastewater Treatment	6.4	6.9	7.6	7.6	7.7	7.8	7.9	8.0
Adipic Acid Production	15.2	17.2	6.0	4.9	5.9	6.2	5.7	6.0
Settlements Remaining Settlements	5.1	5.5	5.6	5.5	5.6	5.8	6.0	5.8
N_2O Product Usage	4.3	4.5	4.8	4.8	4.3	4.3	4.3	4.3
Forest Land Remaining Forest Land	0.8	0.6	1.7	1.0	1.4	1.2	1.1	1.5
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.4	0.4	0.5	0.5
Municipal Solid Waste Combustion	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4
International Bunker Fuels[b]	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*	*0.9*	*0.9*
HFCs, PFCs, and SF_6	**89.3**	**103.5**	**143.8**	**133.8**	**143.0**	**142.7**	**153.9**	**163.0**
Substitution of Ozone Depleting Substances	0.3	32.2	80.9	88.6	96.9	105.5	114.5	123.3
HCFC-22 Production	35.0	27.0	29.8	19.8	19.8	12.3	15.6	16.5
Electrical Transmission and Distribution	27.1	21.8	15.2	15.1	14.3	13.8	13.6	13.2
Semiconductor Manufacture	2.9	5.0	6.3	4.5	4.4	4.3	4.7	4.3
Aluminum Production	18.5	11.8	8.6	3.5	5.2	3.8	2.8	3.0
Magnesium Production and Processing	5.4	5.6	3.0	2.4	2.4	2.9	2.6	2.7
Total	**6,242.0**	**6,571.0**	**7,147.2**	**7,027.0**	**7,064.6**	**7,104.2**	**7,203.7**	**7,260.4**
Net Emissions (Sources and Sinks)	**5,529.2**	**5,742.2**	**6,390.5**	**6,259.5**	**6,252.7**	**6,292.3**	**6,378.9**	**6,431.9**

+ 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 sink in the United States. Sinks are only included in net emissions total.

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

Note: Totals may not sum due to independent rounding.

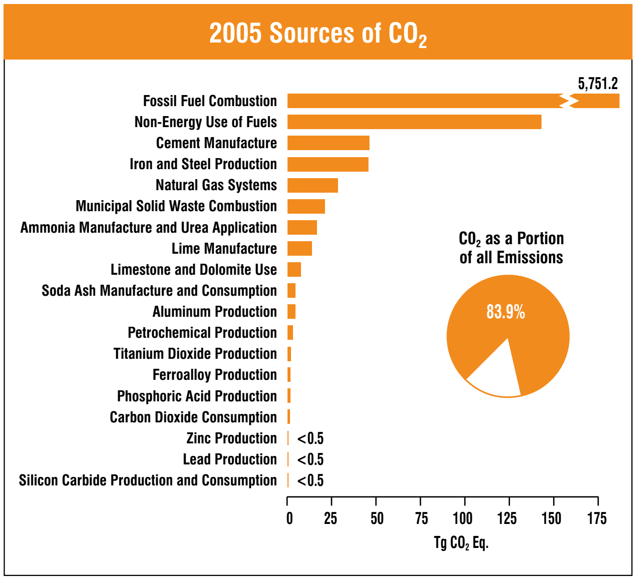
percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, and SF_6 are significant because many of them have extremely high global warming potentials and, in the cases of PFCs and SF_6, long atmospheric lifetimes. Conversely, U.S. 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 11.4 percent of total emissions in 2005. 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 35 percent (IPCC 2001, Hofmann 2004), principally due to the combustion of fossil fuels. Within the United States, fuel combustion accounted for 94 percent of CO_2 emissions in 2005. Globally, approximately 27,044 Tg of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2004, of which the United States accounted for about 22 percent.[9] 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).

U.S. anthropogenic sources of CO_2 are shown in Figure ES-5. As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for approximately 77 percent of GWP-weighted emissions since 1990, growing slowly from 76 percent of total GWP-weighted emissions in 1990 to 79 percent in 2005. Emissions of CO_2 from fossil fuel combustion increased at an average annual rate of 1.3 percent from 1990 to 2005. The fundamental factors influencing this trend include (1) a generally growing domestic economy over the last 15 years, and (2) significant overall growth in emissions from electricity generation and transportation activities. Between 1990 and 2005, CO_2 emissions from fossil fuel combustion increased from 4,724.1 Tg CO_2 Eq. to 5,751.2 Tg CO_2 Eq.—a 21.7 percent total increase over the fifteen-year period. From 2004 to 2005, these emissions increased by 38.2 Tg CO_2 Eq. (0.7 percent).

Figure ES-5



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 generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, in a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams, there would likely be proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants.

The four major end-use sectors contributing to CO_2 emissions from fossil fuel combustion are industrial, transportation, residential, and commercial. Electricity

---

[9] Global CO_2 emissions from fossil fuel combustion were taken from Energy Information Administration *International Energy Annual 2004* (EIA 2006a).

generation also emits CO_2, although these emissions are produced as they consume fossil fuel to provide electricity to one of the four 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.

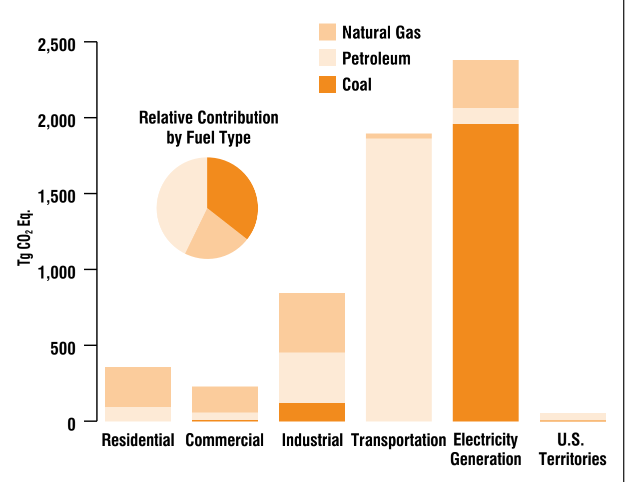
Note that emissions from U.S. territories are calculated separately due to a lack of specific consumption data for the individual end-use sectors.

Figure ES-6, Figure ES-7, and Table ES-3 summarize CO_2 emissions from fossil fuel combustion by end-use sector.

Transportation End-Use Sector. Transportation activities (excluding international bunker fuels) accounted for 33 percent of CO_2 emissions from fossil fuel combustion in 2005.[10] Virtually all of the energy consumed in this end-use sector came from petroleum products. Over 60 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.

Figure ES-6

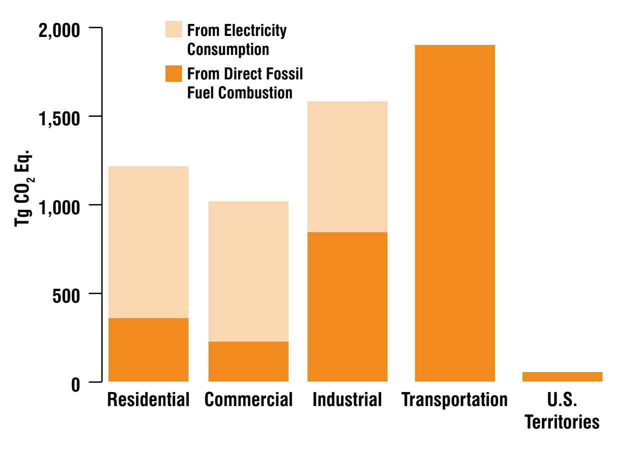
2005 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type



Note: Electricity generation also includes emissions of less than 1 Tg CO_2 Eq. from geothermal-based electricity generation.

Figure ES-7

2005 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion



Industrial End-Use Sector. Industrial CO_2 emissions, resulting both directly from the combustion of fossil fuels and indirectly from the generation of electricity that is consumed by industry, accounted for 27 percent of CO_2 from fossil fuel combustion in 2005. About half of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The other half of the emissions resulted from consuming electricity for motors, electric furnaces, ovens, lighting, and other applications.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 21 and 18 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2005. Both sectors relied heavily on electricity for meeting energy demands, with 70 and 78 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.

Electricity Generation. The United States relies on electricity to meet a significant portion of its energy demands, especially for lighting, electric motors, heating, and air conditioning. Electricity generators consumed 36 percent of U.S. energy from fossil fuels and emitted 41 percent of the

---

[10] If emissions from international bunker fuels are included, the transportation end-use sector accounted for 35 percent of U.S. emissions from fossil fuel combustion in 2005.

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

End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005
Transportation	**1,467.0**	**1,593.3**	**1,787.8**	**1,761.5**	**1,815.7**	**1,814.8**	**1,868.9**	**1,897.9**
Combustion	1,464.0	1,590.2	1,784.4	1,758.2	1,812.3	1,810.5	1,864.5	1,892.8
Electricity	3.0	3.0	3.4	3.3	3.4	4.3	4.4	5.2
Industrial	**1,539.8**	**1,595.8**	**1,660.1**	**1,596.6**	**1,575.5**	**1,595.1**	**1,615.2**	**1,575.2**
Combustion	857.1	882.7	875.0	869.9	857.7	858.3	875.6	840.1
Electricity	682.7	713.1	785.1	726.7	717.8	736.8	739.6	735.1
Residential	**929.9**	**995.4**	**1,131.5**	**1,124.8**	**1,147.9**	**1,179.1**	**1,175.9**	**1,208.7**
Combustion	340.3	356.4	373.5	363.9	362.4	383.8	369.9	358.7
Electricity	589.6	639.0	758.0	760.9	785.5	795.3	806.0	849.9
Commercial	**759.2**	**810.6**	**969.3**	**979.7**	**973.8**	**984.2**	**999.1**	**1,016.8**
Combustion	224.3	226.4	232.3	225.1	225.7	236.6	233.3	225.8
Electricity	534.9	584.2	736.9	754.6	748.0	747.6	765.8	791.0
U.S. Territories	**28.3**	**35.0**	**36.2**	**49.0**	**44.3**	**51.3**	**54.0**	**52.5**
Total	**4,724.1**	**5,030.0**	**5,584.9**	**5,511.7**	**5,557.2**	**5,624.5**	**5,713.0**	**5,751.2**
Electricity Generation	**1,810.2**	**1,939.3**	**2,283.5**	**2,245.5**	**2,254.7**	**2,284.0**	**2,315.8**	**2,381.2**

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.

CO_2 from fossil fuel combustion in 2005. 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 93 percent of all coal consumed for energy in the United States in 2005. 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 25.1 Tg CO_2 Eq. (21 percent) from 1990 through 2005. Emissions from non-energy uses of fossil fuels were 142.4 Tg CO_2 Eq. in 2005, which constituted 2.5 percent of overall fossil fuel CO_2 emissions and 2.3 percent of total national CO_2 emissions, approximately the same proportion as in 1990.
- CO_2 emissions from cement production increased to 45.9 Tg CO_2 Eq. in 2005, a 38 percent increase in emissions since 1990. Emissions mirror growth in the construction industry. In contrast to many other manufacturing sectors, demand for domestic cement remains strong because it is not cost-effective to transport cement far from its point of manufacture.
- CO_2 emissions from iron and steel production decreased to 45.2 Tg CO_2 Eq. in 2005, and have declined by 39.6 Tg CO_2 Eq. (47 percent) from 1990 through 2005, due to restructuring of the industry, technological improvements, and increased scrap utilization.
- CO_2 emissions from municipal solid waste combustion (20.9 Tg CO_2 Eq. in 2005) increased by 10.0 Tg CO_2 Eq. (91 percent) from 1990 through 2005, as the volume of plastics and other fossil carbon-containing materials in municipal solid waste grew.
- Net CO_2 sequestration from Land Use, Land-Use Change, and Forestry increased by 115.7 Tg CO_2 Eq. (16 percent) from 1990 through 2005. 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. Annual carbon accumulation in landfilled yard trimmings and food scraps slowed over this period, while the rate of carbon accumulation in urban trees increased.

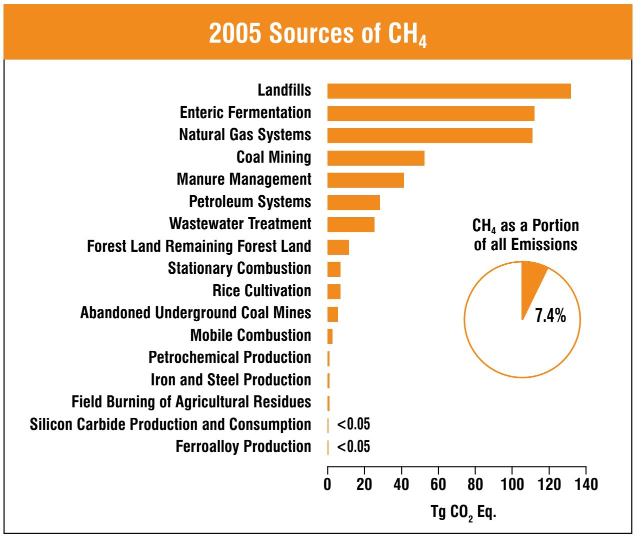
Methane Emissions

According to the IPCC, CH_4 is more than 20 times as effective as CO_2 at trapping heat in the atmosphere. Over the last two hundred and fifty years, the concentration of CH_4 in the atmosphere increased by 143 percent (IPCC 2001, Hofmann 2004). Anthropogenic sources of CH_4 include landfills, natural gas and petroleum systems, agricultural activities, coal mining, wastewater treatment, stationary and mobile combustion, and certain industrial processes (see Figure ES-8).

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

- Landfills are the largest anthropogenic source of CH_4 emissions in the United States. In 2005, landfill CH_4 emissions were 132.0 Tg CO_2 Eq. (approximately 24 percent of total CH_4 emissions), which represents a decline of 29.0 Tg CO_2 Eq., or 18 percent, since 1990. Although the amount of solid waste landfilled each year continues to grow, the amount of CH_4 captured and burned at landfills has increased dramatically, countering this trend.[11]
- In 2005, CH_4 emissions from coal mining were 52.4 Tg CO_2 Eq. This decline of 29.5 Tg CO_2 Eq. (36 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.
- CH_4 emissions from natural gas systems were 111.1 Tg CO_2 Eq. in 2005; emissions have declined by 13.3 Tg CO_2 Eq. (11 percent) since 1990. This decline has been due to improvements in technology and management practices, as well as some replacement of old equipment.
- CH_4 emissions from manure management were 41.3 Tg CO_2 Eq. in 2005. From 1990 to 2005, emissions from this source increased by 10.4 Tg CO_2 Eq. (34 percent). The bulk of this increase was from swine and dairy cow manure, and is attributed to the shift in the composition of the swine and dairy industries toward larger facilities. Larger swine and dairy farms tend to use liquid management systems, where the decomposition of materials in the manure tends to produce CH_4.

Figure ES-8



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. Since 1750, the global atmospheric concentration of N_2O has risen by approximately 18 percent (IPCC 2001, Hofmann 2004). The main anthropogenic activities producing N_2O in the United States are agricultural soil management, fuel combustion in motor vehicles, manure management, nitric acid production, wastewater treatment, and stationary fuel combustion (see Figure ES-9).

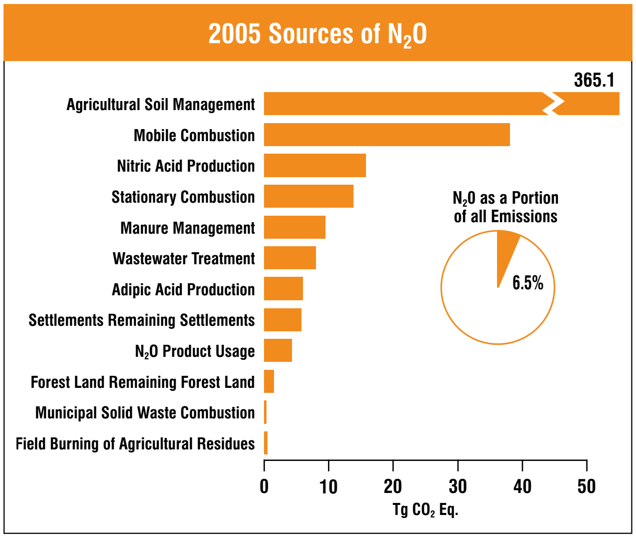
Some significant trends in U.S. emissions of N_2O include the following:

- Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 78 percent (365.1 Tg CO_2 Eq.) of 2005 emissions. N_2O emissions from this source have not shown any significant long-term trend, as they are highly sensitive to the amount of N applied to soils, which has not changed significantly over the time-period.
- In 2005, N_2O emissions from mobile combustion were 38.0 Tg CO_2 Eq. (approximately 8 percent of U.S. N_2O emissions). From 1990 to 2005, N_2O emissions from mobile combustion decreased by 13 percent. However, from 1990 to 1998 emissions increased by 10 percent, due to control technologies that reduced NO_x emissions while increasing N_2O emissions. Since 1998, newer

---

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

Figure ES-9



control technologies have led to a steady decline in N_2O from this source.

HFC, PFC, and SF_6 Emissions

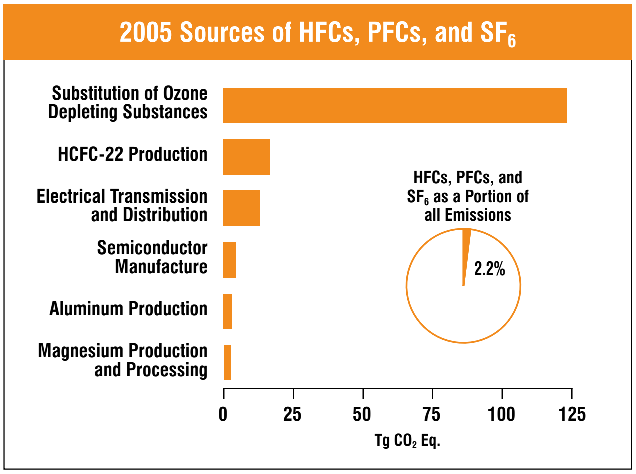
HFCs and PFCs are families of synthetic chemicals that are used as alternatives to the ODSs, which are being phased out under the *Montreal Protocol* and Clean Air Act Amendments of 1990. HFCs and PFCs do not deplete the stratospheric ozone layer, and are therefore acceptable alternatives under the *Montreal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

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

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

Figure ES-10



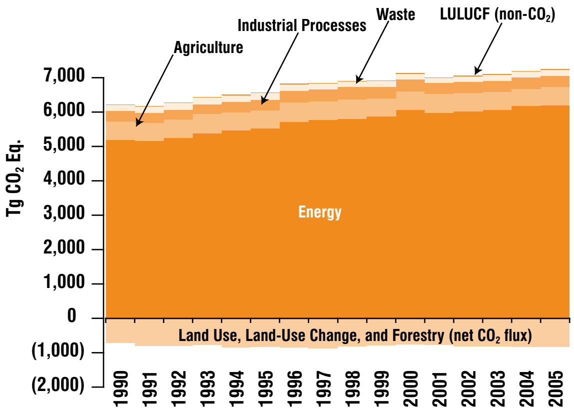
- Emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) have been increasing from small amounts in 1990 to 123.3 Tg CO_2 Eq. in 2005. Emissions from substitutes for ozone depleting substances are both the largest and the fastest growing source of HFC, PFC, and SF_6 emissions. These emissions have been increasing as phase-outs required under the Montreal Protocol come into effect, especially after 1994 when full market penetration was made for the first generation of new technologies featuring ODS substitutes.
- The increase in ODS substitute emissions is offset substantially by decreases in emission of HFCs, PFCs, and SF_6 from other sources. Emissions from aluminum production decreased by 84 percent (15.6 Tg CO_2 Eq.) from 1990 to 2005, due to both industry emission reduction efforts and lower domestic aluminum production.
- Emissions from the production of HCFC-22 decreased by 53 percent (18.4 Tg CO_2 Eq.) from 1990 through 2005, 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.
- Emissions from electric power transmission and distribution systems decreased by 51 percent (13.9 Tg CO_2 Eq.) from 1990 to 2005, primarily because of higher purchase prices for SF_6 and efforts by industry to reduce emissions.

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*

Figure ES-11

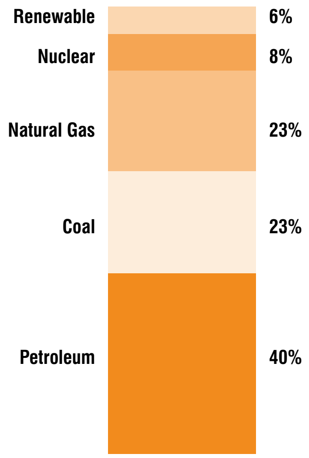
U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector



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

Figure ES-12

2005 U.S. Energy Consumption by Energy Source



Reporting and Review (UNFCCC 2003), the Inventory of U.S. Greenhouse Gas Emissions and Sinks report is segregated into six sector-specific chapters. Figure ES-11 and Table ES-4 aggregate emissions and sinks by these chapters.

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 2005. In 2005, approximately 86 percent of the energy consumed in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 14 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$_2$O emissions (38 percent and 11 percent of total U.S. emissions of each gas, respectively). Overall, emission sources in the Energy chapter account for a combined 85 percent of total U.S. greenhouse gas emissions in 2005.

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$_2$O. The processes

Table ES-4: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (Tg CO$_2$ Eq.)

Chapter/IPCC Sector	1990	1995	2000	2001	2002	2003	2004	2005
Energy	5,202.2	5,525.8	6,069.2	5,978.9	6,021.4	6,079.1	6,181.7	6,201.9
Industrial Processes	300.1	314.8	338.7	309.6	320.2	316.4	330.6	333.6
Solvent and Other Product Use	4.3	4.5	4.8	4.8	4.3	4.3	4.3	4.3
Agriculture	530.3	526.8	547.4	560.3	537.4	521.1	507.4	536.3
Land Use, Land-Use Change, and Forestry (Non-CO$_2$ Emissions)	13.0	10.1	21.3	12.4	17.4	15.0	13.9	18.9
Waste	192.2	189.1	165.9	161.1	163.9	168.4	165.7	165.4
Total	**6,242.0**	**6,571.0**	**7,147.2**	**7,027.0**	**7,064.6**	**7,104.2**	**7,203.7**	**7,260.4**
Net CO$_2$ Flux from Land Use, Land-Use Change, and Forestry*	(712.8)	(828.8)	(756.7)	(767.5)	(811.9)	(811.9)	(824.8)	(828.5)
Net Emissions (Sources and Sinks)	**5,529.2**	**5,742.2**	**6,390.5**	**6,259.5**	**6,252.7**	**6,292.3**	**6,378.9**	**6,431.9**

* 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.

include iron and steel production, lead and zinc production, cement manufacture, ammonia manufacture and urea application, lime manufacture, limestone and dolomite use (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash manufacture and use, titanium dioxide production, phosphoric acid production, ferroalloy production, CO_2 consumption, aluminum production, petrochemical production, silicon carbide production, nitric acid production, and adipic acid production. Additionally, emissions from industrial processes release HFCs, PFCs, and SF_6. Overall, emission sources in the Industrial Process chapter accounted for 4.6 percent of U.S. greenhouse gas emissions in 2005.

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 Product Usage, 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 carbon equivalent basis in 2005.

Agriculture

The Agriculture chapter contains anthropogenic emissions from agricultural activities (except fuel combustion, which is addressed in the Energy chapter, and agricultural CO_2 fluxes, which are addressed in the Land Use, Land-Use Change, and Forestry Chapter). Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes, including the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues. CH_4 and N_2O were the primary greenhouse gases emitted by agricultural activities. CH_4 emissions from enteric fermentation and manure management represented about 21 percent and 8 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2005. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions in 2005, accounting for 78 percent. In 2005, emission sources accounted for in the Agriculture chapter were responsible for 7.4 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 have resulted in a net uptake (sequestration) of C in the United States. Forests (including vegetation, soils, and harvested wood) accounted for approximately 84 percent of total 2005 sequestration, urban trees accounted for 11 percent, agricultural soils (including mineral and organic soils and the application of lime) accounted for 2 percent, and landfilled yard trimmings and food scraps accounted for 1 percent of the total sequestration in 2005. 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 soils account for a net C sink that is almost two times larger than the sum of emissions from organic soils and liming. 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 2005 resulted in a net C sequestration of 828.5 Tg CO_2 Eq. (Table ES-5). This represents an offset of approximately 13.6 percent of total U.S. CO_2 emissions, or 11.4 percent of total greenhouse gas emissions in 2005. Total land use, land-use change, and forestry net C sequestration increased by approximately 16 percent between 1990 and 2005, primarily due to an increase in the rate of net C accumulation in forest C stocks, particularly in aboveground and belowground tree biomass. Annual C accumulation in landfilled yard trimmings and food scraps slowed over this

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

Category	1990	1995	2000	2001	2002	2003	2004	2005
Forest Land Remaining Forest Land	**(598.5)**	**(717.5)**	**(638.7)**	**(645.7)**	**(688.1)**	**(687.0)**	**(697.3)**	**(698.7)**
Changes in Forest Carbon Stocks	(598.5)	(717.5)	(638.7)	(645.7)	(688.1)	(687.0)	(697.3)	(698.7)
Cropland Remaining Cropland	**(28.1)**	**(37.4)**	**(36.5)**	**(38.0)**	**(37.8)**	**(38.3)**	**(39.4)**	**(39.4)**
Changes in Agricultural Soil Carbon Stocks and Liming Emissions	(28.1)	(37.4)	(36.5)	(38.0)	(37.8)	(38.3)	(39.4)	(39.4)
Land Converted to Cropland	**8.7**	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**
Changes in Agricultural Soil Carbon Stocks	8.7	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Grassland Remaining Grassland	**0.1**	**16.4**	**16.3**	**16.2**	**16.2**	**16.2**	**16.1**	**16.1**
Changes in Agricultural Soil Carbon Stocks	0.1	16.4	16.3	16.2	16.2	16.2	16.1	16.1
Land Converted to Grassland	**(14.6)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**
Changes in Agricultural Soil Carbon Stocks	(14.6)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)
Settlements Remaining Settlements	**(57.5)**	**(67.8)**	**(78.2)**	**(80.2)**	**(82.3)**	**(84.4)**	**(86.4)**	**(88.5)**
Urban Trees	(57.5)	(67.8)	(78.2)	(80.2)	(82.3)	(84.4)	(86.4)	(88.5)
Other	**(22.8)**	**(13.3)**	**(10.5)**	**(10.6)**	**(10.8)**	**(9.3)**	**(8.7)**	**(8.8)**
Landfilled Yard Trimmings and Food Scraps	(22.8)	(13.3)	(10.5)	(10.6)	(10.8)	(9.3)	(8.7)	(8.8)
Total	**(712.8)**	**(828.8)**	**(756.7)**	**(767.5)**	**(811.9)**	**(811.9)**	**(824.8)**	**(828.5)**

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

Table ES-6: Non-CO_2 Emissions from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Category	1990	1995	2000	2001	2002	2003	2004	2005
Forest Land Remaining Forest Land	**7.8**	**4.5**	**15.7**	**6.9**	**11.8**	**9.2**	**8.0**	**13.1**
CH_4 Emissions from Forest Fires	7.1	4.0	14.0	6.0	10.4	8.1	6.9	11.6
N_2O Emissions from Forest Fires	0.7	0.4	1.4	0.6	1.1	0.8	0.7	1.2
N_2O Emissions from Soils	0.1	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Settlements Remaining Settlements	**5.1**	**5.5**	**5.6**	**5.5**	**5.6**	**5.8**	**6.0**	**5.8**
N_2O Emissions from Soils	5.1	5.5	5.6	5.5	5.6	5.8	6.0	5.8
Total	**13.0**	**10.1**	**21.3**	**12.4**	**17.4**	**15.0**	**13.9**	**18.9**

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

period, while the rate of annual C accumulation increased in urban trees. Net U.S. emissions (all sources and sinks) increased by 16.4 percent from 1990 to 2005.

Non-CO_2 emissions from Land Use, Land-Use Change, and Forestry are shown in Table ES-6. The application of synthetic fertilizers to forest and settlement soils in 2005 resulted in direct N_2O emissions of 6.2 Tg CO_2 Eq. Direct N_2O emissions from fertilizer application increased by approximately 19 percent between 1990 and 2005. Non-CO_2 emissions from forest fires in 2005 resulted in CH_4 emissions of 11.6 Tg CO_2 Eq., and in N_2O emissions of 1.2 Tg CO_2 Eq.

Waste

The Waste chapter contains emissions from waste management activities (except waste incineration, which is addressed in the Energy chapter). Landfills were the largest source of anthropogenic CH_4 emissions, accounting for 24 percent of total U.S. CH_4 emissions.[12] Additionally, wastewater treatment accounts for just under 5 percent of U.S. CH_4 emissions. 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. Overall, in 2005, emission sources accounted for in the Waste chapter generated 2.3 percent of total U.S. greenhouse gas emissions.

---

[12] 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.

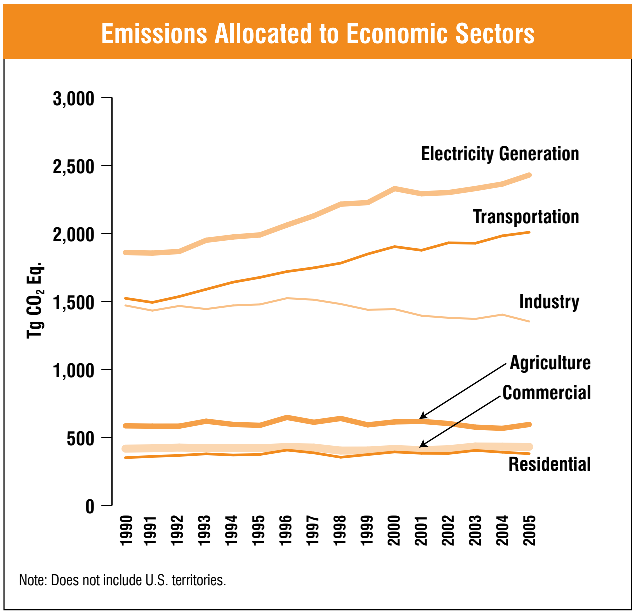
ES.4. Other Information

Emissions by Economic Sector

Throughout this 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, and 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 2005.

Figure ES-13



Emissions Allocated to Economic Sectors

Note: Does not include U.S. territories.

Using this categorization, emissions from electricity generation accounted for the largest portion (33 percent) of U.S. greenhouse gas emissions in 2005. Transportation activities, in aggregate, accounted for the second largest portion (28 percent). Emissions from industry accounted for 19 percent of U.S. greenhouse gas emissions in 2005. 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 20 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 about 5 percent, and primarily consisted of CO_2 emissions from fossil fuel combustion. Activities related to agriculture accounted for roughly 8 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 about 6 percent of emissions, while U.S. territories accounted for 1 percent.

CO_2 was also emitted and sequestered by a variety of activities related to forest management practices, tree

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

Implied Sectors	1990	1995	2000	2001	2002	2003	2004	2005
Electric Power Industry	1,859.7	1,989.5	2,329.9	2,292.0	2,300.7	2,330.2	2,363.4	2,429.8
Transportation	1,523.0	1,677.2	1,903.2	1,876.4	1,931.2	1,928.2	1,982.6	2,008.9
Industry	1,470.9	1,478.4	1,443.3	1,395.4	1,380.0	1,371.8	1,403.3	1,352.8
Agriculture	585.3	589.2	614.4	618.4	602.6	575.7	567.0	595.4
Commercial	417.8	420.5	415.5	406.6	413.7	433.5	432.6	431.4
Residential	351.3	375.1	393.6	383.6	382.7	404.8	391.6	380.7
U.S. Territories	34.1	41.1	47.3	54.5	53.6	60.0	63.2	61.5
Total Emissions	**6,242.0**	**6,571.0**	**7,147.2**	**7,027.0**	**7,064.6**	**7,104.2**	**7,203.7**	**7,260.4**
Land Use, Land-Use Change, and Forestry (Sinks)	(712.8)	(828.8)	(756.7)	(767.5)	(811.9)	(811.9)	(824.8)	(828.5)
Net Emissions (Sources and Sinks)	**5,529.2**	**5,742.2**	**6,390.5**	**6,259.5**	**6,252.7**	**6,292.3**	**6,378.9**	**6,431.9**

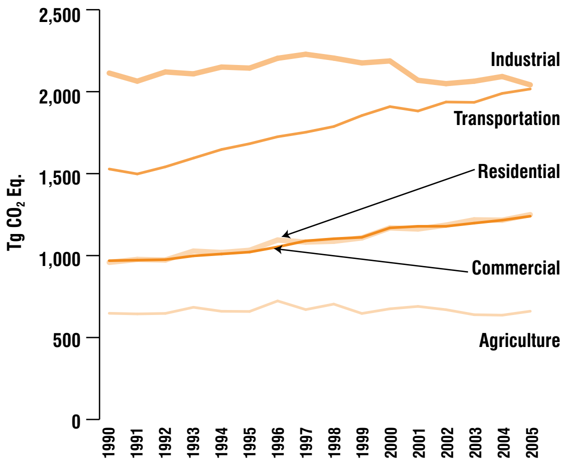
Note: Totals may not sum due to independent rounding. Emissions include CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6.
See Table 2-14 for more detailed data.

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.[13] 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 waste combustion, CH_4 and N_2O from stationary sources, and SF_6 from electrical transmission and distribution systems.

Figure ES-14

Emissions with Electricity Distributed to Economic Sectors



Note: Does not include U.S. territories.

When emissions from electricity are distributed among these sectors, industry accounts for the largest share of U.S. greenhouse gas emissions (28 percent) in 2005. Emissions from the residential and commercial sectors also increase substantially when emissions from electricity are included, due to their relatively large share of electricity consumption (e.g., lighting, appliances, etc.). Transportation activities remain the second largest contributor to total U.S. emissions (28 percent). 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 2005.

Indirect Greenhouse Gases (CO, NO_x, NMVOCs, and SO_2)

The reporting requirements of the UNFCCC[14] 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

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

Implied Sectors	1990	1995	2000	2001	2002	2003	2004	2005
Industry	2,111.1	2,141.5	2,185.0	2,067.1	2,046.6	2,061.4	2,090.1	2,039.3
Transportation	1,526.1	1,680.3	1,906.7	1,879.8	1,934.7	1,932.5	1,987.1	2,014.2
Commercial	967.2	1,019.8	1,167.4	1,176.8	1,177.0	1,196.2	1,214.1	1,238.5
Residential	956.9	1,030.6	1,167.0	1,160.3	1,184.3	1,216.2	1,214.2	1,248.0
Agriculture	646.5	657.6	673.9	688.5	668.4	637.9	635.0	659.1
U.S. Territories	34.1	41.1	47.3	54.5	53.6	60.0	63.2	61.5
Total Emissions	**6,242.0**	**6,571.0**	**7,147.2**	**7,027.0**	**7,064.6**	**7,104.2**	**7,203.7**	**7,260.4**
Land Use, Land-Use Change, and Forestry (Sinks)	(712.8)	(828.8)	(756.7)	(767.5)	(811.9)	(811.9)	(824.8)	(828.5)
Net Emissions (Sources and Sinks)	**5,529.2**	**5,742.2**	**6,390.5**	**6,259.5**	**6,252.7**	**6,292.3**	**6,378.9**	**6,431.9**

See Table 2-16 of this report for more detailed data.

---

[13] 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.

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

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 2005; (4) emissions per unit of total gross domestic product as a measure of national economic activity; or (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 1.0 percent since 1990. This rate is slightly slower than that for total energy or fossil fuel consumption and much slower than that for either electricity consumption or overall gross domestic product. Total U.S. greenhouse gas emissions have also grown slightly slower than national population since 1990 (see Figure ES-15).

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

Variable	1990	1995	2000	2001	2002	2003	2004	2005	Growth Rate[a]
GDP[b]	100	113	138	139	141	145	150	155	3.0%
Electricity Consumption[c]	100	112	127	125	128	129	131	134	2.0%
Fossil Fuel Consumption[c]	100	107	117	115	116	118	119	119	1.2%
Energy Consumption[c]	100	108	117	114	116	117	119	118	1.1%
Population[d]	100	107	113	114	115	116	117	118	1.1%
Greenhouse Gas Emissions[e]	100	105	115	113	113	114	115	116	1.0%

[a] Average annual growth rate

[b] Gross Domestic Product in chained 2000 dollars (BEA 2006)

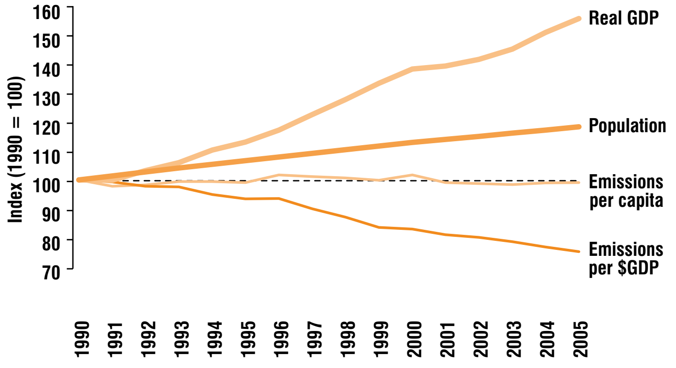
[c] Energy-content-weighted values (EIA 2006b)

[d] U.S. Census Bureau (2006)

[e] GWP-weighted values

Figure ES-15

U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product



Source: BEA (2006), U.S. Census Bureau (2006), and emission estimates in this report.

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 2006),[15] 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.

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."[16] By

Table ES-10: Emissions of NO_x, CO, NMVOCs, and SO_2 (Gg)

Gas/Activity	1990	1995	2000	2001	2002	2003	2004	2005
NO_x	**21,645**	**21,272**	**19,203**	**18,410**	**18,141**	**17,327**	**16,466**	**15,965**
Mobile Fossil Fuel Combustion	10,920	10,622	10,310	9,819	10,319	9,911	9,520	9,145
Stationary Fossil Fuel Combustion	9,883	9,821	8,002	7,667	6,837	6,428	5,952	5,824
Industrial Processes	591	607	626	656	532	533	534	535
Oil and Gas Activities	139	100	111	113	316	317	317	318
Municipal Solid Waste Combustion	82	88	114	114	97	98	98	98
Agricultural Burning	28	29	35	35	33	34	39	39
Solvent Use	1	3	3	3	5	5	5	5
Waste	0	1	2	2	2	2	2	2
CO	**130,581**	**109,157**	**92,897**	**89,333**	**86,796**	**84,370**	**82,073**	**79,811**
Mobile Fossil Fuel Combustion	119,480	97,755	83,680	79,972	77,382	74,756	72,269	69,915
Stationary Fossil Fuel Combustion	5,000	5,383	4,340	4,377	5,224	5,292	5,361	5,431
Municipal Solid Waste Combustion	978	1,073	1,670	1,672	1,440	1,457	1,475	1,493
Industrial Processes	4,125	3,959	2,217	2,339	1,710	1,730	1,751	1,772
Agricultural Burning	691	663	792	774	709	800	879	858
Oil and Gas Activities	302	316	146	147	323	327	331	335
Waste	1	2	8	8	7	7	7	7
Solvent Use	5	5	46	45	1	1	1	1
NMVOCs	**20,930**	**19,520**	**15,228**	**15,048**	**14,968**	**14,672**	**14,391**	**14,123**
Mobile Fossil Fuel Combustion	10,932	8,745	7,230	6,872	6,608	6,302	6,011	5,734
Solvent Use	5,216	5,609	4,384	4,547	3,911	3,916	3,921	3,926
Industrial Processes	2,422	2,642	1,773	1,769	1,811	1,813	1,815	1,818
Stationary Fossil Fuel Combustion	912	973	1,077	1,080	1,733	1,734	1,735	1,736
Oil and Gas Activities	554	582	389	400	546	547	547	548
Municipal Solid Waste Combustion	222	237	257	258	244	244	244	245
Waste	673	731	119	122	116	116	116	116
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA
SO_2	**20,935**	**16,891**	**14,829**	**14,452**	**13,541**	**13,648**	**13,328**	**13,271**
Stationary Fossil Fuel Combustion	18,407	14,724	12,848	12,461	11,852	12,002	11,721	11,698
Industrial Processes	1,307	1,117	1,031	1,047	752	759	766	774
Mobile Fossil Fuel Combustion	793	672	632	624	681	628	579	535
Oil and Gas Activities	390	335	286	289	233	235	238	240
Municipal Solid Waste Combustion	38	42	29	30	23	23	23	23
Waste	0	1	1	1	1	1	1	1
Solvent Use	0	1	1	1	0	0	0	0
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA

Source: (EPA 2006, disaggregated based on EPA 2003) except for estimates from field burning of agricultural residues.
NA (Not Available)
Note: Totals may not sum due to independent rounding.

---

[15] NO_x and CO emission estimates from field burning of agricultural residues were estimated separately, and therefore not taken from EPA (2006).

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

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 2005 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 this report. For more information regarding key categories, see section 1.5 and Annex 1 of this report.

Quality Assurance and Quality Control (QA/QC)

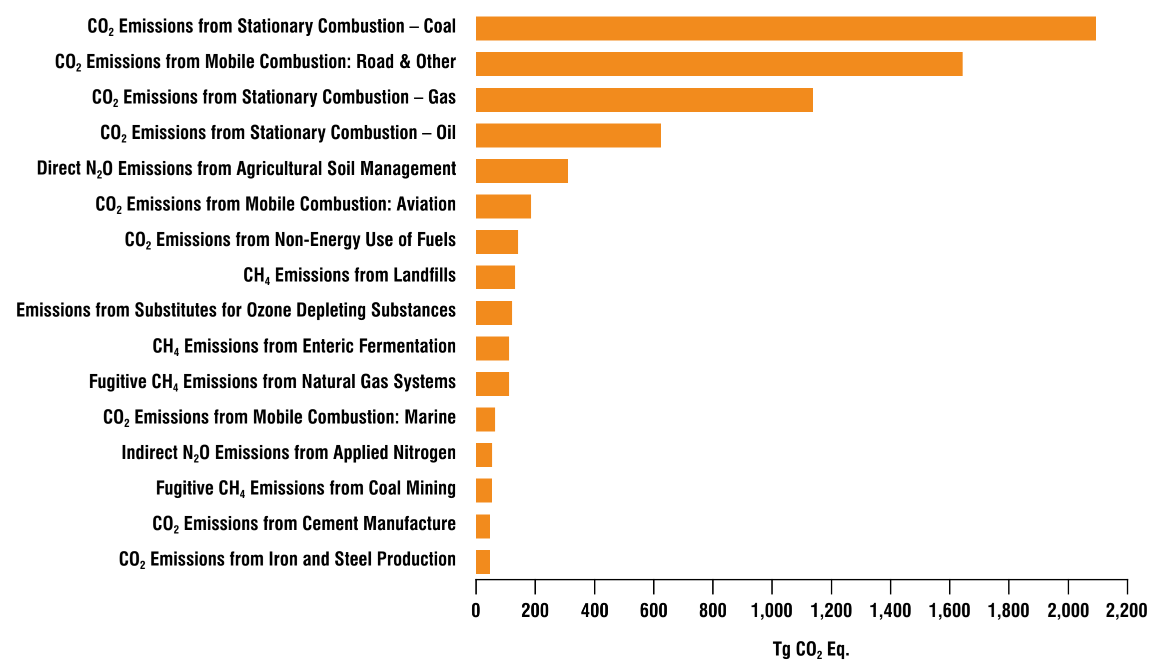
The United States seeks to continually improve the quality, transparency, and credibility of the Inventory of U.S. Greenhouse Gas Emissions and Sinks. To assist in these efforts, the United States implemented a systematic approach to QA/QC. While QA/QC has always been an integral part of the U.S. national 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-

Figure ES-16

2005 Key Categories-Tier 1 Level Assessment



Note: For a complete discussion of the key source analysis see Annex 1.

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 *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.

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 2005. A summary of these estimates is provided in Table 2-3 and Table 2-4 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.[1] This report also discusses the methods and data used to calculate these emission estimates.

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

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

In 1988, preceding the creation of the UNFCCC, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) jointly established the Intergovernmental Panel on Climate Change (IPCC). The role of the IPCC is to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation (IPCC 2003). Under Working Group 1 of the IPCC, nearly 140 scientists and national experts from more than thirty countries collaborated in the creation of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) to ensure that the emission inventories submitted to the UNFCCC are consistent and comparable between nations. The IPCC 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.

---

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

[2] The term "anthropogenic," in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC/UNEP/OECD/IEA 1997).

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

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

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 structure of this report is consistent with the current UNFCCC Guidelines on Annual Inventories (UNFCCC 2006).

1.1. Background Information

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.[5] 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.[6] 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) O_3. Tropospheric O_3 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.

---

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

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

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, 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.

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. 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 376.7 ppmv in 2004, a 35 percent increase (IPCC 2001 and Hofmann 2004).[7,8] 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,

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

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6	CF_4
Pre-industrial atmospheric concentration	280 ppm	0.722 ppm	0.270 ppm	0 ppt	40 ppt
Atmospheric concentration[a]	376.7 ppm	1.756 ppm	0.319 ppm	5.4 ppt	80 ppt
Rate of concentration change[b]	1,610 ppm/yr	0.005 ppm/yr	0.0007 ppm/yr	0.23 ppt/yr	1.0 ppt/yr
Atmospheric lifetime	50–200[c]	12[d]	114[d]	3,200	>50,000

Source: Current atmospheric concentrations and rate of concentration changes for all gases but CF_4 are from Hofmann (2004); data for CF_4 are from IPCC (2001). Pre-industrial atmospheric concentration and atmospheric lifetime taken from IPCC (2001).

[a] Concentration for CF_4 was measured in 2000. Concentrations for all other gases were measured in 2004.

[b] Rate is calculated over the period 1990 to 2004 for CO_2, CH_4, and N_2O; 1996 to 2004 for SF_6; and 1990 to 1999 for CF_4.

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

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

---

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

[8] 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).

other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of CO_2.

In its second assessment, the IPCC also stated that "[t]he increased amount of CO_2 [in the atmosphere] is leading to climate change and will produce, on average, a global warming of the earth's surface because of its enhanced greenhouse effect—although the magnitude and significance of the effects are not fully resolved" (IPCC 1996).

Methane. CH_4 is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes. CH_4 is also emitted during the production and distribution of natural gas and petroleum, and is released as a by-product of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of CH_4 have increased by about 143 percent since 1750, from a pre-industrial value of about 722 ppb to 1,756 ppb in 2004, 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 2001).

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. 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 combustion; 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 319 ppb in 2004, 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 2001).

Ozone. Ozone is present in both the upper stratosphere,[9] where it shields the earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[10] 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, with detection of such recovery not expected to occur much before 2010 (IPCC 2001).

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 [HBFCs]) 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

---

[9] 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.

[10] 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.

stratospheric ozone depletion, which itself is an important greenhouse gas in addition to shielding the earth from harmful levels of ultraviolet radiation. Under the *Montreal Protocol*, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the *Protocol*, a cap was placed on the production and importation of HCFCs by non-Article 5[11] 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.[12] Additionally, NO_x emissions from aircraft are 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

---

[11] 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.

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

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 aerosols, sulfates, and volcanic aerosols, and anthropogenically manufactured aerosols such as industrial dust and carbonaceous[13] 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.[14] 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, may have a positive radiative forcing (Jacobson 2001). 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.)[15] The relationship between gigagrams (Gg) of a gas and Tg CO_2 Eq. can be expressed as follows:

$$\text{Tg CO}_2\text{ Eq} = (\text{Gg of gas}) \times (\text{GWP}) \times \left(\frac{\text{Tg}}{1{,}000\text{ Gg}}\right)$$

where,

Tg CO_2 Eq. = Teragrams of Carbon Dioxide 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 100-year time horizon.*[16]

---

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

[14] 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).

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

[16] 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 1-2: 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.

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.

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 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

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

In 2001, the IPCC published its Third Assessment Report (TAR), 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 IPCC's Second Assessment Report (SAR), and new GWPs have been calculated for an expanded set of gases. Since the SAR, the IPCC has applied an improved calculation of CO_2 radiative forcing and an improved CO_2 response function (presented in WMO 1999). The GWPs are drawn from WMO (1999) and the SAR, with updates for those cases where significantly different new laboratory or radiative transfer results have been published. Additionally, the atmospheric lifetimes of some gases have been recalculated. Because the revised radiative forcing of CO_2 is about 12 percent lower than that in the SAR, the GWPs of the other gases relative to CO_2 tend to be larger, taking into account revisions in lifetimes. In addition, the values for radiative forcing and lifetimes have been calculated for a variety of halocarbons, which were not presented in the SAR. 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	Change	
CO_2	1	1	NC	NC
CH_4*	21	23	2	10%
N_2O	310	296	(14)	(5%)
HFC-23	11,700	12,000	300	3%
HFC-32	650	550	(100)	(15%)
HFC-125	2,800	3,400	600	21%
HFC-134a	1,300	1,300	NC	NC
HFC-143a	3,800	4,300	500	13%
HFC-152a	140	120	(20)	(14%)
HFC-227ea	2,900	3,500	600	21%
HFC-236fa	6,300	9,400	3,100	49%
HFC-4310mee	1,300	1,500	200	15%
CF_4	6,500	5,700	(800)	(12%)
C_2F_6	9,200	11,900	2,700	29%
C_4F_{10}	7,000	8,600	1,600	23%
C_6F_{14}	7,400	9,000	1,600	22%
SF_6	23,900	22,200	(1,700)	(7%)

Source: 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[17] 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 2005 are consistent and comparable with estimates developed prior to the publication of the TAR. For informational purposes, emission estimates that use the updated GWPs are presented in Annex 6.1 of this report. All estimates provided throughout this report are also presented in unweighted units.

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.

---

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

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 coordinator, who has 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). The QA/QC coordinator works closely with the source leads to ensure 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.

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.

Box 1-2: IPCC Reference Approach

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

1.5. Key Categories

The 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."[18] 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 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 either 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.

In addition to conducting Tier 1 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.

Table 1-4 presents the key categories for the United States based on the Tier 1 approach (including and excluding LULUCF categories) using emissions data in this report, and ranked according to their sector and GWP-weighted emissions in 2005. The table also indicates the criteria used in identifying these categories (i.e., level, trend, 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.

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*.

In particular, key attributes of the QA/QC plan include:

- specific detailed procedures (or protocols) and templates (or 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

---

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

Table 1-4: Key Categories for the United States (1990-2005) Based on Tier 1 Approach

IPCC Source Categories	Gas	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Qual[a]	2005 Emissions (Tg CO_2 Eq.)
Energy							
CO_2 Emissions from Stationary Combustion—Coal	CO_2	✓	✓	✓	✓		2,093.6
CO_2 Emissions from Mobile Combustion: Road & Other	CO_2	✓	✓	✓	✓		1,642.9
CO_2 Emissions from Stationary Combustion—Gas	CO_2	✓		✓			1,138.2
CO_2 Emissions from Stationary Combustion—Oil	CO_2	✓	✓	✓	✓		626.3
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	✓	✓	✓	✓		186.1
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	✓		✓	✓		142.4
Fugitive CH_4 Emissions from Natural Gas Systems	CH_4	✓	✓	✓	✓		111.1
International Bunker Fuels[b]	Several					✓	98.2
CO_2 Emissions from Mobile Combustion: Marine	CO_2	✓	✓	✓	✓		63.7
Fugitive CH_4 Emissions from Coal Mining	CH_4	✓	✓	✓	✓		52.4
Fugitive CH_4 Emissions from Petroleum Systems	CH_4	✓	✓	✓	✓		28.5
CO_2 Emissions from Natural Gas Systems	CO_2	✓	✓	✓	✓		28.2
CO_2 Emissions from Municipal Solid Waste Combustion	CO_2		✓		✓		20.9
N_2O Emissions from Mobile Combustion: Road & Other	N_2O	✓	✓	✓	✓		13.8
Industrial Processes							
Emissions from Substitutes for Ozone Depleting Substances	Several	✓	✓	✓	✓		123.3
CO_2 Emissions from Cement Production	CO_2	✓	✓	✓	✓		45.9
CO_2 Emissions from Iron and Steel Production	CO_2	✓	✓	✓	✓		45.2
HFC-23 Emissions from HCFC-22 Production	HFCs	✓	✓	✓	✓		16.5
CO_2 Emissions from Ammonia Manufacture and Urea Application	CO_2		✓		✓		16.3
SF_6 Emissions from Electrical Transmission and Distribution	SF_6		✓		✓		13.2
N_2O Emissions from Adipic Acid Production	N_2O		✓		✓		6.0
PFC Emissions from Aluminum Production	PFCs		✓		✓		3.0
Agriculture							
Direct N_2O Emissions from Agricultural Soils	N_2O	✓	✓	✓	✓		310.5
CH_4 Emissions from Enteric Fermentation in Domestic Livestock	CH_4	✓	✓	✓	✓		112.1
Indirect N_2O Emissions from Nitrogen Used in Agriculture	N_2O	✓	✓	✓	✓		54.6
CH_4 Emissions from Manure Management	CH_4			✓			9.5
Waste							
CH_4 Emissions from Landfills	CH_4	✓	✓	✓	✓		132.0
Land Use, Land-Use Change, and Forestry							
CO_2 Emissions from Forest Land Remaining Forest Land	CO_2			✓			(698.7)
CO_2 Emissions from Settlements Remaining Settlements	CO_2			✓	✓		(88.5)
CO_2 Emissions from Cropland Remaining Cropland	CO_2			✓	✓		(39.4)
CO_2 Emissions from Grassland Remaining Grassland	CO_2				✓		16.1
CO_2 Emissions from Landfilled Yard Trimmings and Food Scraps	CO_2				✓		(8.8)
Subtotal Without LULUCF							**7,036.4**
Total Emissions Without LULUCF							**7,241.5**
Percent of Total Without LULUCF							**97.2%**
Subtotal With LULUCF							**6,217.0**
Total Emissions With LULUCF							**6,431.9**
Percent of Total With LULUCF							**96.7%**

[a] Qualitative criteria.

[b] Emissions from this source not included in totals.

Note: Parentheses indicate negative values or sequestration. The Tier 1 approach for identifying key source categories does not directly include assessment of uncertainty in emissions estimates.

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 the current Inventory, source-specific plans have been developed and implemented for the majority of sources within the Energy and Industrial Process sectors. Throughout 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 checking and 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.

QA/QC procedures guide 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.

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 and cement processing, 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 of uncertainty 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. A preliminary estimate of the overall quantitative uncertainty is 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. Consistent with the IPCC good practice guidance, over a multi-year timeframe, the United States expects to continue to improve the uncertainty estimates presented in this report.

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 uncertainties associated with 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.

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

Gas	2005 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)		Mean[b] (Tg CO_2 Eq.)	Standard Deviation (Tg CO_2 Eq.)
		Lower Bound[c]	Upper Bound[c]	Lower Bound[c]	Upper Bound[c]		
CO_2	6,089.5	5,992.1	6,397.2	-2%	5%	6,193.5	106.0
CH_4	539.3	487.5	623.6	-10%	16%	554.0	34.6
N_2O	468.6	392.7	578.8	-16%	24%	486.0	47.5
PFC, HFC & SF_6[d]	163.0	152.8	188.6	-6%	16%	170.2	9.3
Total	**7,260.4**	**7,170.3**	**7,634.0**	**-1%**	**5%**	**7,403.7**	**120.9**
Net Emissions (Sources and Sinks)	**6,431.9**	**6,256.1**	**6,862.4**	**-3%**	**7%**	**6,559.9**	**155.5**

[a] Range of emission estimates for a 95 percent confidence interval.

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

[c] The 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.

[d] The overall uncertainty estimate 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 2005.

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 2005. 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 made, new emission sources are quantified and included in the Inventory. For a complete list of sources excluded, 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 2003 *UNFCCC Guidelines on Reporting and Review* (UNFCCC 2003), 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.

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 necessitated 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.

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 usage.
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)

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 Emissions from Petroleum Systems
	3.6.	Methodology for Estimating CO_2 and N_2O Emissions from Municipal Solid Waste Combustion
	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 from Agricultural Soil Management
	3.12.	Methodology for Estimating Net Carbon Stock Changes in Forest Lands Remaining Forest Lands
	3.13.	Methodology for Estimating Net Changes in Carbon Stocks in Mineral and Organic Soils on Croplands and Grasslands
	3.14.	Methodology for Estimating CH_4 Emissions from Landfills
ANNEX 4	**IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion**	
ANNEX 5	**Assessment of the Sources and Sinks of Greenhouse Gas Emissions Excluded**	
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 Analysis by Source

2. Trends in Greenhouse Gas Emissions

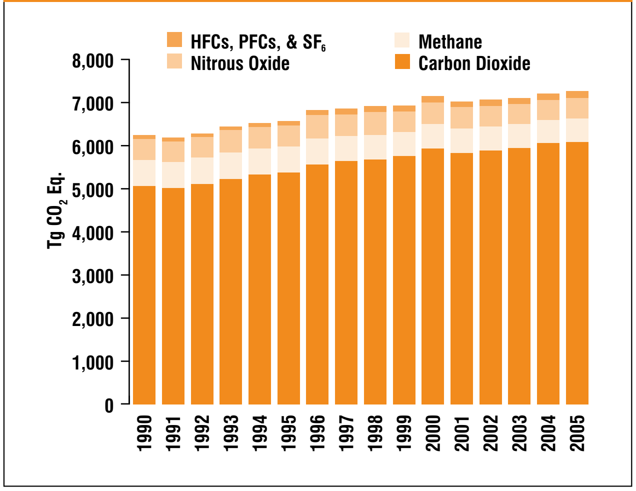
2.1. Recent Trends in U.S. Greenhouse Gas Emissions

In 2005, total U.S. greenhouse gas emissions were 7,260.4 teragrams of carbon dioxide equivalents (Tg CO_2 Eq.).[1] Overall, total U.S. emissions have risen by 16.3 percent from 1990 to 2005, while the U.S. gross domestic product has increased by 55 percent over the same period (BEA 2006). Emissions rose from 2004 to 2005, increasing by 0.8 percent (56.7 Tg CO_2 Eq.). The following factors were primary contributors to this increase: (1) strong economic growth in 2005, leading to increased demand for electricity and (2) an increase in the demand for electricity due to warmer summer conditions. These factors were moderated by decreasing demand for fuels due to warmer winter conditions and higher fuel prices. Figure 2-1 through Figure 2-3 illustrate the overall trends in total U.S. emissions by gas,[2] annual changes, and absolute changes since 1990.

As the largest source of U.S. greenhouse gas emissions, carbon dioxide (CO_2) from fossil fuel combustion has accounted for approximately 77 percent of global warming potential (GWP) weighted emissions since 1990, growing slowly from 76 percent of total GWP-weighted emissions in 1990 to 79 percent in 2005. Emissions from this source category grew by 21.7 percent (1,027.1 Tg CO_2 Eq.) from 1990 to 2005 and were responsible for most of the increase in national emissions during this period. From 2004 to 2005, these emissions increased by 0.7 percent (38.2 Tg CO_2 Eq.), slightly less than the source's average annual growth rate of 1.4 percent from 1990 through 2005. Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends.

Figure 2-1

U.S. Greenhouse Gas Emissions by Gas



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 generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives.

---

[1] 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, Chapter 1.)

[2] See the following section for an analysis of emission trends by general economic sector.

Figure 2-2

Annual Percent Change in U.S. Greenhouse Gas Emissions

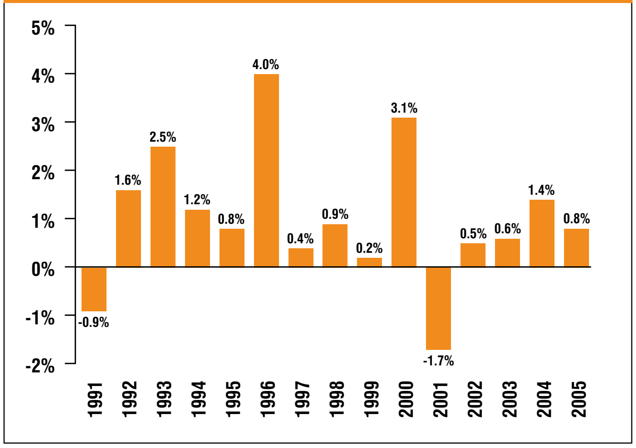
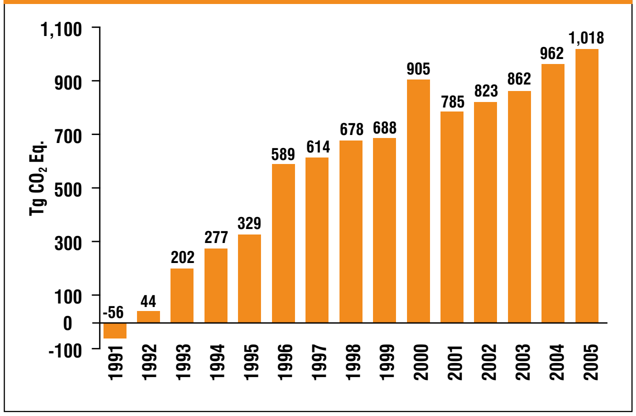


Figure 2-3

Cumulative Change in U.S. Greenhouse Gas Emissions Relative to 1990



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 consumer behavior (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. Table 2-1 shows annual changes in emissions during the last five years for coal, petroleum, and natural gas in selected sectors.

After emissions significantly decreased in 2001 due to the economic slowdown, emissions from fuel combustion resumed modest growth in 2002, slightly less than the average annual growth rate since 1990. There were a number of reasons behind this increase. The U.S. economy experienced moderate growth, recovering from weak economic conditions in 2001. Prices for fuels remained at or below 2001 levels; the cost of natural gas, motor gasoline, and electricity were all lower—triggering an increase in demand for fuel. In addition, the United States experienced one of the hottest summers on record, causing a significant increase in electricity use in the residential sector as the use of air-conditioners increased. Partially offsetting this increased consumption of fossil fuels, however, were

Table 2-1: Annual Change in CO_2 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (Tg CO_2 Eq. and Percent)

Sector	Fuel Type	2001 to 2002		2002 to 2003		2003 to 2004		2004 to 2005	
Electricity Generation	Coal	16.0	0.9%	38.0	2.0%	11.4	0.6%	40.8	2.1%
Electricity Generation	Natural Gas	16.1	5.5%	-27.7	-9.0%	18.4	6.6%	22.4	7.5%
Electricity Generation	Petroleum	-22.9	-22.5%	19.0	24.0%	2.0	2.0%	2.2	2.2%
Transportation[a]	Petroleum	51.8	3.0%	2.0	0.1%	55.1	3.1%	28.8	1.6%
Residential	Natural Gas	6.4	2.5%	11.5	4.3%	-12.2	-4.4%	-3.4	-1.3%
Commercial	Natural Gas	6.6	4.0%	2.6	1.5%	-3.1	-1.8%	-4.2	-2.5%
Industrial	Coal	-10.1	-7.6%	0.6	0.5%	2.3	1.8%	-4.0	-3.2%
Industrial	Natural Gas	9.4	2.2%	-14.5	-3.3%	0.6	0.1%	-34.8	-8.2%
All Sectors[b]	**All Fuels[b]**	**45.5**	**0.8%**	**67.3**	**1.2%**	**88.5**	**1.6%**	**38.2**	**0.7%**

[a] Excludes emissions from International Bunker Fuels.

[b] Includes fuels and sectors not shown in table (see Table 3-3 for complete list of fuels by sector).

increases in the use of nuclear and renewable fuels. Nuclear facilities operated at the highest capacity on record in 2002. Furthermore, there was a considerable increase in the use of hydroelectric power in 2002 after a very low output the previous year.

Emissions from fuel combustion continued growing in 2003, at about the average annual growth rate since 1990. A number of factors played a major role in the magnitude of this increase. The U.S. economy experienced moderate growth from 2002, causing an increase in the demand for fuels. The price of natural gas escalated dramatically, causing some electric power producers to switch to coal, which remained at relatively stable prices. Colder winter conditions brought on more demand for heating fuels, primarily in the residential sector. Though a cooler summer partially offset demand for electricity as the use of air-conditioners decreased, electricity consumption continued to increase in 2003. The primary drivers behind this trend were the growing economy and the increase in U.S. housing stock. Nuclear capacity decreased slightly, for the first time since 1997. Use of renewable fuels rose slightly due to increases in the use of hydroelectric power and biofuels.

From 2003 to 2004, these emissions increased at a rate slightly higher than the average growth rate since 1990. A number of factors played a major role in the magnitude of this increase. A primary reason behind this trend was strong growth in the U.S. economy and industrial production, particularly in energy-intensive industries, causing an increase in the demand for electricity and fossil fuels. Demand for travel was also higher, causing an increase in petroleum consumed for transportation. In contrast, the warmer winter conditions led to decreases in demand for heating fuels, principally natural gas, in both the residential and commercial sectors. Moreover, much of the increased electricity demanded was generated by natural gas combustion and nuclear power, which moderated the increase in CO_2 emissions from electricity generation. Use of renewable fuels rose very slightly due to increases in the use of biofuels.

Emissions from fuel combustion increased from 2004 to 2005 at a rate slightly lower than the average annual growth rate since 1990. A number of factors played a role in this slight increase. This small increase is primarily a result of the restraint on fuel consumption, primarily in the transportation sector, caused by rising fuel prices. Although electricity prices increased slightly, there was a significant increase in electricity consumption in the residential and commercial sectors due to warmer summer weather conditions. This led to an increase in emissions in these sectors with the increased use of air-conditioners. As electricity emissions increased among all end-use sectors, the fuels used to generate electricity increased as well. Despite a slight decrease in industrial energy-related emissions, industrial production and manufacturing output actually increased. The price of natural gas escalated dramatically, causing a decrease in consumption of natural gas in the industrial sector. Use of renewable fuels decreased slightly due to decreased use of biofuels and decreased electricity output by hydroelectric power plants.

Other significant trends in emissions from additional source categories over the fifteen-year period from 1990 through 2005 included the following:

- CO_2 emissions from waste combustion increased by 10.0 Tg CO_2 Eq. (91percent), as the volume of plastics and other fossil-carbon-containing materials in municipal solid waste grew.
- Net CO_2 sequestration from Land Use, Land-Use Change, and Forestry increased by 115.7 Tg CO_2 Eq. (16 percent) from 1990 through 2005. This increase was primarily due to an increase in the rate of net C accumulation in forest C stocks, particularly in aboveground and belowground tree biomass. Annual C accumulation in landfilled yard trimmings and food scraps slowed over this period, while the rate of C accumulation in urban trees increased.
- Methane (CH_4) emissions from coal mining declined by 29.5 Tg CO_2 Eq. (36 percent) from 1990 to 2005 as a result of the mining of less gassy coal from underground mines and the increased combustion of CH_4 collected from degasification systems.
- From 1990 to 2005, nitrous oxide (N_2O) emissions from mobile combustion decreased by 13.1 percent. However, from 1990 to 1998 emissions increased by 26 percent, due to control technologies that reduced CH_4 emissions while increasing N_2O emissions. Since 1998, new control technologies have led to a steady decline in N_2O from this source.
- Emissions resulting from the substitution of ozone depleting substances (ODS, e.g., chlorofluorocarbons

Box 2-1: 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 2005; (4) emissions per unit of total gross domestic product as a measure of national economic activity; or (5) emissions per capita.

Table 2-2 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 1.1 percent since 1990. This rate is slightly slower than that for total energy or fossil fuel consumption and much slower than that for either electricity consumption or overall gross domestic product. Total U.S. greenhouse gas emissions have also grown slightly slower than national population since 1990 (see Figure 2-4).

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

Variable	1990	1995	2000	2001	2002	2003	2004	2005	Growth Rate[a]
GDP[b]	100	113	138	139	141	145	150	155	3.0%
Electricity Consumption[c]	100	112	127	125	128	129	131	134	2.0%
Fossil Fuel Consumption[c]	100	107	117	115	116	118	119	119	1.2%
Energy Consumption[c]	100	108	117	114	116	117	119	118	1.1%
Population[d]	100	107	113	114	115	116	117	118	1.1%
Greenhouse Gas Emissions[e]	100	105	115	113	113	114	115	116	1.0%

[a] Average annual growth rate

[b] Gross Domestic Product in chained 2000 dollars (BEA 2006)

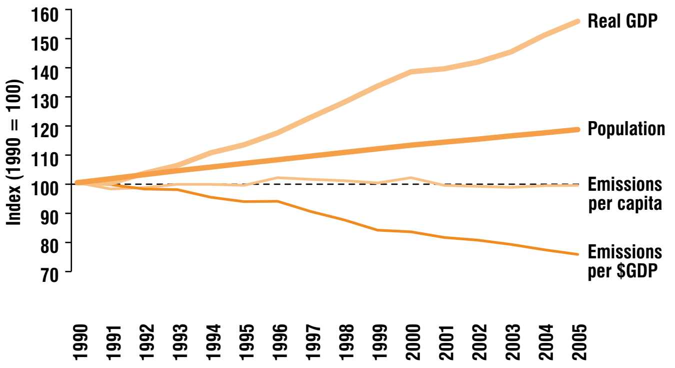
[c] Energy-content-weighted values (EIA 2006b)

[d] U.S. Census Bureau (2006)

[e] GWP-weighted values

Figure 2-4

U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product



Source: BEA (2006), U.S. Census Bureau (2006), and emission estimates in the this report.

[CFCs]) have increased dramatically, from small amounts in 1990 to 123.3 Tg CO_2 Eq. in 2005. These emissions have been increasing as phase-outs of ODS required under the Montreal Protocol come into effect.

- The increase in ODS substitutes emissions is offset substantially by decreases in emission of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) from other sources. Emissions from aluminum production decreased by 84 percent (15.6 Tg CO_2 Eq.) from 1990 to 2005, due to both industry emission reduction efforts and lower domestic aluminum production. Emissions from the production of HCFC-22 decreased by 53 percent (18.4 Tg CO_2 Eq.) from 1990 to 2005, 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. Emissions from electric power transmission and distribution systems decreased by 51 percent (13.9 Tg CO_2 Eq.) from 1990 to 2005, primarily because of higher purchase prices for SF_6 and efforts by industry to reduce emissions.

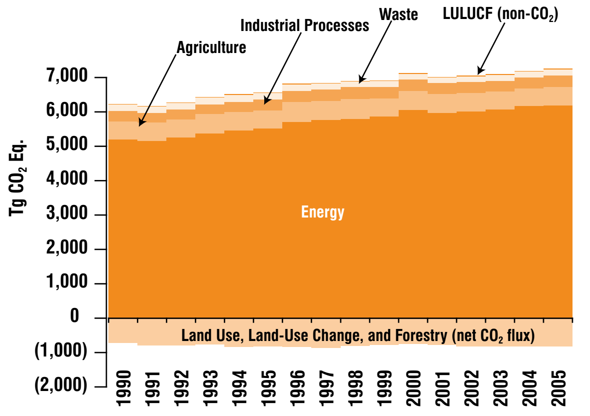
Overall, from 1990 to 2005, total emissions of CO_2 increased by 1,027.9 Tg CO_2 Eq. (20 percent), while CH_4 and N_2O emissions decreased by 69.8 Tg CO_2 Eq. (11 percent) and 13.4 Tg CO_2 Eq. (2.8 percent) respectively. During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 73.7 Tg CO_2 Eq. (82.5 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, which was estimated to be 11 percent of total emissions in 2005.

Table 2-3 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 2-4. Figure 2-5 and Table 2-5 show emissions and sinks aggregated by sector/chapter.

Emissions of all gases can be summed from each source category from Intergovernmental Panel on Climate Change (IPCC) guidance. Over the fifteen-year period of 1990 to 2005, total emissions in the Energy, Industrial Processes, and Agriculture sectors climbed by 1,001.5 Tg CO_2 Eq. (19 percent), 33.6 Tg CO_2 Eq. (11 percent), and 6.0 Tg CO_2 Eq. (1.1 percent), respectively. Emissions decreased from the Solvent and Other Product Use and Waste sectors by 0.02 Tg CO_2 Eq. (less than 1 percent) and 26.7 Tg CO_2 Eq. (14 percent), respectively. Over the same period, estimates of net C sequestration in the Land Use, Land-Use Change, and Forestry sector increased by 109.5 Tg CO_2 Eq. (16 percent).

Figure 2-5

U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector



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

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

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**5,061.6**	**5,384.6**	**5,940.0**	**5,843.0**	**5,892.7**	**5,952.5**	**6,064.3**	**6,089.5**
Fossil Fuel Combustion	4,724.1	5,030.0	5,584.9	5,511.7	5,557.2	5,624.5	5,713.0	5,751.2
Non-Energy Use of Fuels	117.3	133.2	141.0	131.4	135.3	131.3	150.2	142.4
Cement Manufacture	33.3	36.8	41.2	41.4	42.9	43.1	45.6	45.9
Iron and Steel Production	84.9	73.3	65.1	57.9	54.6	53.4	51.3	45.2
Natural Gas Systems	33.7	33.8	29.4	28.8	29.6	28.4	28.2	28.2
Municipal Solid Waste Combustion	10.9	15.7	17.9	18.3	18.5	19.5	20.1	20.9
Ammonia Manufacture and Urea Application	19.3	20.5	19.6	16.7	17.8	16.2	16.9	16.3
Lime Manufacture	11.3	12.8	13.3	12.9	12.3	13.0	13.7	13.7
Limestone and Dolomite Use	5.5	7.4	6.0	5.7	5.9	4.7	6.7	7.4
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.1	4.1	4.1	4.2	4.2
Aluminum Production	6.8	5.7	6.1	4.4	4.5	4.5	4.2	4.2
Petrochemical Production	2.2	2.8	3.0	2.8	2.9	2.8	2.9	2.9
Titanium Dioxide Production	1.3	1.7	1.9	1.9	2.0	2.0	2.3	1.9
Ferroalloy Production	2.2	2.0	1.9	1.5	1.3	1.3	1.4	1.4
Phosphoric Acid Production	1.5	1.5	1.4	1.3	1.3	1.4	1.4	1.4
CO_2 Consumption	1.4	1.4	1.4	0.8	1.0	1.3	1.2	1.3
Zinc Production	0.9	1.0	1.1	1.0	0.9	0.5	0.5	0.5
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Production and Consumption	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Net CO_2 Flux from Land Use, Land-Use Change, and Forestry[a]	*(712.8)*	*(828.8)*	*(756.7)*	*(767.5)*	*(811.9)*	*(811.9)*	*(824.8)*	*(828.5)*
International Bunker Fuels[b]	*113.7*	*100.6*	*101.1*	*97.6*	*89.1*	*83.7*	*97.2*	*97.2*
Wood Biomass and Ethanol Consumption[b]	*219.3*	*236.8*	*228.3*	*203.2*	*204.4*	*209.6*	*224.8*	*206.5*
CH_4	**609.1**	**598.7**	**563.7**	**547.7**	**549.7**	**549.2**	**540.3**	**539.3**
Landfills	161.0	157.1	131.9	127.6	130.4	134.9	132.1	132.0
Enteric Fermentation	115.7	120.6	113.5	112.5	112.6	113.0	110.5	112.1
Natural Gas Systems	124.5	128.1	126.6	125.4	125.0	123.7	119.0	111.1
Coal Mining	81.9	66.5	55.9	55.5	52.0	52.1	54.5	52.4
Manure Management	30.9	35.1	38.7	40.1	41.1	40.5	39.7	41.3
Petroleum Systems	34.4	31.1	27.8	27.4	26.8	25.8	25.4	28.5
Wastewater Treatment	24.8	25.1	26.4	25.9	25.8	25.6	25.7	25.4
Forest Land Remaining Forest Land	7.1	4.0	14.0	6.0	10.4	8.1	6.9	11.6
Stationary Combustion	8.0	7.8	7.4	6.8	6.8	7.0	7.1	6.9
Rice Cultivation	7.1	7.6	7.5	7.6	6.8	6.9	7.6	6.9
Abandoned Underground Coal Mines	6.0	8.2	7.3	6.7	6.1	5.9	5.8	5.5
Mobile Combustion	4.7	4.3	3.5	3.2	3.1	2.9	2.8	2.6
Petrochemical Production	0.9	1.1	1.2	1.1	1.1	1.1	1.2	1.1
Iron and Steel Production	1.3	1.3	1.2	1.1	1.0	1.0	1.0	1.0
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.8	0.7	0.8	0.9	0.9
Ferroalloy Production	+	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**482.0**	**484.2**	**499.8**	**502.5**	**479.2**	**459.8**	**445.2**	**468.6**
Agricultural Soil Management	366.9	353.4	376.8	389.0	366.1	350.2	338.8	365.1
Mobile Combustion	43.7	53.7	53.2	49.7	47.1	43.8	41.2	38.0
Nitric Acid Production	17.8	19.9	19.6	15.9	17.2	16.7	16.0	15.7
Stationary Combustion	12.3	12.8	14.0	13.5	13.4	13.7	13.9	13.8
Manure Management	8.6	9.0	9.6	9.8	9.7	9.3	9.4	9.5
Wastewater Treatment	6.4	6.9	7.6	7.6	7.7	7.8	7.9	8.0
Adipic Acid Production	15.2	17.2	6.0	4.9	5.9	6.2	5.7	6.0
Settlements Remaining Settlements	5.1	5.5	5.6	5.5	5.6	5.8	6.0	5.8
N_2O Product Usage	4.3	4.5	4.8	4.8	4.3	4.3	4.3	4.3
Forest Land Remaining Forest Land	0.8	0.6	1.7	1.0	1.4	1.2	1.1	1.5
Municipal Solid Waste Combustion	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.4	0.4	0.5	0.5
International Bunker Fuels[b]	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*	*0.9*	*0.9*
HFCs, PFCs, and SF_6	**89.3**	**103.5**	**143.8**	**133.8**	**143.0**	**142.7**	**153.9**	**163.0**
Substitution of Ozone Depleting Substances	0.3	32.2	80.9	88.6	96.9	105.5	114.5	123.3
HCFC-22 Production	35.0	27.0	29.8	19.8	19.8	12.3	15.6	16.5
Electrical Transmission and Distribution	27.1	21.8	15.2	15.1	14.3	13.8	13.6	13.2
Semiconductor Manufacture	2.9	5.0	6.3	4.5	4.4	4.3	4.7	4.3
Aluminum Production	18.5	11.8	8.6	3.5	5.2	3.8	2.8	3.0
Magnesium Production and Processing	5.4	5.6	3.0	2.4	2.4	2.9	2.6	2.7
Total	**6,242.0**	**6,571.0**	**7,147.2**	**7,027.0**	**7,064.6**	**7,104.2**	**7,203.7**	**7,260.4**
Net Emissions (Sources and Sinks)	**5,529.2**	**5,742.2**	**6,390.5**	**6,259.5**	**6,252.7**	**6,292.3**	**6,378.9**	**6,431.9**

+ 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 International Bunker Fuels and Wood Biomass and Ethanol Consumption are not included in totals.

Note: Totals may not sum due to independent rounding.

Table 2-4: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**5,061,634**	**5,384,615**	**5,939,968**	**5,843,025**	**5,892,744**	**5,952,538**	**6,064,329**	**6,089,490**
Fossil Fuel Combustion	4,724,149	5,030,036	5,584,880	5,511,719	5,557,242	5,624,500	5,713,018	5,751,200
Non-Energy Use of Fuels	117,307	133,228	141,005	131,375	135,327	131,334	150,208	142,368
Cement Manufacture	33,278	36,847	41,190	41,357	42,898	43,082	45,603	45,910
Iron and Steel Production	84,904	73,333	65,115	57,927	54,595	53,370	51,309	45,235
Natural Gas Systems	33,729	33,807	29,390	28,793	29,630	28,445	28,190	28,185
Municipal Solid Waste Combustion	10,950	15,712	17,889	18,344	18,513	19,490	20,115	20,912
Ammonia Manufacture and Urea Application	19,306	20,453	19,616	16,719	17,766	16,173	16,894	16,321
Lime Manufacture	11,273	12,844	13,344	12,861	12,330	13,022	13,728	13,660
Limestone and Dolomite Use	5,533	7,359	5,960	5,733	5,885	4,720	6,702	7,397
Soda Ash Manufacture and Consumption	4,141	4,304	4,181	4,147	4,139	4,111	4,205	4,228
Aluminum Production	6,831	5,659	6,086	4,381	4,490	4,503	4,231	4,208
Petrochemical Production	2,221	2,750	3,004	2,787	2,857	2,777	2,895	2,897
Titanium Dioxide Production	1,308	1,670	1,918	1,857	1,997	2,013	2,259	1,921
Ferroalloy Production	2,152	2,036	1,893	1,459	1,349	1,305	1,419	1,392
Phosphoric Acid Production	1,529	1,513	1,382	1,264	1,338	1,382	1,395	1,383
CO_2 Consumption	1,415	1,423	1,416	825	978	1,310	1,199	1,324
Zinc Production	949	1,013	1,140	986	937	507	477	465
Lead Production	285	298	311	293	290	289	259	265
Silicon Carbide Production and Consumption	375	329	248	199	183	202	224	219
Net CO_2 Flux from Land Use, Land-Use Change, and Forestry[a]	*(712,778)*	*(828,798)*	*(756,705)*	*(767,472)*	*(811,892)*	*(811,945)*	*(824,785)*	*(828,453)*
International Bunker Fuels[b]	*113,683*	*100,627*	*101,125*	*97,563*	*89,101*	*83,690*	*97,177*	*97,191*
Wood Biomass and Ethanol Consumption[b]	*219,341*	*236,775*	*228,308*	*203,163*	*204,351*	*209,603*	*224,825*	*206,475*
CH_4	**29,003**	**28,509**	**26,842**	**26,080**	**26,176**	**26,154**	**25,727**	**25,681**
Landfills	7,668	7,479	6,280	6,078	6,210	6,425	6,292	6,286
Enteric Fermentation	5,510	5,744	5,404	5,356	5,361	5,379	5,262	5,340
Natural Gas Systems	5,927	6,101	6,027	5,971	5,951	5,891	5,669	5,292
Coal Mining	3,899	3,165	2,662	2,644	2,476	2,480	2,597	2,494
Manure Management	1,471	1,673	1,844	1,911	1,959	1,928	1,892	1,966
Petroleum Systems	1,640	1,482	1,325	1,303	1,275	1,229	1,209	1,357
Wastewater Treatment	1,180	1,195	1,257	1,232	1,229	1,220	1,222	1,210
Forest Land Remaining Forest Land	337	189	667	285	494	384	330	551
Stationary Combustion	382	373	351	324	324	334	340	330
Rice Cultivation	339	363	357	364	325	328	360	328
Abandoned Underground Coal Mines	286	391	349	318	292	282	275	263
Mobile Combustion	226	207	165	154	146	136	131	125
Petrochemical Production	41	52	58	51	52	51	55	51
Iron and Steel Production	63	62	57	51	48	49	50	45
Field Burning of Agricultural Residues	33	32	38	37	34	38	42	41
Ferroalloy Production	1	1	1	+	+	+	+	+
Silicon Carbide Production and Consumption	1	1	1	+	+	+	+	+
International Bunker Fuels[b]	*8*	*6*	*6*	*5*	*4*	*4*	*5*	*5*
N_2O	**1,555**	**1,562**	**1,612**	**1,621**	**1,546**	**1,483**	**1,436**	**1,512**
Agricultural Soil Management	1,184	1,140	1,215	1,255	1,181	1,130	1,093	1,178
Mobile Combustion	141	173	172	160	152	141	133	123
Nitric Acid Production	58	64	63	51	56	54	52	51
Stationary Combustion	40	41	45	44	43	44	45	45
Manure Management	28	29	31	32	31	30	30	31
Wastewater Treatment	21	22	24	25	25	25	26	26
Adipic Acid Production	49	56	19	16	19	20	19	19
Settlements Remaining Settlements	17	18	18	18	18	19	19	19
N_2O Product Usage	14	14	15	15	14	14	14	14
Forest Land Remaining Forest Land	2	2	6	3	5	4	3	5
Municipal Solid Waste Combustion	2	1	1	1	1	1	1	1
Field Burning of Agricultural Residues	1	1	1	1	1	1	2	2
International Bunker Fuels[b]	*3*	*3*	*3*	*3*	*3*	*2*	*3*	*3*
HFCs, PFCs, and SF_6	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M	M
HCFC-22 Production	3	2	3	2	2	1	1	1
Electrical Transmission and Distribution	1	1	1	1	1	1	1	1
Semiconductor Manufacture	M	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M	M
Magnesium Production and Processing	+	+	+	+	+	+	+	+

+ 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 International Bunker Fuels and Wood Biomass and Ethanol Consumption are not included in totals.

Note: Totals may not sum due to independent rounding.

Table 2-5: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (Tg CO_2 Eq.)

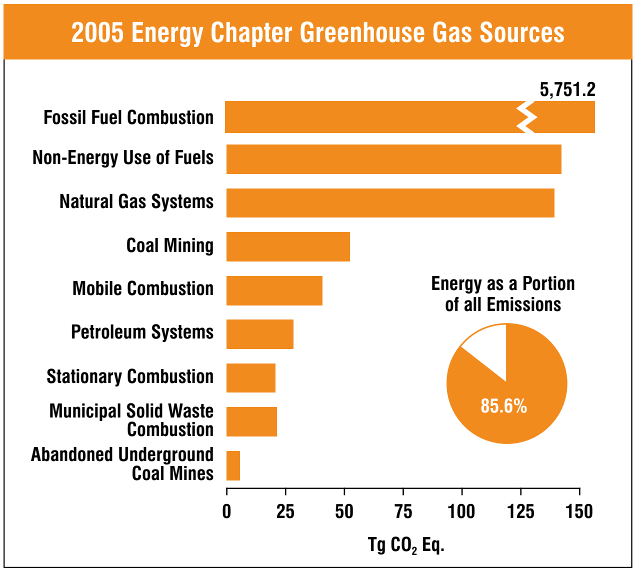
Chapter/IPCC Sector	1990	1995	2000	2001	2002	2003	2004	2005
Energy	5,202.2	5,525.8	6,069.2	5,978.9	6,021.4	6,079.1	6,181.7	6,201.9
Industrial Processes	300.1	314.8	338.7	309.6	320.2	316.4	330.6	333.6
Solvent and Other Product Use	4.3	4.5	4.8	4.8	4.3	4.3	4.3	4.3
Agriculture	530.3	526.8	547.4	560.3	537.4	521.1	507.4	536.3
Land Use, Land-Use Change, and Forestry (Non-CO_2 Emissions)	13.0	10.1	21.3	12.4	17.4	15.0	13.9	18.9
Waste	192.2	189.1	165.9	161.1	163.9	168.4	165.7	165.4
Total	**6,242.0**	**6,571.0**	**7,147.2**	**7,027.0**	**7,064.6**	**7,104.2**	**7,203.7**	**7,260.4**
Net CO_2 Flux from Land Use, Land-Use Change, and Forestry*	(712.8)	(828.8)	(756.7)	(767.5)	(811.9)	(811.9)	(824.8)	(828.5)
Net Emissions (Sources and Sinks)	**5,529.2**	**5,742.2**	**6,390.5**	**6,259.5**	**6,252.7**	**6,292.3**	**6,378.9**	**6,431.9**

* 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.
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 2005. In 2005, approximately 86 percent of the energy consumed in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 14 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy (see Figure 2-6 and Figure 2-7). A discussion of specific trends related to CO_2 as well as other greenhouse gas emissions from energy consumption is presented below. Energy-related activities are also responsible for CH_4 and N_2O emissions (38 percent and 11 percent of total U.S. emissions of each gas, respectively). Table 2-6 presents greenhouse gas emissions from the Energy chapter, by source and gas.

Figure 2-6



2005 Energy Chapter Greenhouse Gas Sources

Fossil Fuel Combustion (5,751.2 Tg CO_2 Eq.)

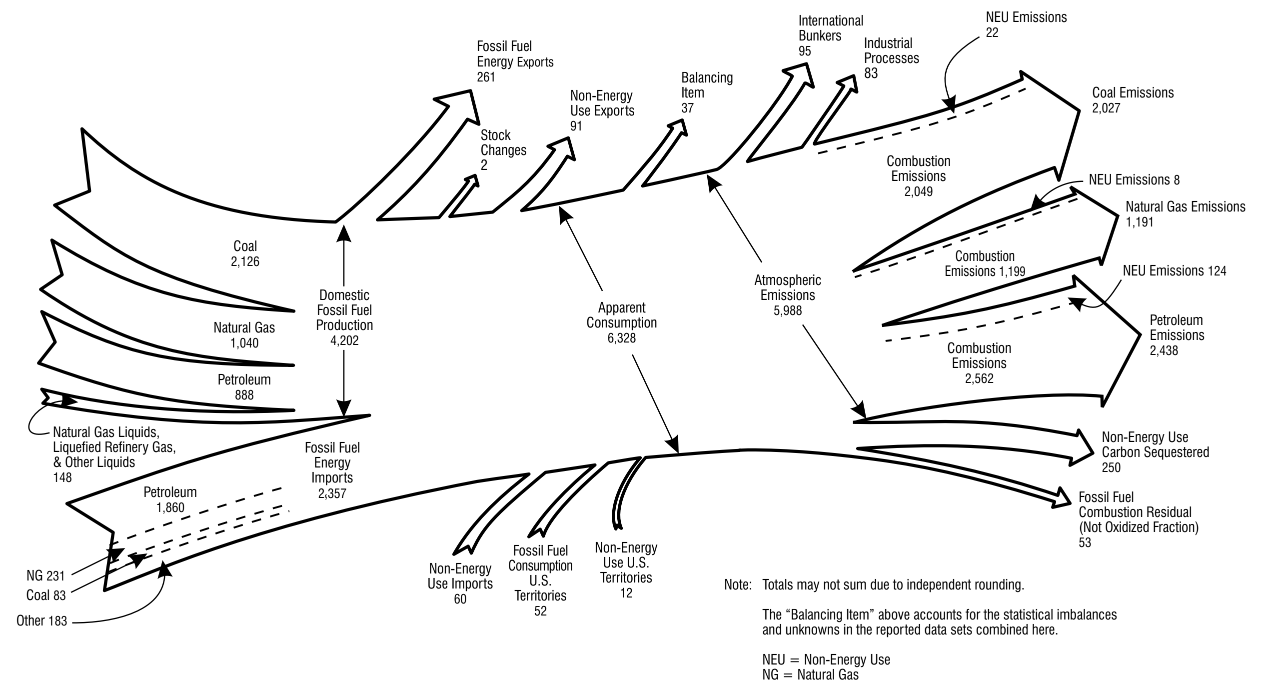
As fossil fuels are combusted, the C stored in them is emitted almost entirely as CO_2. The amount of C in fuels per unit of energy content varies significantly by fuel type. For example, coal contains the highest amount of C per unit of energy, while petroleum and natural gas have about 25 percent and 45 percent less C than coal, respectively. From 1990 through 2005, petroleum supplied the largest share of U.S. energy demands, accounting for an average of 44 percent of total energy consumption, with natural gas and coal each accounting for 28 percent of total energy consumption. Petroleum was consumed primarily in the transportation end-use sector, the vast majority of coal was used by electric power generators, and natural gas was consumed largely in the industrial and residential end-use sectors.

Emissions of CO_2 from fossil fuel combustion increased at an average annual rate of 1.4 percent from 1990 to 2005. The fundamental factors influencing this trend include (1) a generally growing domestic economy over the last 15 years, and (2) significant growth in emissions from electricity generation and transportation activities. Between 1990 and 2005, CO_2 emissions from fossil fuel combustion increased from 4,724.1 Tg CO_2 Eq. to 5,751.2 Tg CO_2 Eq.—a 21.7 percent total increase over the fifteen-year period.

The four major end-use sectors contributing to CO_2 emissions from fossil fuel combustion are industrial, transportation, residential, and commercial. Electricity generation also emits CO_2, although these emissions are produced as they consume fossil fuel to provide electricity to one of the four end-use sectors. For the discussion below, electricity generation emissions have been distributed to

Figure 2-7

2005 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)



Note: Totals may not sum due to independent rounding.

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

NEU = Non-Energy Use
NG = Natural Gas

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

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**4,886.1**	**5,212.8**	**5,773.2**	**5,690.2**	**5,740.7**	**5,803.8**	**5,911.5**	**5,942.7**
Fossil Fuel Combustion	4,724.1	5,030.0	5,584.9	5,511.7	5,557.2	5,624.5	5,713.0	5,751.2
Non-Energy Use of Fuels	117.3	133.2	141.0	131.4	135.3	131.3	150.2	142.4
Natural Gas Systems	33.7	33.8	29.4	28.8	29.6	28.4	28.2	28.2
Municipal Solid Waste Combustion	10.9	15.7	17.9	18.3	18.5	19.5	20.1	20.9
*International Bunker Fuels**	*113.7*	*100.6*	*101.1*	*97.6*	*89.1*	*83.7*	*97.2*	*97.2*
*Wood Biomass and Ethanol Consumption**	*219.3*	*236.8*	*228.3*	*203.2*	*204.4*	*209.6*	*224.8*	*206.5*
CH_4	**259.6**	**246.1**	**228.5**	**225.0**	**219.7**	**217.4**	**214.6**	**207.1**
Natural Gas Systems	124.5	128.1	126.6	125.4	125.0	123.7	119.0	111.1
Coal Mining	81.9	66.5	55.9	55.5	52.0	52.1	54.5	52.4
Petroleum Systems	34.4	31.1	27.8	27.4	26.8	25.8	25.4	28.5
Stationary Combustion	8.0	7.8	7.4	6.8	6.8	7.0	7.1	6.9
Abandoned Underground Coal Mines	6.0	8.2	7.3	6.7	6.1	5.9	5.8	5.5
Mobile Combustion	4.7	4.3	3.5	3.2	3.1	2.9	2.8	2.6
*International Bunker Fuels**	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**56.5**	**66.9**	**67.6**	**63.6**	**60.9**	**57.9**	**55.5**	**52.2**
Mobile Combustion	43.7	53.7	53.2	49.7	47.1	43.8	41.2	38.0
Stationary Combustion	12.3	12.8	14.0	13.5	13.4	13.7	13.9	13.8
Municipal Solid Waste Combustion	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4
*International Bunker Fuels**	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*	*0.9*	*0.9*
Total	**5,202.2**	**5,525.8**	**6,069.2**	**5,978.9**	**6,021.4**	**6,079.1**	**6,181.7**	**6,201.9**

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

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 C 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.

Table 2-7, Figure 2-8, and Figure 2-9 summarize CO_2 emissions from fossil fuel combustion by end-use sector.

Transportation End-Use Sector. Transportation activities (excluding international bunker fuels) accounted for 33 percent of CO_2 emissions from fossil fuel combustion in 2005.[3] Virtually all of the energy consumed in this end-use sector came from petroleum products. Over 60 percent of the emissions resulted from gasoline consumption for personal vehicle use. The remaining emissions came from other

Table 2-7: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005
Transportation	**1,467.0**	**1,593.3**	**1,787.8**	**1,761.5**	**1,815.7**	**1,814.8**	**1,868.9**	**1,897.9**
Combustion	1,464.0	1,590.2	1,784.4	1,758.2	1,812.3	1,810.5	1,864.5	1,892.8
Electricity	3.0	3.0	3.4	3.3	3.4	4.3	4.4	5.2
Industrial	**1,539.8**	**1,595.8**	**1,660.1**	**1,596.6**	**1,575.5**	**1,595.1**	**1,615.2**	**1,575.2**
Combustion	857.1	882.7	875.0	869.9	857.7	858.3	875.6	840.1
Electricity	682.7	713.1	785.1	726.7	717.8	736.8	739.6	735.1
Residential	**929.9**	**995.4**	**1,131.5**	**1,124.8**	**1,147.9**	**1,179.1**	**1,175.9**	**1,208.7**
Combustion	340.3	356.4	373.5	363.9	362.4	383.8	369.9	358.7
Electricity	589.6	639.0	758.0	760.9	785.5	795.3	806.0	849.9
Commercial	**759.2**	**810.6**	**969.3**	**979.7**	**973.8**	**984.2**	**999.1**	**1,016.8**
Combustion	224.3	226.4	232.3	225.1	225.7	236.6	233.3	225.8
Electricity	534.9	584.2	736.9	754.6	748.0	747.6	765.8	791.0
U.S. Territories	**28.3**	**35.0**	**36.2**	**49.0**	**44.3**	**51.3**	**54.0**	**52.5**
Total	**4,724.1**	**5,030.0**	**5,584.9**	**5,511.7**	**5,557.2**	**5,624.5**	**5,713.0**	**5,751.2**
Electricity Generation	**1,810.2**	**1,939.3**	**2,283.5**	**2,245.5**	**2,254.7**	**2,284.0**	**2,315.8**	**2,381.2**

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 2-8

2005 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

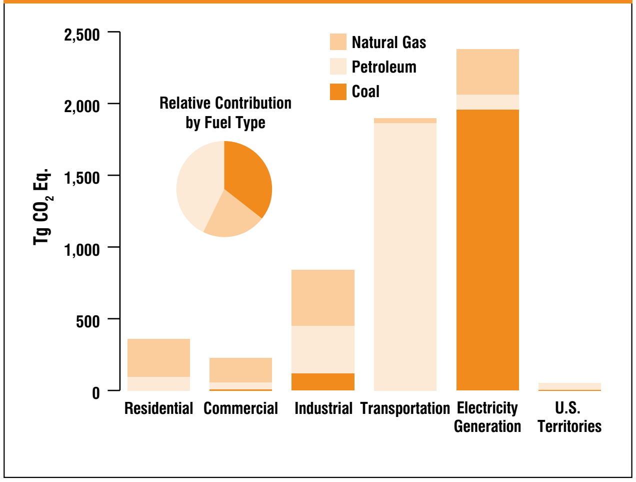
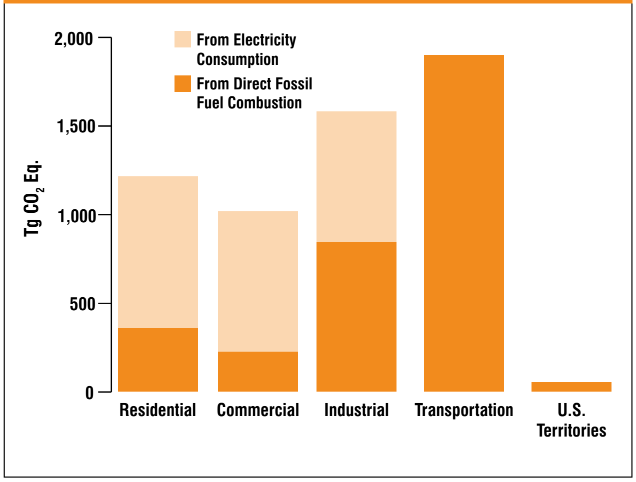


Figure 2-9

2005 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion



---

[3] If emissions from international bunker fuels are included, the transportation end-use sector accounted for 35 percent of U.S. emissions from fossil fuel combustion in 2005.

transportation activities, including the combustion of diesel fuel in heavy-duty vehicles and jet fuel in aircraft.

Industrial End-Use Sector. Industrial CO_2 emissions, resulting both directly from the combustion of fossil fuels and indirectly from the generation of electricity that is consumed by industry, accounted for 27 percent of CO_2 emissions from fossil fuel combustion in 2005. About half of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The other half of the emissions resulted from consuming electricity for motors, electric furnaces, ovens, lighting, and other applications.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 21 and 18 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2005. Both sectors relied heavily on electricity for meeting energy demands, with 70 and 78 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.

Electricity Generation. The United States relies on electricity to meet a significant portion of its energy demands, especially for lighting, electric motors, heating, and air conditioning. Electricity generators consumed 36 percent of U.S. energy from fossil fuels and emitted 41 percent of the CO_2 from fossil fuel combustion in 2005. 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 93 percent of all coal consumed for energy in the United States in 2005. Consequently, changes in electricity demand have a significant impact on coal consumption and associated CO_2 emissions.

Non-Energy Use of Fossil Fuels (142.4 Tg CO_2 Eq.)

In addition to being combusted for energy, fossil fuels are also consumed for non-energy uses (NEUs). Fuels are used in the industrial and transportation end-use sectors for a variety of NEUs, including application as solvents, lubricants, and waxes, or as raw materials in the manufacture of plastics, rubber, and synthetic fibers. 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. Where appropriate data and methodologies are available, NEUs of fossil fuels used for industrial processes are reported in the Industrial Processes chapter. Emissions in 2005 for non-energy uses of fossil fuels were 142.4 Tg CO_2 Eq., which constituted 2.5 percent of overall fossil fuel CO_2 emissions and 2 percent of total national CO_2 emissions, approximately the same proportion as in 1990. CO_2 emissions from non-energy use of fossil fuels increased by 25.1 Tg CO_2 Eq. (21 percent) from 1990 through 2005.

Natural Gas Systems (139.3 Tg CO_2 Eq.)

CH_4 and non-energy 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. In 2005, CH_4 emissions from U.S. natural gas systems accounted for approximately 21 percent of U.S. CH_4 emissions. Also in 2005, natural gas systems accounted for approximately 0.5 percent of U.S. CO_2 emissions (28.2 Tg CO_2 Eq.). From 1990 through 2005, CH_4 and CO_2 emissions from natural gas systems decreased by 13.3 Tg CO_2 Eq. (11 percent), and 5.5 Tg CO_2 Eq. (16 percent) respectively.

Coal Mining (52.4 Tg CO_2 Eq.)

Produced millions of years ago during the formation of coal, CH_4 trapped within coal seams and surrounding rock strata is released when the coal is mined. The quantity of CH_4 released to the atmosphere during coal mining operations depends primarily upon the type of coal and the method and rate of mining.

CH_4 from surface mines is emitted directly to the atmosphere as the rock strata overlying the coal seam are removed. Because CH_4 in underground mines is explosive at concentrations of 5 to 15 percent in air, most active underground mines are required to vent this CH_4, typically to the atmosphere. At some mines, CH_4-recovery systems may supplement these ventilation systems. During 2005, coal mining activities emitted 10 percent of U.S. CH_4 emissions. From 1990 to 2005, emissions from this source decreased by 29.5 Tg CO_2 Eq. (36 percent) due to increased use of the CH_4 collected by mine degasification systems and a general shift toward surface mining.

Mobile Combustion (40.6 Tg CO_2 Eq.)

In addition to CO_2, mobile combustion results in N_2O and CH_4 emissions. N_2O is a product of the reaction that occurs between nitrogen and oxygen during fuel combustion. The quantity emitted varies according to the type of fuel, technology, and pollution control device used, as well as maintenance and operating practices. For example, some types of catalytic converters installed to reduce motor vehicle pollution can promote the formation of N_2O. In 2005, N_2O emissions from mobile combustion were 38.0 Tg CO_2 Eq. (8 percent of U.S. N_2O emissions). From 1990 to 2005, N_2O emissions from mobile combustion decreased by 5.7 Tg CO_2 Eq. (13 percent). In 2005, CH_4 emissions were estimated to be 2.6 Tg CO_2 Eq. The combustion of gasoline in highway vehicles was responsible for the majority of the CH_4 emitted from mobile combustion. From 1990 to 2005, CH_4 emissions from mobile combustion decreased by 2.1 Tg CO_2 Eq. (45 percent).

Petroleum Systems (28.5 Tg CO_2 Eq.)

Petroleum is often found in the same geological structures as natural gas, and the two are often retrieved together. Crude oil is saturated with many lighter hydrocarbons, including CH_4. When the oil is brought to the surface and processed, many of the dissolved lighter hydrocarbons (as well as water) are removed through a series of high-pressure and low-pressure separators. The remaining hydrocarbons in the oil are emitted at various points along the system. CH_4 emissions from the components of petroleum systems generally occur as a result of system leaks, disruptions, and routine maintenance. In 2005, emissions from petroleum systems were about 5 percent of U.S. CH_4 emissions. From 1990 to 2005, CH_4 emissions from petroleum systems decreased by 6 Tg CO_2 Eq. (17 percent).

Municipal Solid Waste Combustion (21.3 Tg CO_2 Eq.)

Combustion is used to manage about 14 percent of the municipal solid waste generated in the United States. The burning of garbage and non-hazardous solids, referred to as municipal solid waste, as well as the burning of hazardous waste, is usually performed to recover energy from the waste materials. CO_2 and N_2O emissions arise from the organic materials found in these wastes. The CO_2 emissions from municipal solid waste containing C of biogenic origin (e.g., paper, yard trimmings) are not accounted for in this Inventory, since they are presumed to be offset by regrowth of the original living source, and are ultimately accounted for in the Land Use, Land-Use Change, and Forestry chapter. Several components of municipal solid waste, such as plastics, synthetic rubber, synthetic fibers, and carbon black, are of fossil-fuel origin, and are included as sources of CO_2 and N_2O emissions. In 2005, CO_2 emissions from waste combustion amounted to 20.9 Tg CO_2 Eq., while N_2O emissions amounted to 0.4 Tg CO_2 Eq. From 1990 through 2005, CO_2 emissions from waste combustion increased by 10 Tg CO_2 Eq. (91 percent), while N_2O emissions decreased by 0.1 Tg CO_2 Eq. (15 percent).

Stationary Combustion (20.7 Tg CO_2 Eq.)

In addition to CO_2, stationary combustion results in N_2O and CH_4 emissions. In 2005, N_2O emissions from stationary combustion accounted for 13.8 Tg CO_2 Eq. (3 percent of U.S. N_2O emissions). From 1990 to 2005, N_2O emissions from stationary combustion increased by 1.5 Tg CO_2 Eq. (12 percent), due to increased fuel consumption. In 2005, CH_4 emissions were 6.9 Tg CO_2 Eq. (1 percent of U.S. CH_4 emissions). From 1990 to 2005, CH_4 emissions from stationary combustion decreased by 1.1 Tg CO_2 Eq. (13.5 percent). The majority of CH_4 emissions from stationary combustion resulted from the burning of wood in the residential end-use sector.

Abandoned Underground Coal Mines (5.5 Tg CO_2 Eq.)

Coal mining activities result in the emission of CH_4 into the atmosphere. However, the closure of a coal mine does not correspond with an immediate cessation in the release of emissions. 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. In 2005, the emissions from abandoned underground coal mines constituted 1 percent of U.S. CH_4 emissions. Between 1990 and 2005, emissions from this source decreased by 0.5 Tg CO_2 Eq. (8 percent).

Wood Biomass and Ethanol Consumption (206.5 Tg CO_2 Eq.)

Biomass refers to organically-based C fuels (as opposed to fossil-based). Biomass in the form of fuel wood and wood waste was used primarily in the industrial sector, while the transportation sector was the predominant user of biomass-based fuels, such as ethanol from corn and woody crops.

Although these fuels do emit CO_2, in the long run the CO_2 emitted from biomass consumption does not increase atmospheric CO_2 concentrations if the biogenic C emitted is offset by the growth of new biomass. For example, fuel wood burned one year but re-grown the next only recycles C, rather than creating a net increase in total atmospheric C. Net C fluxes from changes in biogenic C reservoirs in forest lands or croplands are accounted for in the estimates for the Land Use, Land-Use Change, and Forestry sector. As a result, CO_2 emissions from biomass combustion have been estimated separately from fossil-fuel-based emissions and are not included in the U.S. totals. CH_4 emissions from biomass combustion are included in the Stationary Combustion source.

The consumption of wood biomass in the industrial, residential, electric power, and commercial end-use sectors accounted for 56, 21, 8, and 4 percent of gross CO_2 emissions from wood biomass and ethanol consumption, respectively. Ethanol consumption in the transportation end-use sector accounted for the remaining 11 percent.

CO_2 emissions from wood biomass and ethanol consumption decreased by 12.9 Tg CO_2 Eq. (approximately 6 percent) from 1990 through 2005.

International Bunker Fuels (98.2 Tg CO_2 Eq.)

Greenhouse gases emitted from the combustion of fuels used for international transport activities, termed international bunker fuels under the UNFCCC, include CO_2, CH_4, and N_2O. Emissions from these activities are currently 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. These decisions are reflected in the *Revised 1996 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/UNEP/OECD/IEA 1997).

Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine.

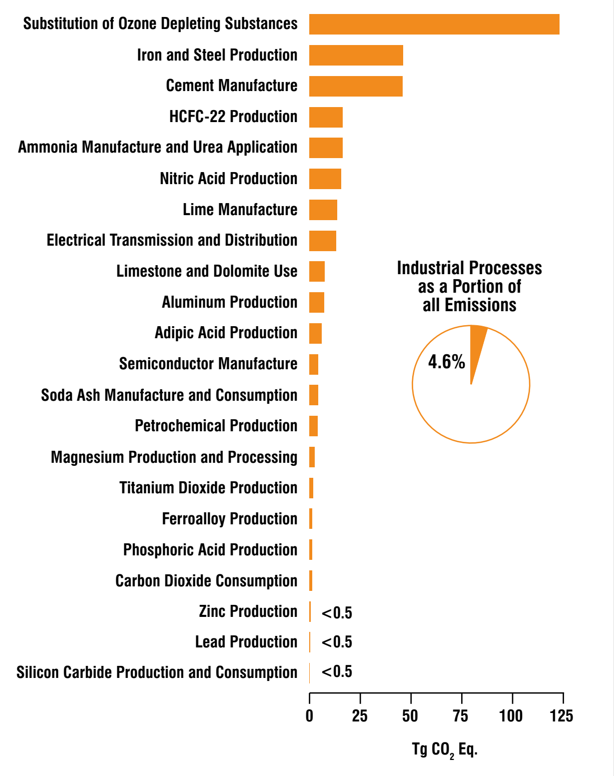
Emissions from ground transport activities—by road vehicles and trains, even when crossing international borders—are allocated to the country where the fuel was loaded into the vehicle and, therefore, are not counted as bunker fuel emissions. Emissions of CO_2, CH_4, and N_2O from international bunker fuel combustion were 97.2, 0.1, and 0.9 Tg CO_2 Eq. in 2005, respectively. From 1990 through 2005, CO_2, CH_4, and N_2O emissions from international bunker fuels decreased by 16.5 Tg CO_2 Eq. (15 percent), 0.1 Tg CO_2 Eq. (35 percent), and 0.1 Tg CO_2 Eq. (9 percent), respectively.

Industrial Processes

Emissions are produced as a by-product of many non-energy-related industrial process 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, cement manufacture, ammonia manufacture and urea application, lime manufacture, limestone and dolomite use (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash manufacture and use, titanium dioxide production, phosphoric acid production, ferroalloy production, CO_2

Figure 2-10

2005 Industrial Processes Chapter Greenhouse Gas Sources



consumption, silicon carbide production and consumption, aluminum production, petrochemical production, nitric acid production, adipic acid production, lead production, and zinc production (see Figure 2-10). Additionally, emissions from industrial processes release HFCs, PFCs and SF_6. Table 2-8 presents greenhouse gas emissions from industrial processes by source category.

Substitution of Ozone Depleting Substances (123.3 Tg CO_2 Eq.)

The use and subsequent emissions of HFCs and PFCs as substitutes for ODSs have increased from small amounts in 1990 to 123 Tg CO_2 Eq. in 2005, accounting for 76 percent of aggregate HFC, PFC, and SF_6 emissions, an increase of 36,899 percent over this time period. This increase was in large part the result of efforts to phase-out CFCs and other ODSs in the United States, especially the introduction of HFC-134a as a CFC substitute in refrigeration and air-conditioning applications. In the short term, this trend is expected to continue, and will likely accelerate over the coming decade as HCFCs, which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the Montreal

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

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**175.5**	**171.8**	**166.8**	**152.8**	**152.0**	**148.8**	**152.8**	**146.8**
Cement Manufacture	33.3	36.8	41.2	41.4	42.9	43.1	45.6	45.9
Iron and Steel Production	84.9	73.3	65.1	57.9	54.6	53.4	51.3	45.2
Ammonia Manufacture & Urea Application	19.3	20.5	19.6	16.7	17.8	16.2	16.9	16.3
Lime Manufacture	11.3	12.8	13.3	12.9	12.3	13.0	13.7	13.7
Limestone and Dolomite Use	5.5	7.4	6.0	5.7	5.9	4.7	6.7	7.4
Aluminum Production	4.1	4.3	4.2	4.1	4.1	4.1	4.2	4.2
Soda Ash Manufacture and Consumption	6.8	5.7	6.1	4.4	4.5	4.5	4.2	4.2
Petrochemical Production	2.2	2.8	3.0	2.8	2.9	2.8	2.9	2.9
Titanium Dioxide Production	1.3	1.7	1.9	1.9	2.0	2.0	2.3	1.9
Phosphoric Acid Production	2.2	2.0	1.9	1.5	1.3	1.3	1.4	1.4
Ferroalloy Production	1.5	1.5	1.4	1.3	1.3	1.4	1.4	1.4
CO_2 Consumption	1.4	1.4	1.4	0.8	1.0	1.3	1.2	1.3
Zinc Production	0.9	1.0	1.1	1.0	0.9	0.5	0.5	0.5
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Production and Consumption	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2
CH_4	**2.2**	**2.4**	**2.5**	**2.2**	**2.1**	**2.1**	**2.2**	**2.0**
Petrochemical Production	0.9	1.1	1.2	1.1	1.1	1.1	1.2	1.1
Iron and Steel Production	1.3	1.3	1.2	1.1	1.0	1.0	1.0	1.0
Ferroalloy Production	+	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+	+
N_2O	**33.0**	**37.1**	**25.6**	**20.8**	**23.1**	**22.9**	**21.8**	**21.7**
Nitric Acid Production	17.8	19.9	19.6	15.9	17.2	16.7	16.0	15.7
Adipic Acid Production	15.2	17.2	6.0	4.9	5.9	6.2	5.7	6.0
HFCs, PFCs, and SF_6	**89.3**	**103.5**	**143.8**	**133.8**	**143.0**	**142.7**	**153.9**	**163.0**
Substitution of Ozone Depleting Substances	0.3	32.2	80.9	88.6	96.9	105.5	114.5	123.3
HCFC-22 Production	35.0	27.0	29.8	19.8	19.8	12.3	15.6	16.5
Electrical Transmission and Distribution	27.1	21.8	15.2	15.1	14.3	13.8	13.6	13.2
Semiconductor Manufacture	2.9	5.0	6.3	4.5	4.4	4.3	4.7	4.3
Aluminum Production	18.5	11.8	8.6	3.5	5.2	3.8	2.8	3.0
Magnesium Production and Processing	5.4	5.6	3.0	2.4	2.4	2.9	2.6	2.7
Total	**300.1**	**314.8**	**338.7**	**309.6**	**320.2**	**316.4**	**330.6**	**333.6**

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

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.

Iron and Steel Production (46.2 Tg CO_2 Eq.)

Pig iron is the product of combining iron oxide (i.e., iron ore) and sinter with metallurgical coke in a blast furnace. The pig iron production process, as well as the thermal processes used to create sinter and metallurgical coke, results in emissions of CO_2 and CH_4. In 2005, iron and steel production resulted in 1.0 Tg CO_2 Eq. of CH_4 emissions, with the majority of the emissions coming from the pig iron production process. The majority of CO_2 emissions from iron and steel processes come from the production of coke for use in pig iron creation, with smaller amounts evolving from the removal of carbon from pig iron used to produce steel. CO_2 emissions from iron and steel amounted to 45.2 Tg CO_2 Eq. in 2005. From 1990 to 2005, CO_2 and CH_4 emissions from this source decreased by 39.7 Tg CO_2 Eq. (47 percent), and 0.4 Tg CO_2 Eq. (28 percent) respectively.

Cement Manufacture (45.9 Tg CO_2 Eq.)

Clinker is an intermediate product in the formation of finished portland and masonry cement. Heating calcium carbonate ($CaCO_3$) in a cement kiln forms lime and CO_2. The lime combines with other materials to produce clinker, and the CO_2 is released into the atmosphere. From 1990 to 2005, emissions from this source increased by 12.6 Tg CO_2 Eq. (38 percent).

HCFC-22 Production (16.5 Tg CO_2 Eq.)

HFC-23 is a by-product of the production of HCFC-22. Emissions from this source have decreased by 18.4 Tg CO_2 Eq. (53 percent) since 1990. The HFC-23 emission rate (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) has declined significantly since 1990, although production has been increasing.

Ammonia Manufacture and Urea Application (16.3 Tg CO_2 Eq.)

In the United States, roughly 98 percent of synthetic ammonia is produced by catalytic steam reforming of natural gas, and the remainder is produced using naphtha (i.e., a petroleum fraction) or the electrolysis of brine at chlorine plants (EPA 1997). The two fossil fuel-based reactions produce carbon monoxide and hydrogen gas. This carbon monoxide is transformed into CO_2 in the presence of a catalyst. The CO_2 is generally released into the atmosphere, but some of the CO_2, together with ammonia, is used as a raw material in the production of urea [$CO(NH_2)_2$], which is a type of nitrogenous fertilizer. The carbon in the urea that is produced and assumed to be subsequently applied to agricultural land as a nitrogenous fertilizer is ultimately released into the environment as CO_2. Since 1990, CO_2 emissions from ammonia manufacture and urea application have decreased by 3.0 Tg CO_2 Eq. (15.5 percent).

Nitric Acid Production (15.7 Tg CO_2 Eq.)

Nitric acid production is an industrial source of N_2O emissions. Used primarily to make synthetic commercial fertilizer, this raw material is also a major component in the production of adipic acid and explosives. Virtually all of the nitric acid manufactured in the United States is produced by the oxidation of ammonia, during which N_2O is formed and emitted to the atmosphere. In 2005, N_2O emissions from nitric acid production accounted for 3 percent of U.S. N_2O emissions. From 1990 to 2005, emissions from this source category decreased by 2.2 Tg CO_2 Eq. (12 percent) with the trend in the time series closely tracking the changes in production.

Lime Manufacture (13.7 Tg CO_2 Eq.)

Lime is used in steel making, construction, flue gas desulfurization, and water and sewage treatment. It is manufactured by heating limestone (mostly $CaCO_3$) in a kiln, creating quicklime (calcium oxide, CaO) and CO_2, which is normally emitted to the atmosphere. From 1990 to 2005, CO_2 emissions from lime manufacture increased by 2.4 Tg CO_2 Eq. (21 percent).

Electrical Transmission and Distribution Systems (13.2 Tg CO_2 Eq.)

The primary use of SF_6 is as a dielectric in electrical transmission and distribution systems. Fugitive emissions of SF_6 occur from leaks in and servicing of substations and circuit breakers, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and disposal. Estimated emissions from this source decreased by 13.9 Tg CO_2 Eq. (51 percent) since 1990, primarily due to higher SF_6 prices and industrial efforts to reduce emissions.

Limestone and Dolomite Use (7.4 Tg CO_2 Eq.)

Limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are basic raw materials used in a wide variety of industries, including construction, agriculture, chemical, and metallurgy. For example, limestone can be used as a purifier in refining metals. In the case of iron ore, limestone heated in a blast furnace reacts with impurities in the iron ore and fuels, generating CO_2 as a by-product. Limestone is also used in flue gas desulfurization systems to remove sulfur dioxide from the exhaust gases. From 1990 to 2005, emissions from this source increased by 1.9 Tg CO_2 Eq. (34 percent).

Aluminum Production (7.2 Tg CO_2 Eq.)

Aluminum production results in emissions of CO_2, CF_4 and C_2F_6. CO_2 is emitted when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite. 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, some of this carbon is oxidized and released to the atmosphere as CO_2. In 2005, CO_2 emissions from aluminum production amounted to 4.2 Tg CO_2 Eq. Since 1990, CO_2 emissions from this source have decreased by 2.6 Tg CO_2 Eq. (38 percent).

During the production of primary aluminum, CF_4 and C_2F_6 are emitted as intermittent by-products of the smelting process. These PFCs are formed when fluorine from the cryolite bath combines with carbon from the electrolyte anode. PFC emissions from aluminum production have decreased by 15.6 Tg CO_2 Eq. (84 percent) between 1990 and 2005 due to emission reduction efforts by the industry and falling domestic aluminum production, although there was a slight increase in emissions between 2004 and 2005, due to slightly higher production. In 2005, CF_4 and C_2F_6 emissions from aluminum production amounted to 3.0 Tg CO_2 Eq.

Adipic Acid Production (6.0 Tg CO_2 Eq.)

Most adipic acid produced in the United States is used to manufacture nylon 6,6. Adipic acid is also used to produce some low-temperature lubricants and to add a “tangy” flavor to foods. N_2O is emitted as a by-product of the chemical synthesis of adipic acid. In 2005, U.S. adipic acid plants emitted 1.3 percent of U.S. N_2O emissions. Even though adipic acid production has increased in recent years, by 1998 all three major adipic acid plants in the United States had voluntarily implemented N_2O abatement technology. As a result, emissions have decreased by 9.2 Tg CO_2 Eq. (61 percent) between 1990 and 2005.

Semiconductor Manufacture (4.3 Tg CO_2 Eq.)

The semiconductor industry uses combinations of HFCs, PFCs, SF_6, and other gases for plasma etching and to clean chemical vapor deposition tools. Emissions from this source category have increased 1.4 Tg CO_2 Eq. (48 percent) since 1990 with the growth in the semiconductor industry and the rising intricacy of chip designs. However, the growth rate in emissions has slowed since 1997, and emissions actually declined between 1999 and 2005. This later reduction is due to the implementation of PFC emission reduction methods, such as process optimization.

Soda Ash Manufacture and Consumption (4.2 Tg CO_2 Eq.)

Commercial soda ash (sodium carbonate, Na_2CO_3) is used in many consumer products, such as glass, soap and detergents, paper, textiles, and food. During the manufacturing of soda ash, some natural sources of sodium carbonate are heated and transformed into a crude soda ash, in which CO_2 is generated as a by-product. In addition, CO_2 is often released when the soda ash is consumed. From 1990 to 2005, emissions from this source increased by 0.1 Tg CO_2 Eq. (2 percent).

Petrochemical Production (4.0 Tg CO_2 Eq.)

The production process for carbon black results in the release CO_2 emissions to the atmosphere. Carbon black is a black powder generated by the incomplete combustion of an aromatic petroleum or coal-based feedstock production. The majority of carbon black produced in the United States is consumed by the tire industry, which adds it to rubber to increase strength and abrasion resistance. Small amounts of CH_4 are also released during the production of five petrochemicals: carbon black, ethylene, ethylene dichloride, styrene, and methanol. These production processes resulted in emissions of 2.9 Tg CO_2 Eq. of CO_2 and 1.1 Tg CO_2 Eq. of CH_4 in 2005. Emissions from this source increased by 0.9 Tg CO_2 Eq. (29 percent) between 1990 and 2005.

Magnesium Production and Processing (2.7 Tg CO_2 Eq.)

Sulfur hexafluoride is also used as a protective cover gas for the casting of molten magnesium. Emissions from primary magnesium production and magnesium casting have decreased by 2.8 Tg CO_2 Eq. (51 percent) since 1990. This decrease has primarily taken place since 1999, due to a decline in the quantity of magnesium die cast and the closure of a U.S. primary magnesium production facility.

Titanium Dioxide Production (1.9 Tg CO_2 Eq.)

Titanium dioxide (TiO_2) is a metal oxide manufactured from titanium ore, and is principally used as a pigment. It is used in white paint and as a pigment in the manufacture of white paper, foods, and other products. Two processes, the chloride process and the sulfate process, are used for making TiO_2. CO_2 is emitted from the chloride process, which uses petroleum coke and chlorine as raw materials. Since 1990, emissions from this source increased by 0.6 Tg CO_2 Eq. (47 percent).

Phosphoric Acid Production (1.4 Tg CO_2 Eq.)

Phosphoric acid is a basic raw material in the production of phosphate-based fertilizers. The phosphate rock consumed in the United States originates from both domestic mines, located primarily in Florida, North Carolina, Idaho, and Utah, and foreign mining operations in Morocco. The primary use of this material is as a basic component of a series of chemical reactions that lead to the production of phosphoric acid, as well as the by-products CO_2 and phosphogypsum. From 1990 to 2005, CO_2 emissions from phosphoric acid production decreased by 0.1 Tg CO_2 Eq. (9.5 percent).

Ferroalloy Production (1.4 Tg CO_2 Eq.)

CO_2 is 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. From 1990 to 2005, emissions from this source decreased by 0.8 Tg CO_2 Eq. (35 percent).

Carbon Dioxide Consumption (1.3 Tg CO_2 Eq.)

Many segments of the economy consume CO_2, including food processing, beverage manufacturing, chemical processing, and a host of industrial and other miscellaneous applications. CO_2 may be produced as a by-product from the production of certain chemicals (e.g., ammonia), from select natural gas wells, or by separating it from crude oil and natural gas. The majority of the CO_2 used in these applications is eventually released to the atmosphere. Since 1990, emissions from CO_2 consumption have decreased by 0.1 Tg CO_2 Eq. (6.5 percent).

Zinc Production (0.5 Tg CO_2 Eq.)

CO_2 emissions from the production of zinc in the United States occur through the primary production of zinc in the electro-thermic production process, or through the secondary production of zinc using a Waelz Kiln furnace or the electro-thermic production process. Both the electro-thermic and Waelz Kiln processes are emissive due to the use of a carbon-based material (often metallurgical coke); however, zinc is also produced in the United States using non-emissive processes. Due to the closure of an electro-thermic plant in 2003, the only emissive zinc production process remaining occurs through the recycling of electric-arc-furnace (EAF) dust in a Waelz Kiln furnace (secondary production) at a plant in Palmerton, Pennsylvania. From 1990 to 2005, CO_2 emissions from zinc production decreased by 0.5 Tg CO_2 Eq. (51 percent).

Lead Production (0.3 Tg CO_2 Eq.)

Primary and secondary production of lead in the United States results in CO_2 emissions when carbon-based materials (often metallurgical coke) are used as a reducing agent. Primary production involves the direct smelting of lead concentrates while secondary production largely occurs through the recycling of lead-acid batteries. In 2005, emissions from primary lead production decreased by 40 percent due to the closure of one of two primary lead production plants located in Missouri. Secondary lead production accounted for 86 percent of total lead production emissions in 2005. Since 1990, emissions from this source have decreased by 7.2 percent.

Silicon Carbide Production and Consumption (0.2 Tg CO_2 Eq.)

Small amounts of CH_4 are released during the production of silicon carbide (SiC), a material used as an industrial abrasive. Additionally, small amounts of CO_2 are released when SiC is consumed for metallurgical and other non-abrasive purposes (e.g., iron and steel production). Silicon carbide is made through a reaction of quartz (SiO_2) and carbon (in the form of petroleum coke). CH_4 is produced during this reaction from volatile compounds in the petroleum coke. CH_4 emissions from silicon carbide production have declined significantly due to a 67 percent decrease in silicon carbide production since 1990. CO_2 emissions from SiC

Table 2-9: N_2O Emissions from Solvent and Other Product Use (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
N_2O	**4.3**	**4.5**	**4.8**	**4.8**	**4.3**	**4.3**	**4.3**	**4.3**
N_2O Product Usage	4.3	4.5	4.8	4.8	4.3	4.3	4.3	4.3
Total	**4.3**	**4.5**	**4.8**	**4.8**	**4.3**	**4.3**	**4.3**	**4.3**

consumption have fluctuated significantly between years dependent on consumption, but overall have decreased by 42 percent since 1990.

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 N_2O Product Usage, the only source of greenhouse gas emissions from this chapter, accounted for 4.3 Tg CO_2 Eq. of N_2O, or less than 0.1 percent of total U.S. emissions in 2005 (see Table 2-9).

N_2O Product Usage (4.3 Tg CO_2 Eq.)

N_2O is 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. In 2005, N_2O emissions from product usage constituted approximately 1 percent of U.S. N_2O emissions. From 1990 to 2005, emissions from this source category decreased by less than 1 percent.

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 2005, agricultural activities were responsible for emissions of 536.3 Tg CO_2 Eq., or 7.4 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 percent and 8 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2005. Agricultural soil management activities, such as fertilizer application and other cropping practices, were the largest source of U.S. N_2O emissions in 2005, accounting for 78 percent. Table 2-10 and Figure 2-11 present emission estimates for the Agriculture chapter.

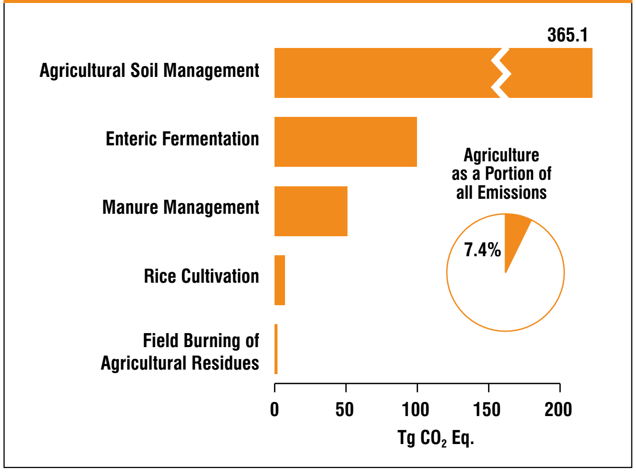
Table 2-10: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**154.4**	**164.0**	**160.5**	**161.0**	**161.2**	**161.1**	**158.7**	**161.2**
Enteric Fermentation	115.7	120.6	113.5	112.5	112.6	113.0	110.5	112.1
Manure Management	30.9	35.1	38.7	40.1	41.1	40.5	39.7	41.3
Rice Cultivation	7.1	7.6	7.5	7.6	6.8	6.9	7.6	6.9
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.8	0.7	0.8	0.9	0.9
N_2O	**375.9**	**362.7**	**386.9**	**399.2**	**376.3**	**359.9**	**348.7**	**375.1**
Agricultural Soil Management	366.9	353.4	376.8	389.0	366.1	350.2	338.8	365.1
Manure Management	8.6	9.0	9.6	9.8	9.7	9.3	9.4	9.5
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.4	0.4	0.5	0.5
Total	**530.3**	**526.8**	**547.4**	**560.3**	**537.4**	**521.1**	**507.4**	**536.3**

Note: Totals may not sum due to independent rounding.

Figure 2-11

2005 Agriculture Chapter Greenhouse Gas Sources



Agricultural Soil Management (365.1 Tg CO_2 Eq.)

N_2O is produced naturally in soils through microbial nitrification and denitrification processes. A number of anthropogenic activities add to the amount of nitrogen available to be emitted as N_2O by microbial processes. These activities may add nitrogen to soils either directly or indirectly. Direct additions occur through the application of synthetic and organic fertilizers; production of nitrogen-fixing crops and forages; the application of livestock manure, crop residues, and sewage sludge; cultivation of high-organic-content soils; and direct excretion by animals onto soil. Indirect additions result from volatilization and subsequent atmospheric deposition, and from leaching and surface run-off of some of the nitrogen applied to or deposited on soils as fertilizer, livestock manure, and sewage sludge. In 2005, agricultural soil management accounted for 78 percent of U.S. N_2O emissions. From 1990 to 2005, emissions from this source decreased by 1.8 Tg CO_2 Eq. (0.5 percent); year-to-year fluctuations are largely a reflection of annual variations in weather, synthetic fertilizer consumption, and crop production.

Enteric Fermentation (112.1 Tg CO_2 Eq.)

During animal digestion, CH_4 is produced through the process of enteric fermentation, in which microbes residing in animal digestive systems break down food. Ruminants, which include cattle, buffalo, sheep, and goats, have the highest CH_4 emissions among all animal types because they have a rumen, or large fore-stomach, in which CH_4-producing fermentation occurs. Non-ruminant domestic animals, such as pigs and horses, have much lower CH_4 emissions. In 2005, enteric fermentation was the source of about 21 percent of U.S. CH_4 emissions, and about 70 percent of the CH_4 emissions from agriculture. From 1990 to 2005, emissions from this source decreased by 3.6 Tg CO_2 Eq. (3 percent). Generally, emissions have been decreasing since 1995, mainly due to decreasing populations of both beef and dairy cattle and improved feed quality for feedlot cattle.

Manure Management (50.8 Tg CO_2 Eq.)

Both CH_4 and N_2O result from manure management. The decomposition of organic animal waste in an anaerobic environment produces CH_4. The most important factor affecting the amount of CH_4 produced is how the manure is managed, because certain types of storage and treatment systems promote an oxygen-free environment. In particular, liquid systems tend to encourage anaerobic conditions and produce significant quantities of CH_4, whereas solid waste management approaches produce little or no CH_4. Higher temperatures and moist climatic conditions also promote CH_4 production.

CH_4 emissions from manure management were 41.3 Tg CO_2 Eq., or about 8 percent of U.S. CH_4 emissions in 2005 and 26 percent of the CH_4 emissions from agriculture. From 1990 to 2005, emissions from this source increased by 10.4 Tg CO_2 Eq. (34 percent). The bulk of this increase was from swine and dairy cow manure, and is attributed to the shift of the swine and dairy industries towards larger facilities. Larger swine and dairy farms tend to use liquid management systems.

N_2O is also produced as part of microbial nitrification and denitrification processes in managed and unmanaged manure. Emissions from unmanaged manure are accounted for within the agricultural soil management source category. Total N_2O emissions from managed manure systems in 2005 accounted for 9.5 Tg CO_2 Eq., or 2 percent of U.S. N_2O emissions. From 1990 to 2005, emissions from this source category increased by 0.9 Tg CO_2 Eq. (10 percent), primarily due to increases in swine and poultry populations over the same period.

Rice Cultivation (6.9 Tg CO_2 Eq.)

Most of the world's rice, and all of the rice in the United States, is grown on flooded fields. When fields are flooded, anaerobic conditions develop and the organic matter in the soil decomposes, releasing CH_4 to the atmosphere, primarily through the rice plants. In 2005, rice cultivation was the source of 1 percent of U.S. CH_4 emissions, and about 4 percent of U.S. CH_4 emissions from agriculture. Emission estimates from this source have decreased about 3 percent since 1990.

Field Burning of Agricultural Residues (1.4 Tg CO_2 Eq.)

Burning crop residues releases N_2O and CH_4. Because field burning is not a common debris clearing method in the United States, it was responsible for only 0.2 percent of U.S. CH_4 (0.9 Tg CO_2 Eq.) and 0.1 percent of U.S. N_2O (0.5 Tg CO_2 Eq.) emissions in 2005. Since 1990, emissions from this source have increased by approximately 28 percent.

Land Use, Land-Use Change, and Forestry

When humans alter the terrestrial biosphere through land use, changes in land use, and land management practices, they also alter the background carbon fluxes between biomass, soils, and the atmosphere. Forest management practices, tree planting in urban areas, the management of agricultural soils, and the landfilling of yard trimmings and food scraps have resulted in a net uptake (sequestration) of carbon in the United States, which offset about 11 percent of total U.S. greenhouse gas emissions in 2005. Forests (including vegetation, soils, and harvested wood) accounted for approximately 85 percent of total 2005 sequestration, urban trees accounted for 11 percent, agricultural soils (including mineral and organic soils and the application of lime) accounted for 3 percent, and landfilled yard trimmings and food scraps accounted for 1 percent of the total sequestration in 2005. 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 soils account for a net carbon sink that is almost two times larger than the sum of emissions from organic soils and liming. 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 2005 resulted in a net C sequestration of 828.4 Tg CO_2 Eq. (Table 2-11). This represents an offset of approximately 13.6 percent of total U.S. CO_2 emissions, or 11.4 percent of total greenhouse gas emissions in 2005. Total land use, land-use change, and forestry net C sequestration increased by approximately 16 percent between 1990 and 2005, primarily due to an increase in the rate of net C accumulation in forest C stocks, particularly in aboveground and belowground tree biomass. 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. Net U.S. emissions (all sources and sinks) increased by 16.4 percent from 1990 to 2005.

Table 2-11: Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Sink Category	1990	1995	2000	2001	2002	2003	2004	2005
Forest Land Remaining Forest Land	**(598.5)**	**(717.5)**	**(638.7)**	**(645.7)**	**(688.1)**	**(687.0)**	**(697.3)**	**(698.7)**
Changes in Forest Carbon Stocks	(598.5)	(717.5)	(638.7)	(645.7)	(688.1)	(687.0)	(697.3)	(698.7)
Cropland Remaining Cropland	**(28.1)**	**(37.4)**	**(36.5)**	**(38.0)**	**(37.8)**	**(38.3)**	**(39.4)**	**(39.4)**
Changes in Agricultural Soil Carbon Stocks and Liming Emissions	(28.1)	(37.4)	(36.5)	(38.0)	(37.8)	(38.3)	(39.4)	(39.4)
Land Converted to Cropland	**8.7**	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**
Changes in Agricultural Soil Carbon Stocks	8.7	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Grassland Remaining Grassland	**0.1**	**16.4**	**16.3**	**16.2**	**16.2**	**16.2**	**16.1**	**16.1**
Changes in Agricultural Soil Carbon Stocks	0.1	16.4	16.3	16.2	16.2	16.2	16.1	16.1
Land Converted to Grassland	**(14.6)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**
Changes in Agricultural Soil Carbon Stocks	(14.6)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)
Settlements Remaining Settlements	**(57.5)**	**(67.8)**	**(78.2)**	**(80.2)**	**(82.3)**	**(84.4)**	**(86.4)**	**(88.5)**
Urban Trees	(57.5)	(67.8)	(78.2)	(80.2)	(82.3)	(84.4)	(86.4)	(88.5)
Other	**(22.8)**	**(13.3)**	**(10.5)**	**(10.6)**	**(10.8)**	**(9.3)**	**(8.7)**	**(8.8)**
Landfilled Yard Trimmings and Food Scraps	(22.8)	(13.3)	(10.5)	(10.6)	(10.8)	(9.3)	(8.7)	(8.8)
Total	**(712.8)**	**(828.8)**	**(756.7)**	**(767.5)**	**(811.9)**	**(811.9)**	**(824.8)**	**(828.5)**

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

Table 2-12: Non-CO_2 Emissions from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Land-Use Category	1990	1995	2000	2001	2002	2003	2004	2005
Forest Land Remaining Forest Land	**7.8**	**4.5**	**15.7**	**6.9**	**11.8**	**9.2**	**8.0**	**13.1**
CH_4 Emissions from Forest Fires	7.1	4.0	14.0	6.0	10.4	8.1	6.9	11.6
N_2O Emissions from Forest Fires	0.7	0.4	1.4	0.6	1.1	0.8	0.7	1.2
N_2O Emissions from Soils	0.1	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Settlements Remaining Settlements	**5.1**	**5.5**	**5.6**	**5.5**	**5.6**	**5.8**	**6.0**	**5.8**
N_2O Emissions from Soils	5.1	5.5	5.6	5.5	5.6	5.8	6.0	5.8
Total	**13.0**	**10.1**	**21.3**	**12.4**	**17.4**	**15.0**	**13.9**	**18.9**

Note: Totals may not sum due to independent rounding.

Land use, land-use change, and forestry activities in 2005 also resulted in emissions of N_2O (7.3 Tg CO_2 Eq.) from application of fertilizers to forests and settlements and from forest fires, and of CH_4 (11.6 Tg CO_2 Eq.) from forest fires, as shown in Table 2-12. Total N_2O emissions from the application of fertilizers to forests and settlements increased by approximately 19 percent between 1990 and 2005. Emissions of CH_4 and N_2O from forest fires fluctuate widely from year to year, but overall increased by 64 percent between 1990 and 2005.

Forest Land Remaining Forest Land (13.1 Tg CO_2 Eq.)

As with other agricultural applications, forests may be fertilized to stimulate growth rates. The relative magnitude of the impact of this practice is limited, however, because forests are generally only fertilized twice during their life cycles, and applications account for no more than one percent of total U.S. fertilizer applications annually. In terms of trends, however, N_2O emissions from forest soils for 2005 were more than 5 times higher than in 1990, primarily the result of an increase in the fertilized area of pine plantations in the southeastern United States. This source accounts for approximately 0.1 percent of total U.S. N_2O emissions. Non-CO_2 emissions from forest fires are directly related to the area of forest burned, which varies greatly from year to year. CH_4 from this source (11.6 Tg CO_2 Eq.) accounts for approximately 2 percent of total U.S. CH_4 emissions, while N_2O from forest fires (1.2 Tg CO_2 Eq.) accounts for about 0.3 percent of U.S. N_2O emissions. From 1990 to 2005, CH_4 and N_2O emissions from *Forest Land Remaining Forest Land* increased by 4.5 Tg CO_2 Eq. (64 percent) and 0.8 Tg CO_2 Eq. (98 percent), respectively.

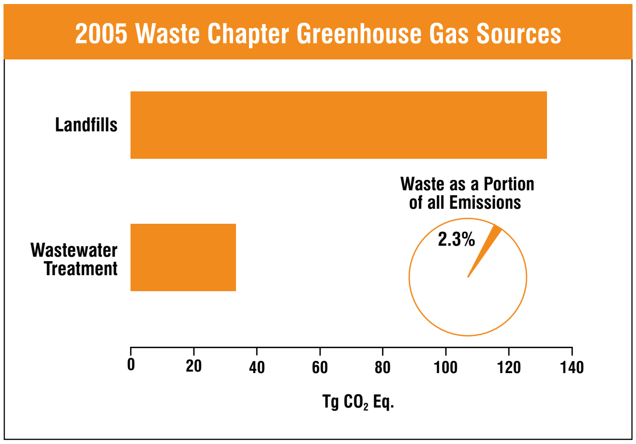
Settlements Remaining Settlements (5.8 Tg CO_2 Eq.)

Of the fertilizers applied to soils in the United States, approximately 10 percent are applied to lawns, golf courses, and other landscaping within settled areas. In 2005, N_2O emissions from settlement soils constituted approximately 1 percent of total U.S. N_2O emissions. There has been an overall increase in emissions of 13 percent since 1990, a result of a general increase in the applications of synthetic fertilizers.

Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 2-12). Landfills were the largest source of anthropogenic CH_4 emissions, accounting for 24 percent of total U.S. CH_4 emissions.[4] Additionally, wastewater treatment accounts for 5 percent of U.S. CH_4 emissions, and 2 percent of N_2O emissions. Nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are also emitted by

Figure 2-12



2005 Waste Chapter Greenhouse Gas Sources

---

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

Table 2-13: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**185.8**	**182.2**	**158.3**	**153.5**	**156.2**	**160.5**	**157.8**	**157.4**
Landfills	161.0	157.1	131.9	127.6	130.4	134.9	132.1	132.0
Wastewater Treatment	24.8	25.1	26.4	25.9	25.8	25.6	25.7	25.4
N_2O	**6.4**	**6.9**	**7.6**	**7.6**	**7.7**	**7.8**	**7.9**	**8.0**
Wastewater Treatment	6.4	6.9	7.6	7.6	7.7	7.8	7.9	8.0
Total	**192.2**	**189.1**	**165.9**	**161.1**	**163.9**	**168.4**	**165.7**	**165.4**

Note: Totals may not sum due to independent rounding.

waste activities. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 2-13.

Overall, in 2005, waste activities generated emissions of 165.4 Tg CO_2 Eq., or 2.3 percent of total U.S. greenhouse gas emissions.

Landfills (132.0 Tg CO_2 Eq.)

Landfills are the largest anthropogenic source of CH_4 emissions in the United States, accounting for approximately 24 percent of total CH_4 emissions in 2005. In an environment where the oxygen content is low or zero, anaerobic bacteria decompose organic materials, such as yard waste, household waste, food waste, and paper, resulting in the generation of CH_4 and biogenic CO_2. Factors such as waste composition and moisture influence the level of CH_4 generation. From 1990 to 2005, net CH_4 emissions from landfills decreased by 29 Tg CO_2 Eq. (18 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,[5] which has more than offset the additional CH_4 emissions resulting from an increase in the amount of municipal solid waste landfilled.

Wastewater Treatment (33.4 Tg CO_2 Eq.)

Wastewater from domestic sources (i.e., municipal sewage) and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms and chemical contaminants. Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, with the latter condition producing 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. Untreated wastewater may also produce CH_4 if contained under anaerobic conditions. N_2O may be generated during both nitrification and denitrification of the nitrogen present, usually in the form of urea, ammonia, and proteins. In 2005, wastewater treatment was the source of approximately 5 percent of U.S. CH_4 emissions, and 2 percent of N_2O emissions. From 1990 to 2005, CH_4 and N_2O emissions from wastewater treatment increased by 0.6 Tg CO_2 Eq. (2.5 percent) and 1.6 Tg CO_2 Eq. (26 percent), respectively.

2.2. Emissions by Economic Sector

Throughout this report, emission estimates are grouped into six sectors (i.e., chapters) defined by the IPCC: Energy; Industrial Processes; Solvent and Other Product Use; Agriculture; Land Use, Land-Use Change, and Forestry; and Waste. While it is important to use this characterization for consistency with UNFCCC reporting guidelines, it is also useful to allocate emissions into more commonly used sectoral categories. This section reports emissions by the following 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 2005. Transportation activities, in aggregate, accounted for the second largest portion (28 percent). Emissions from industry accounted for 19 percent of U.S. greenhouse gas emissions in 2005. 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

---

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

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 20 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 about 5 percent, and primarily consisted of CO_2 emissions from fossil fuel combustion. Activities related to agriculture accounted for roughly 8 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 about 6 percent of emissions, while U.S. territories accounted for 1 percent.

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.

Table 2-14 presents a detailed breakdown of emissions from each of these economic sectors by source category, as they are defined in this report. Figure 2-13 shows the trend in emissions by sector from 1990 to 2005.

Table 2-14: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg CO_2 Eq. and Percent of Total in 2005)

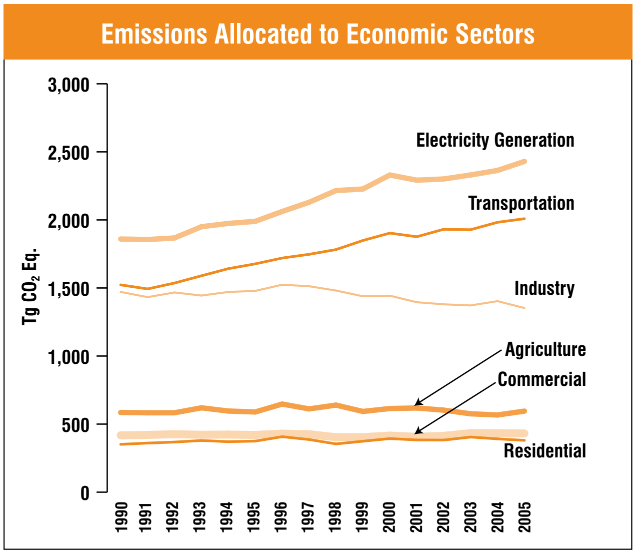
Sector/Source	1990	1995	2000	2001	2002	2003	2004	2005	Percent[a]
Electric Power Industry	**1,859.7**	**1,989.5**	**2,329.9**	**2,292.0**	**2,300.7**	**2,330.2**	**2,363.4**	**2,429.8**	**33.5%**
CO_2 from Fossil Fuel Combustion	1,810.2	1,939.3	2,283.5	2,245.5	2,254.7	2,284.0	2,315.8	2,381.2	32.8%
Municipal Solid Waste Combustion	11.4	16.2	18.3	18.7	18.9	19.9	20.5	21.3	0.3%
Electrical Transmission and Distribution	27.1	21.8	15.2	15.1	14.3	13.8	13.6	13.2	0.2%
Stationary Combustion	8.1	8.6	10.0	9.8	9.8	10.1	10.1	10.4	0.1%
Limestone and Dolomite Use	2.8	3.7	3.0	2.9	2.9	2.4	3.4	3.7	0.1%
Transportation	**1,523.0**	**1,677.2**	**1,903.2**	**1,876.4**	**1,931.2**	**1,928.2**	**1,982.6**	**2,008.9**	**27.7%**
CO_2 from Fossil Fuel Combustion	1,464.0	1,590.2	1,784.4	1,758.2	1,812.3	1,810.5	1,864.5	1,892.8	26.1%
Substitution of Ozone Depleting Substances	+	19.2	51.6	55.8	59.4	62.5	65.6	67.1	0.9%
Mobile Combustion	47.2	56.5	55.2	51.3	48.5	45.0	42.2	38.9	0.5%
Non-Energy Use of Fuels	11.9	11.3	12.1	11.1	10.9	10.1	10.2	10.2	0.1%
Industry	**1,470.9**	**1,478.4**	**1,443.3**	**1,395.4**	**1,380.0**	**1,371.8**	**1,403.3**	**1,352.8**	**18.6%**
CO_2 from Fossil Fuel Combustion	810.3	825.4	824.1	819.3	804.8	813.3	824.5	794.6	10.9%
Natural Gas Systems	158.2	161.9	156.0	154.2	154.6	152.1	147.2	139.3	1.9%
Non-Energy Use of Fuels	99.7	115.9	118.0	115.0	115.2	112.8	130.9	123.4	1.7%
Coal Mining	81.9	66.5	55.9	55.5	52.0	52.1	54.5	52.4	0.7%
Iron and Steel Production	86.2	74.6	66.3	59.0	55.6	54.4	52.4	46.2	0.6%
Cement Manufacture	33.3	36.8	41.2	41.4	42.9	43.1	45.6	45.9	0.6%
Petroleum Systems	34.4	31.1	27.8	27.4	26.8	25.8	25.4	28.5	0.4%
HCFC-22 Production	35.0	27.0	29.8	19.8	19.8	12.3	15.6	16.5	0.2%
Ammonia Manufacture and Urea Application	19.3	20.5	19.6	16.7	17.8	16.2	16.9	16.3	0.2%
Nitric Acid Production	17.8	19.9	19.6	15.9	17.2	16.7	16.0	15.7	0.2%
Lime Manufacture	11.3	12.8	13.3	12.9	12.3	13.0	13.7	13.7	0.2%
Aluminum Production	25.4	17.5	14.7	7.8	9.7	8.3	7.1	7.2	0.1%
Adipic Acid Production	15.2	17.2	6.0	4.9	5.9	6.2	5.7	6.0	0.1%
Substitution of Ozone Depleting Substances	+	1.2	3.3	3.2	3.9	4.6	5.1	5.5	0.1%
Abandoned Underground Coal Mines	6.0	8.2	7.3	6.7	6.1	5.9	5.8	5.5	0.1%
Stationary Combustion	5.3	5.6	5.5	5.1	5.0	4.9	5.2	4.6	0.1%
Semiconductor Manufacture	2.9	5.0	6.3	4.5	4.4	4.3	4.7	4.3	0.1%
N_2O Product Usage	4.3	4.5	4.8	4.8	4.3	4.3	4.3	4.3	0.1%
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.1	4.1	4.1	4.2	4.2	0.1%
Petrochemical Production	3.1	3.8	4.2	3.9	4.0	3.9	4.1	4.0	0.1%
Limestone and Dolomite Use	2.8	3.7	3.0	2.9	2.9	2.4	3.4	3.7	0.1%
Magnesium Production and Processing	5.4	5.6	3.0	2.4	2.4	2.9	2.6	2.7	+
Titanium Dioxide Production	1.3	1.7	1.9	1.9	2.0	2.0	2.3	1.9	+
Ferroalloy Production	2.2	2.0	1.9	1.5	1.4	1.3	1.4	1.4	+
Phosphoric Acid Production	1.5	1.5	1.4	1.3	1.3	1.4	1.4	1.4	+
Carbon Dioxide Consumption	1.4	1.4	1.4	0.8	1.0	1.3	1.2	1.3	+
Mobile Combustion	0.9	1.0	1.1	1.2	1.2	1.3	1.3	1.3	+
Zinc Production	0.9	1.0	1.1	1.0	0.9	0.5	0.5	0.5	+
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	+

Table 2-14: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg CO_2 Eq. and Percent of Total in 2005) (continued)

Sector/Source	1990	1995	2000	2001	2002	2003	2004	2005	Percent[a]
Silicon Carbide Production and Consumption	0.4	0.3	0.3	0.2	0.2	0.2	0.2	0.2	+
Agriculture	**585.3**	**589.2**	**614.4**	**618.4**	**602.6**	**575.7**	**567.0**	**595.4**	**8.2%**
Agricultural Soil Management	366.9	353.4	376.8	389.0	366.1	350.2	338.8	365.1	5.0%
Enteric Fermentation	115.7	120.6	113.5	112.5	112.6	113.0	110.5	112.1	1.5%
Manure Management	39.5	44.1	48.3	50.0	50.8	49.8	49.2	50.8	0.7%
CO_2 from Fossil Fuel Combustion	46.8	57.3	50.9	50.7	52.9	45.0	51.1	45.5	0.6%
Forest Land Remaining Forest Land	7.9	4.5	15.7	6.9	11.8	9.2	8.0	13.1	0.2%
Rice Cultivation	7.1	7.6	7.5	7.6	6.8	6.9	7.6	6.9	0.1%
Field Burning of Agricultural Residues	1.1	1.0	1.3	1.2	1.1	1.2	1.4	1.4	+
Mobile Combustion	0.4	0.5	0.4	0.4	0.5	0.4	0.4	0.4	+
Stationary Combustion	+	+	+	+	+	+	+	+	+
Commercial	**417.8**	**420.5**	**415.5**	**406.6**	**413.7**	**433.5**	**432.6**	**431.4**	**5.9%**
CO_2 from Fossil Fuel Combustion	224.3	226.4	232.3	225.1	225.7	236.6	233.3	225.8	3.1%
Landfills	161.0	157.1	131.9	127.6	130.4	134.9	132.1	132.0	1.8%
Substitution of Ozone Depleting Substances	+	3.8	16.0	19.1	22.9	27.3	32.3	38.9	0.5%
Wastewater Treatment	31.2	32.0	34.0	33.5	33.5	33.4	33.6	33.4	0.5%
Stationary Combustion	1.3	1.3	1.3	1.2	1.2	1.3	1.3	1.2	+
Residential	**351.3**	**375.1**	**393.6**	**383.6**	**382.7**	**404.8**	**391.6**	**380.7**	**5.2%**
CO_2 from Fossil Fuel Combustion	340.3	356.4	373.5	363.9	362.4	383.8	369.9	358.7	4.9%
Substitution of Ozone Depleting Substances	0.3	8.1	10.1	10.4	10.7	11.0	11.5	11.9	0.2%
Settlement Soil Fertilization	5.1	5.5	5.6	5.5	5.6	5.8	6.0	5.8	0.1%
Stationary Combustion	5.5	5.0	4.4	3.9	4.0	4.2	4.3	4.3	0.1%
U.S. Territories	**34.1**	**41.1**	**47.3**	**54.5**	**53.6**	**60.0**	**63.2**	**61.5**	**0.8%**
CO_2 from Fossil Fuel Combustion	34.1	41.1	47.3	54.5	53.6	60.0	63.2	61.5	0.8%
Total Emissions	**6,242.0**	**6,571.0**	**7,147.2**	**7,027.0**	**7,064.6**	**7,104.2**	**7,203.7**	**7,260.4**	**100.0%**
Sinks	**(712.8)**	**(828.8)**	**(756.7)**	**(767.5)**	**(811.9)**	**(811.9)**	**(824.8)**	**(828.5)**	**-11.4%**
Forests	(598.5)	(717.5)	(638.7)	(645.7)	(688.1)	(687.0)	(697.3)	(698.7)	-9.6%
Urban Trees	(57.5)	(67.8)	(78.2)	(80.2)	(82.3)	(84.4)	(86.4)	(88.5)	-1.2%
CO_2 Flux from Agricultural Soils	(33.9)	(30.1)	(29.4)	(30.9)	(30.7)	(31.2)	(32.4)	(32.4)	-0.4%
Landfilled Yard Trimmings and Food Scraps	(22.8)	(13.3)	(10.5)	(10.6)	(10.8)	(9.3)	(8.7)	(8.8)	-0.1%
Net Emissions (Sources and Sinks)	**5,529.2**	**5,742.2**	**6,390.5**	**6,259.5**	**6,252.7**	**6,292.3**	**6,378.9**	**6,431.9**	**88.6%**

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.
+ Does not exceed 0.05 Tg CO_2 Eq. or 0.05%.
[a] Percent of total emissions for year 2005.

Figure 2-13


Emissions Allocated to Economic Sectors

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 2005. Emissions increased by 31 percent since 1990, as electricity demand grew and fossil fuels remained the dominant energy source for 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 nonutility 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 2-15 provides a detailed summary of emissions from electricity generation-related activities.

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 retail sales of electricity (EIA 2006c and Duffield 2006). These three source categories include CO_2 from Fossil Fuel Combustion, CH_4 and N_2O from Stationary Combustion, and SF_6 from Electrical Transmission and Distribution Systems.[6]

When emissions from electricity are distributed among these sectors, industry accounts for the largest share of U.S. greenhouse gas emissions (28 percent), followed closely by emissions from transportation activities, which also account for 28 percent of total emissions. Emissions from the residential and commercial sectors also increase substantially when emissions from electricity are included, due to their relatively large share of electricity consumption. 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 2-16 presents a detailed breakdown of emissions from each of these economic sectors, with emissions from electricity generation distributed to them. Figure 2-14 shows the trend in these emissions by sector from 1990 to 2005.

Figure 2-14

Emissions with Electricity Distributed to Economic Sectors

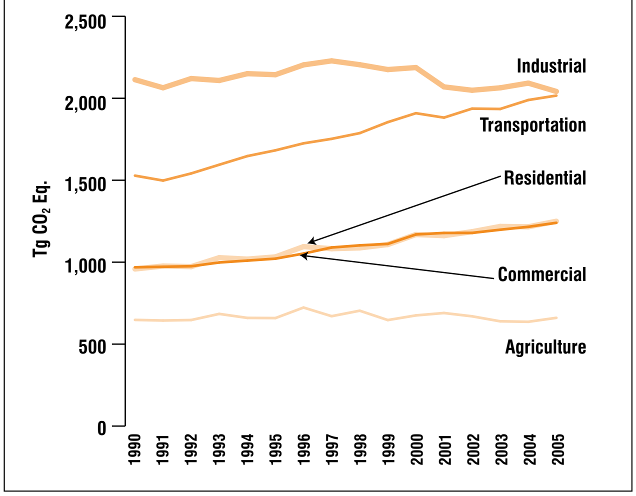


Table 2-15: Electricity Generation-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Fuel Type or Source	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**1,823.9**	**1,958.7**	**2,304.3**	**2,266.7**	**2,276.2**	**2,305.8**	**2,339.2**	**2,405.8**
CO_2 from Fossil Fuel Combustion	1,810.2	1,939.3	2,283.5	2,245.5	2,254.7	2,284.0	2,315.8	2,381.2
Coal	*1,531.3*	*1,648.7*	*1,909.6*	*1,852.3*	*1,868.3*	*1,906.2*	*1,917.6*	*1,958.4*
Natural Gas	*176.8*	*229.5*	*282.0*	*290.8*	*307.0*	*279.3*	*297.7*	*320.1*
Petroleum	*101.8*	*60.7*	*91.5*	*102.0*	*79.1*	*98.1*	*100.1*	*102.3*
Geothermal	*0.4*	*0.3*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*
Municipal Solid Waste Combustion	10.9	15.7	17.9	18.3	18.5	19.5	20.1	20.9
Limestone and Dolomite Use	2.8	3.7	3.0	2.9	2.9	2.4	3.4	3.7
CH_4	**0.6**	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Stationary Combustion*	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7
N_2O	**8.0**	**8.5**	**9.7**	**9.5**	**9.5**	**9.8**	**9.8**	**10.0**
Stationary Combustion*	7.6	8.0	9.3	9.1	9.1	9.4	9.4	9.6
Municipal Solid Waste Combustion	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4
SF_6	**27.1**	**21.8**	**15.2**	**15.1**	**14.3**	**13.8**	**13.6**	**13.2**
Electrical Transmission and Distribution	27.1	21.8	15.2	15.1	14.3	13.8	13.6	13.2
Total	**1,859.7**	**1,989.5**	**2,329.9**	**2,292.0**	**2,300.7**	**2,330.2**	**2,363.4**	**2,429.8**

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

---

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

Table 2-16: U.S Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (Tg CO_2 Eq. and Percent of Total in 2005)

Sector/Gas	1990	1995	2000	2001	2002	2003	2004	2005	Percent[a]
Industry	**2,111.1**	**2,141.5**	**2,185.0**	**2,067.1**	**2,046.6**	**2,061.4**	**2,090.1**	**2,039.2**	**28.1%**
Direct Emissions	1,470.9	1,478.4	1,443.3	1,395.4	1,380.0	1,371.8	1,403.3	1,352.8	18.6%
CO_2	1,082.8	1,109.5	1,105.9	1,084.2	1,069.2	1,072.5	1,104.9	1,061.2	14.6%
CH_4	284.9	272.5	251.8	248.1	243.8	240.2	237.4	229.8	3.2%
N_2O	41.3	45.8	34.6	29.7	31.4	31.2	30.3	29.9	0.4%
HFCs, PFCs, and SF_6	61.9	50.6	50.9	33.4	35.6	27.9	30.8	32.0	0.4%
Electricity-Related	640.2	663.1	741.7	671.6	666.6	689.6	686.7	686.5	9.5%
CO_2	627.9	652.8	733.6	664.2	659.5	682.4	679.7	679.7	9.4%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.8	2.8	3.1	2.8	2.8	2.9	2.9	2.8	+
SF_6	9.3	7.3	4.8	4.4	4.2	4.1	4.0	3.7	0.1%
Transportation	**1,526.1**	**1,680.3**	**1,906.7**	**1,879.8**	**1,934.7**	**1,932.5**	**1,987.1**	**2,014.2**	**27.7%**
Direct Emissions	1,523.0	1,677.2	1,903.2	1,876.4	1,931.2	1,928.2	1,982.6	2,008.9	27.7%
CO_2	1,475.8	1,601.5	1,796.5	1,769.3	1,823.3	1,820.6	1,874.7	1,903.0	26.2%
CH_4	4.5	4.1	3.2	2.9	2.8	2.6	2.5	2.3	+
N_2O	42.7	52.5	52.0	48.4	45.8	42.4	39.8	36.5	0.5%
HFCs[b]	+	19.2	51.6	55.8	59.4	62.5	65.7	67.1	0.9%
Electricity-Related	3.1	3.1	3.5	3.4	3.5	4.3	4.5	5.3	0.1%
CO_2	3.1	3.1	3.5	3.3	3.4	4.3	4.4	5.2	0.1%
CH_4	+	+	+	+	+	+	+	+	+
N_2O	+	+	+	+	+	+	+	+	+
SF_6	+	+	+	+	+	+	+	+	+
Commercial	**967.2**	**1,019.8**	**1,167.4**	**1,176.8**	**1,177.0**	**1,196.2**	**1,214.1**	**1,238.5**	**17.1%**
Direct Emissions	417.8	420.5	415.5	406.6	413.7	433.5	432.6	431.4	5.9%
CO_2	224.3	226.4	232.3	225.1	225.7	236.6	233.3	225.8	3.1%
CH_4	186.7	183.1	159.2	154.4	157.1	161.5	158.7	158.3	2.2%
N_2O	6.8	7.2	7.9	7.9	8.0	8.2	8.3	8.4	0.1%
HFCs	+	3.8	16.0	19.1	22.9	27.3	32.3	38.9	0.5%
Electricity-Related	549.5	599.3	751.9	770.2	763.3	762.7	781.5	807.1	11.1%
CO_2	538.9	590.0	743.7	761.7	755.2	754.8	773.5	799.2	11.0%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.4	2.6	3.1	3.2	3.2	3.2	3.2	3.3	+
SF_6	8.0	6.6	4.9	5.1	4.8	4.5	4.5	4.4	0.1%
Residential	**956.9**	**1,030.6**	**1,167.0**	**1,160.3**	**1,184.3**	**1,216.2**	**1,214.2**	**1,248.0**	**17.2%**
Direct Emissions	351.3	375.1	393.6	383.6	382.7	404.8	391.6	380.7	5.2%
CO_2	340.3	356.4	373.5	363.9	362.4	383.8	369.9	358.7	4.9%
CH_4	4.4	4.0	3.5	3.1	3.1	3.3	3.3	3.4	+
N_2O	6.2	6.5	6.5	6.3	6.5	6.7	6.9	6.7	0.1%
HFCs	0.3	8.1	10.1	10.4	10.7	11.0	11.5	11.9	0.2%
Electricity-Related	605.7	655.5	773.4	776.6	801.5	811.4	822.6	867.3	11.9%
CO_2	594.0	645.4	764.9	768.1	793.0	802.9	814.2	858.7	11.8%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	+
N_2O	2.6	2.8	3.2	3.2	3.3	3.4	3.4	3.6	+
SF_6	8.8	7.2	5.0	5.1	5.0	4.8	4.7	4.7	0.1%
Agriculture	**646.5**	**657.6**	**673.9**	**688.5**	**668.4**	**637.9**	**635.0**	**659.1**	**9.1%**
Direct Emissions	585.3	589.2	614.4	618.4	602.6	575.7	567.0	595.4	8.2%
CO_2	46.8	57.3	50.9	50.7	52.9	45.0	51.1	45.5	0.6%
CH_4	161.6	168.2	174.6	167.2	171.8	169.3	165.8	172.9	2.4%
N_2O	377.0	363.7	388.9	400.5	377.9	361.4	350.1	377.0	5.2%
Electricity-Related	61.2	68.5	59.4	70.1	65.8	62.1	68.0	63.7	0.9%
CO_2	60.0	67.4	58.8	69.3	65.1	61.5	67.4	63.0	0.9%
CH_4	+	+	+	+	+	+	+	+	+
N_2O	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.3	+
SF_6	0.9	0.8	0.4	0.5	0.4	0.4	0.4	0.3	+
U.S. Territories	**34.1**	**41.1**	**47.3**	**54.5**	**53.6**	**60.0**	**63.2**	**61.5**	**0.8%**
Total	**6,242.0**	**6,571.0**	**7,147.2**	**7,027.0**	**7,064.6**	**7,104.2**	**7,203.7**	**7,260.4**	**100.0%**

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 2005.

[b] Includes primarily HFC-134a.

Transportation

Transportation activities accounted for 28 percent of U.S. greenhouse gas emissions in 2005. Table 2-17 provides a detailed summary of greenhouse gas emissions from transportation-related activities. Total emissions in Table 2-17 differ slightly from those shown in Table 2-16 primarily because the table below excludes a few minor non-transportation mobile sources, such as construction and industrial equipment.

From 1990 to 2005, transportation emissions rose by 32 percent due, in part, to increased demand for travel and the stagnation of fuel efficiency across the U.S. vehicle fleet. Since the 1970s, the number of highway vehicles registered in the United States has increased faster than the overall population, according to the Federal Highway Administration (FHWA). Likewise, the number of miles driven (up 21 percent from 1990 to 2005) and the gallons of gasoline consumed each year in the United States have increased steadily since the 1980s, according to the FHWA and Energy Information Administration, respectively. These increases in motor vehicle usage are the result of a confluence of factors including population growth, economic growth, urban sprawl, low fuel prices, and increasing popularity of sport utility vehicles and other light-duty trucks that tend to have lower fuel efficiency. A similar set of social and economic trends has led to a significant increase in air travel

Table 2-17: Transportation-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**1,478.8**	**1,604.6**	**1,799.9**	**1,772.6**	**1,826.7**	**1,824.9**	**1,879.1**	**1,908.1**
Passenger Cars	615.1	599.6	632.0	634.7	649.6	629.1	628.7	614.9
Light-Duty Trucks	314.0	401.6	459.2	462.7	476.6	510.7	533.6	550.3
Other Trucks	227.0	270.9	343.2	343.3	358.1	355.4	368.5	384.6
Buses	8.3	9.0	11.0	10.1	9.7	10.6	14.9	15.1
Aircraft[a]	180.0	174.6	196.4	186.6	178.0	174.7	179.7	186.1
Ships and Boats	46.8	55.4	63.8	43.0	60.6	53.3	61.1	63.7
Locomotives	38.1	42.2	45.1	45.1	44.9	46.6	49.2	50.3
Other[b]	49.6	51.3	49.1	47.2	49.2	44.4	43.5	43.1
International Bunker Fuels[c]	*113.7*	*100.6*	*101.1*	*97.6*	*89.1*	*83.7*	*97.2*	*97.2*
CH_4	**4.5**	**4.1**	**3.2**	**2.9**	**2.8**	**2.6**	**2.5**	**2.3**
Passenger Cars	2.6	2.1	1.6	1.5	1.4	1.3	1.2	1.1
Light-Duty Trucks	1.4	1.4	1.1	1.0	1.0	0.9	0.8	0.8
Other Trucks and Buses	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Ships and Boats	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Locomotives	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Motorcycles	+	+	+	+	+	+	+	+
International Bunker Fuels[c]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**42.7**	**52.5**	**52.0**	**48.4**	**45.8**	**42.4**	**39.7**	**36.5**
Passenger Cars	25.4	26.9	24.7	23.2	21.9	20.3	18.8	17.0
Light-Duty Trucks	14.1	22.1	23.3	21.4	20.1	18.3	17.0	15.6
Other Trucks and Buses	0.8	1.0	1.2	1.3	1.3	1.3	1.3	1.2
Aircraft	1.7	1.7	1.9	1.8	1.7	1.7	1.7	1.8
Ships and Boats	0.4	0.4	0.5	0.3	0.5	0.4	0.5	0.5
Locomotives	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4
Motorcycles	+	+	+	+	+	+	+	+
International Bunker Fuels[c]	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*	*0.9*	*0.9*
HFCs	**+**	**19.2**	**51.6**	**55.8**	**59.4**	**62.5**	**65.6**	**67.1**
Mobile Air Conditioners[d]	+	16.8	41.6	44.9	47.7	50.0	52.2	53.1
Comfort Cooling in Buses and Trains	+	+	0.2	0.2	0.2	0.2	0.3	0.3
Refrigerated Transport	+	2.3	9.8	10.8	11.5	12.3	13.1	13.6
Total	**1,526.1**	**1,680.4**	**1,906.7**	**1,879.7**	**1,934.6**	**1,932.4**	**1,986.9**	**2,014.0**

\+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

[a] Aircraft emissions consist of emissions from all jet fuel (less bunker fuels) and aviation gas consumption.

[b] "Other" CO_2 emissions include motorcycles, pipelines, and lubricants.

[c] Emissions from International Bunker Fuels include emissions from both civilian and military activities, but are not included in totals.

[d] Includes primarily HFC-134a.

and freight transportation by both air and road modes during the time series.

Almost all of the energy consumed for transportation was supplied by petroleum-based products, with nearly two-thirds 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 29 percent from 1990 to 2005. This rise in CO_2 emissions, combined with an increase of 67.1 Tg CO_2 Eq. in HFC emissions over the same period, led to an increase in overall emissions from transportation activities of 32 percent.

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

The reporting requirements of the UNFCCC[7] request that information be provided on indirect greenhouse gases, which include CO, NO_x, NMVOCs, and SO_2. These gases do not have a direct global warming effect, but indirectly affect terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone, or, in the case of SO_2, by affecting the absorptive characteristics of the atmosphere. Additionally, some of these gases may react with other chemical compounds in the

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

In order to aggregate emissions by economic sector, source category emission estimates were generated according to the methodologies outlined in the appropriate sections of this report. Those emissions were then simply reallocated into economic sectors. In most cases, the IPCC subcategories distinctly fit into an apparent economic sector category. Several exceptions exist, and the methodologies used to disaggregate these subcategories are described below:

- *Agricultural CO_2 Emissions from Fossil Fuel Combustion, and Non-CO_2 Emissions from Stationary and Mobile Combustion.* Emissions from on-farm energy use were accounted for in the Energy chapter as part of the industrial and transportation end-use sectors. To calculate agricultural emissions related to fossil fuel combustion, energy consumption estimates were obtained from economic survey data from the U.S. Department of Agriculture (Duffield 2006) and fuel sales data (EIA 1991 through 2005). To avoid double-counting, emission estimates of CO_2 from fossil fuel combustion and non-CO_2 from stationary and mobile combustion were subtracted from the industrial economic sector, although some of these fuels may have been originally accounted for under the transportation end-use sector.
- *Landfills and Wastewater Treatment.* CH_4 emissions from landfills and CH_4 and N_2O emissions from wastewater treatment were allocated to the commercial sector.
- *Municipal Solid Waste Combustion.* CO_2 and N_2O emissions from waste combustion were allocated completely to the electricity generation sector since nearly all waste combustion occurs in waste-to-energy facilities.
- *Limestone and Dolomite Use.* CO_2 emissions from limestone and dolomite use are allocated to the electricity generation (50 percent) and industrial (50 percent) sectors, because 50 percent of the total emissions for this source are due to flue gas desulfurization.
- *Substitution of Ozone Depleting Substances.* All greenhouse gas emissions resulting from the substitution of ozone depleting substances were placed in the industrial economic sector, with the exception of emissions from domestic, commercial, and mobile and transport refrigeration/air-conditioning systems, which were placed in the residential, commercial, and transportation sectors, respectively. Emissions from non-MDI aerosols were attributed to the residential economic sector.
- *Settlement Soil Fertilization, Forest Soil Fertilization.* Emissions from settlement soil fertilization were allocated to the residential economic sector; forest soil fertilization was allocated to the agriculture economic sector.
- *Forest Fires.* N_2O and CH_4 emissions from forest fires were allocated to the agriculture economic sector.

---

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

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 2005),[8] which are regulated under the Clean Air Act. Table 2-18 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.

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 88 percent in 2005. 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.

---

[8] NO_x and CO emission estimates from field burning of agricultural residues were estimated separately, and therefore not taken from EPA (2005).

Table 2-18: Emissions of NO_x, CO, NMVOCs, and SO_2 (Gg)

Gas/Activity	1990	1995	2000	2001	2002	2003	2004	2005
NO_x	**21,645**	**21,272**	**19,203**	**18,410**	**18,141**	**17,327**	**16,466**	**15,965**
Mobile Fossil Fuel Combustion	10,920	10,622	10,310	9,819	10,319	9,911	9,520	9,145
Stationary Fossil Fuel Combustion	9,883	9,821	8,002	7,667	6,837	6,428	5,952	5,824
Industrial Processes	591	607	626	656	532	533	534	535
Oil and Gas Activities	139	100	111	113	316	317	317	318
Municipal Solid Waste Combustion	82	88	114	114	97	98	98	98
Agricultural Burning	28	29	35	35	33	34	39	39
Solvent Use	1	3	3	3	5	5	5	5
Waste	0	1	2	2	2	2	2	2
CO	**130,581**	**109,157**	**92,897**	**89,333**	**86,796**	**84,370**	**82,073**	**79,811**
Mobile Fossil Fuel Combustion	119,480	97,755	83,680	79,972	77,382	74,756	72,269	69,915
Stationary Fossil Fuel Combustion	5,000	5,383	4,340	4,377	5,224	5,292	5,361	5,431
Industrial Processes	4,125	3,959	2,217	2,339	1,710	1,730	1,751	1,772
Municipal Solid Waste Combustion	978	1,073	1,670	1,672	1,440	1,457	1,475	1,493
Agricultural Burning	691	663	792	774	709	800	879	858
Oil and Gas Activities	302	316	146	147	323	327	331	335
Waste	1	2	8	8	7	7	7	7
Solvent Use	5	5	46	45	1	1	1	1
NMVOCs	**20,930**	**19,520**	**15,228**	**15,048**	**14,968**	**14,672**	**14,391**	**14,123**
Mobile Fossil Fuel Combustion	10,932	8,745	7,230	6,872	6,608	6,302	6,011	5,734
Solvent Use	5,216	5,609	4,384	4,547	3,911	3,916	3,921	3,926
Industrial Processes	2,422	2,642	1,773	1,769	1,811	1,813	1,815	1,818
Stationary Fossil Fuel Combustion	912	973	1,077	1,080	1,733	1,734	1,735	1,736
Oil and Gas Activities	554	582	389	400	546	547	547	548
Municipal Solid Waste Combustion	222	237	257	258	244	244	244	245
Waste	673	731	119	122	116	116	116	116
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA
SO_2	**20,935**	**16,891**	**14,829**	**14,452**	**13,541**	**13,648**	**13,328**	**13,271**
Stationary Fossil Fuel Combustion	18,407	14,724	12,848	12,461	11,852	12,002	11,721	11,698
Industrial Processes	1,307	1,117	1,031	1,047	752	759	766	774
Mobile Fossil Fuel Combustion	793	672	632	624	681	628	579	535
Oil and Gas Activities	390	335	286	289	233	235	238	240
Municipal Solid Waste Combustion	38	42	29	30	23	23	23	23
Waste	0	1	1	1	1	1	1	1
Solvent Use	0	1	1	1	0	0	0	0
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA

Source: (EPA 2005) except for estimates from field burning of agricultural residues.
NA (Not Available)
Note: Totals may not sum due to independent rounding.

3. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 85 percent of total emissions on a carbon (C) equivalent basis in 2005. This included 98, 38, and 11 percent of the nation's carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions, respectively. Energy-related CO_2 emissions alone constituted 82 percent of national emissions from all sources on a C equivalent basis, while the non-CO_2 emissions from energy-related activities represented a much smaller portion of total national emissions (4 percent collectively).

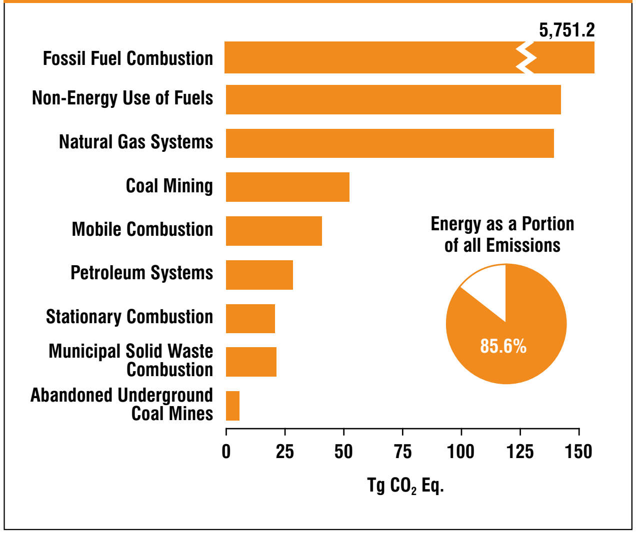
Emissions from fossil fuel combustion comprise the vast majority of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 3-1). Globally, approximately 27,044 Tg of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2004, of which the United States accounted for about 22 percent.[1] Due to the relative importance of fossil fuel combustion-related CO_2 emissions, they 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, as well as indirect greenhouse gases such as nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs). Mobile fossil fuel combustion was the second largest source of N_2O emissions in the United States, and overall energy-related activities were collectively the largest source of these indirect greenhouse gas emissions.

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. Smaller quantities of CO_2, CO, NMVOCs, and NO_x are also emitted.

The combustion of biomass and biomass-based fuels also emits greenhouse gases. CO_2 emissions from these activities, however, are not included in national emissions totals because biomass fuels are of biogenic origin. It is assumed that the C released during the consumption of biomass is recycled as U.S. forests and crops regenerate, causing no net addition of CO_2 to the atmosphere. The net impacts of land-use and forestry activities on the C cycle are accounted for within the Land Use, Land-Use Change, and Forestry chapter. Emissions of other greenhouse gases from the combustion of biomass

Figure 3-1

2005 Energy Chapter Greenhouse Gas Sources

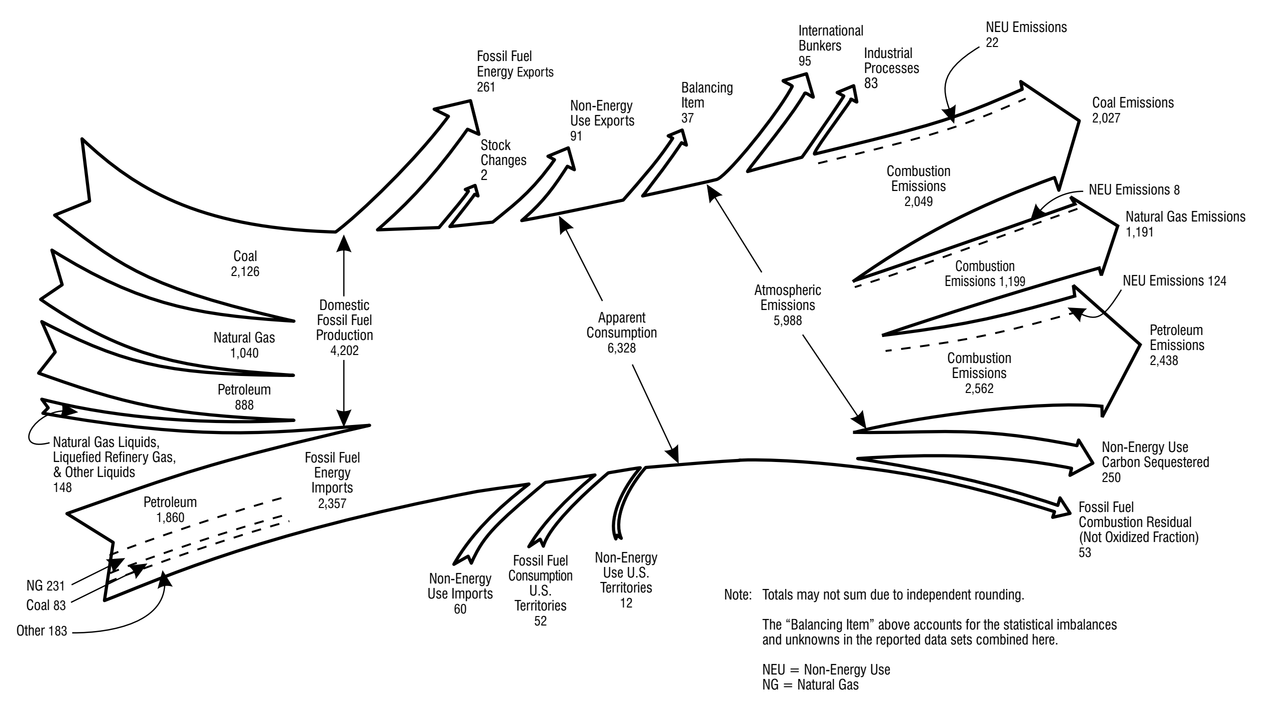


---

[1] Global CO_2 emissions from fossil fuel combustion were taken from Energy Information Administration *International Energy Annual 2004* <http://www.eia.doe.gov/iea/carbon.html> EIA (2006).

Figure 3-2

2005 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)



Note: Totals may not sum due to independent rounding.

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

NEU = Non-Energy Use
NG = Natural Gas

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

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**4,886.1**	**5,212.8**	**5,773.2**	**5,690.2**	**5,740.7**	**5,803.8**	**5,911.5**	**5,942.7**
Fossil Fuel Combustion	4,724.1	5,030.0	5,584.9	5,511.7	5,557.2	5,624.5	5,713.0	5,751.2
Non-Energy Use of Fuels	117.3	133.2	141.0	131.4	135.3	131.3	150.2	142.4
Natural Gas Systems	33.7	33.8	29.4	28.8	29.6	28.4	28.2	28.2
Municipal Solid Waste Combustion	10.9	15.7	17.9	18.3	18.5	19.5	20.1	20.9
*International Bunker Fuels**	*113.7*	*100.6*	*101.1*	*97.6*	*89.1*	*83.7*	*97.2*	*97.2*
*Wood Biomass and Ethanol Consumption**	*219.3*	*236.8*	*228.3*	*203.2*	*204.4*	*209.6*	*224.8*	*206.5*
CH_4	**259.6**	**246.1**	**228.5**	**225.0**	**219.7**	**217.4**	**214.6**	**207.1**
Natural Gas Systems	124.5	128.1	126.6	125.4	125.0	123.7	119.0	111.1
Coal Mining	81.9	66.5	55.9	55.5	52.0	52.1	54.5	52.4
Petroleum Systems	34.4	31.1	27.8	27.4	26.8	25.8	25.4	28.5
Stationary Combustion	8.0	7.8	7.4	6.8	6.8	7.0	7.1	6.9
Abandoned Underground Coal Mines	6.0	8.2	7.3	6.7	6.1	5.9	5.8	5.5
Mobile Combustion	4.7	4.3	3.5	3.2	3.1	2.9	2.8	2.6
*International Bunker Fuels**	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**56.5**	**66.9**	**67.6**	**63.6**	**60.9**	**57.9**	**55.5**	**52.2**
Mobile Combustion	43.7	53.7	53.2	49.7	47.1	43.8	41.2	38.0
Stationary Combustion	12.3	12.8	14.0	13.5	13.4	13.7	13.9	13.8
Municipal Solid Waste Combustion	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4
*International Bunker Fuels**	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*	*0.9*	*0.9*
Total	**5,202.2**	**5,525.8**	**6,069.2**	**5,978.9**	**6,021.4**	**6,079.1**	**6,181.7**	**6,201.9**

*These values are presented for informational purposes only and are not included or are already accounted for in totals.
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	1995	2000	2001	2002	2003	2004	2005
CO_2	**4,886,134**	**5,212,782**	**5,773,163**	**5,690,231**	**5,740,712**	**5,803,770**	**5,911,530**	**5,942,665**
Fossil Fuel Combustion	4,724,149	5,030,036	5,584,880	5,511,719	5,557,242	5,624,500	5,713,018	5,751,200
Non-Energy Use of Fuels	117,307	133,228	141,005	131,375	135,327	131,334	150,208	142,368
Natural Gas Systems	33,729	33,807	29,390	28,793	29,630	28,445	28,190	28,185
Municipal Solid Waste Combustion	10,950	15,712	17,889	18,344	18,513	19,490	20,115	20,912
*International Bunker Fuels**	*113,683*	*100,627*	*101,125*	*97,563*	*89,101*	*83,690*	*97,177*	*97,191*
*Wood Biomass and Ethanol Consumption**	*219,341*	*236,775*	*228,308*	*203,163*	*204,351*	*209,603*	*224,825*	*206,475*
CH_4	**12,360**	**11,718**	**10,879**	**10,714**	**10,463**	**10,352**	**10,221**	**9,862**
Natural Gas Systems	5,927	6,101	6,027	5,971	5,951	5,891	5,669	5,292
Coal Mining	3,899	3,165	2,662	2,644	2,476	2,480	2,597	2,494
Petroleum Systems	1,640	1,482	1,325	1,303	1,275	1,229	1,209	1,357
Stationary Combustion	382	373	351	324	324	334	340	330
Abandoned Underground Coal Mines	286	391	349	318	292	282	275	263
Mobile Combustion	226	207	165	154	146	136	131	125
*International Bunker Fuels**	*8*	*6*	*6*	*5*	*4*	*4*	*5*	*5*
N_2O	**182**	**216**	**218**	**205**	**197**	**187**	**179**	**168**
Mobile Combustion	141	173	172	160	152	141	133	123
Stationary Combustion	40	41	45	44	43	44	45	45
Municipal Solid Waste Combustion	2	1	1	1	1	1	1	1
*International Bunker Fuels**	*3*	*3*	*3*	*3*	*3*	*2*	*3*	*3*

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

and biomass-based fuels are included in national totals under stationary and mobile combustion.

Table 3-1 summarizes emissions from the Energy sector in units of teragrams 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 6,201.9 Tg CO_2 Eq. in 2005, an increase of 19 percent since 1990.

3.1. Carbon Dioxide Emissions from Fossil Fuel Combustion (IPCC Source Category 1A)

CO_2 emissions from fossil fuel combustion in 2005 increased by 0.7 percent from the previous year. This small increase is primarily a result of the restraint on fuel consumption caused by rising fuel prices, primarily in the transportation sector. Additionally, warmer winter conditions in 2005 decreased the demand for heating fuels. In contrast, warmer summer conditions in 2005 increased the demand for electricity. In 2005, CO_2 emissions from fossil fuel combustion were 5,751.2 Tg CO_2 Eq., or 22 percent above emissions in 1990 (see Table 3-3).[2]

Trends in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors. On a year-to-year basis, the overall demand for fossil fuels in the United States and other countries generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, in a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams, there would likely be proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants.

Longer-term changes in energy consumption patterns, however, tend to be more a function of aggregate societal trends that affect the scale of consumption (e.g., population, number of cars, and size 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).

---

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

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

Fuel/Sector	1990	1995	2000	2001	2002	2003	2004	2005
Coal	**1,699.0**	**1,805.5**	**2,053.9**	**1,997.2**	**2,003.3**	**2,043.3**	**2,058.6**	**2,093.6**
Residential	3.0	1.7	1.1	1.1	1.2	1.2	1.3	1.0
Commercial	11.8	11.1	8.8	9.2	8.6	7.8	9.6	8.0
Industrial	152.3	143.0	133.5	133.5	123.4	124.0	126.2	122.2
Transportation	NE	NE	NE	NE	NE	NE	NE	NE
Electricity Generation	1,531.3	1,648.7	1,909.6	1,852.3	1,868.3	1,906.2	1,917.6	1,958.4
U.S. Territories	0.6	0.9	0.9	1.0	1.9	4.1	3.9	4.0
Natural Gas	**1,011.4**	**1,169.6**	**1,227.6**	**1,178.7**	**1,219.6**	**1,187.9**	**1,190.4**	**1,170.0**
Residential	240.0	264.3	272.0	260.5	266.9	278.4	266.2	262.8
Commercial	143.3	165.2	173.2	165.0	171.7	174.3	171.2	167.0
Industrial	415.3	472.2	464.0	426.2	435.6	421.2	421.8	387.0
Transportation	36.1	38.4	35.7	34.9	37.2	33.4	32.3	31.8
Electricity Generation	176.8	229.5	282.0	290.8	307.0	279.3	297.7	320.1
U.S. Territories	NO	NO	0.7	1.2	1.2	1.4	1.3	1.3
Petroleum	**2,013.3**	**2,054.6**	**2,303.0**	**2,335.5**	**2,333.9**	**2,392.9**	**2,463.6**	**2,487.2**
Residential	97.4	90.5	100.5	102.2	94.4	104.2	102.5	95.0
Commercial	69.2	50.1	50.3	50.9	45.5	54.5	52.5	50.9
Industrial	289.5	267.5	277.4	310.2	298.7	313.2	327.6	330.9
Transportation	1,427.9	1,551.8	1,748.7	1,723.3	1,775.1	1,777.1	1,832.2	1,861.0
Electricity Generation	101.8	60.7	91.5	102.0	79.1	98.1	100.1	102.3
U.S. Territories	27.6	34.0	34.6	46.8	41.1	45.8	48.7	47.2
Geothermal*	**0.40**	**0.34**	**0.36**	**0.35**	**0.37**	**0.37**	**0.37**	**0.37**
Total	**4,724.1**	**5,030.0**	**5,584.9**	**5,511.7**	**5,557.2**	**5,624.5**	**5,713.0**	**5,751.2**

NE (Not estimated)
NO (Not occurring)
*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.

Table 3-4: Annual Change in CO_2 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (Tg CO_2 Eq. and Percent)

Sector	Fuel Type	2001 to 2002		2002 to 2003		2003 to 2004		2004 to 2005	
Electricity Generation	Coal	16.0	1%	38.0	2%	11.4	1%	40.8	2%
Electricity Generation	Natural Gas	16.1	6%	-27.7	-9%	18.4	7%	22.4	8%
Electricity Generation	Petroleum	-22.9	-22%	19.0	24%	2.0	2%	2.2	2%
Transportation[a]	Petroleum	51.8	3%	2.0	0%	55.1	3%	28.8	2%
Residential	Natural Gas	6.4	2%	11.5	4%	-12.2	-4%	-3.4	-1%
Commercial	Natural Gas	6.6	4%	2.6	2%	-3.1	-2%	-4.2	-2%
Industrial	Coal	-10.1	-8%	0.6	0%	2.3	2%	-4.0	-3%
Industrial	Natural Gas	9.4	2%	-14.5	-3%	0.6	0%	-34.8	-8%
All Sectors[b]	**All Fuels[b]**	**45.5**	**1%**	**67.3**	**1%**	**88.5**	**2%**	**38.2**	**1%**

[a] Excludes emissions from International Bunker Fuels.
[b] Includes fuels and sectors not shown in table.

CO_2 emissions also depend on the source of energy and its 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.[3] Producing a unit of heat or electricity using natural gas instead of coal can reduce the CO_2 emissions associated with energy consumption, and using nuclear or renewable energy sources (e.g., wind) can essentially eliminate emissions (see Box 3-2). Table 3-4 shows annual changes in emissions during the last five years for coal, petroleum, and natural gas in selected sectors.

In the United States, 86 percent of the energy consumed in 2005 was produced through the combustion of fossil fuels

---

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

such as coal, natural gas, and petroleum (see Figure 3-3 and Figure 3-4). The remaining portion was supplied by nuclear electric power (8 percent) and by a variety of renewable energy sources (6 percent), primarily hydroelectric power and biofuels (EIA 2006a). Specifically, petroleum supplied the largest share of domestic energy demands, accounting for an average of 44 percent of total fossil fuel based energy consumption in 2005. Natural gas and coal followed in order of importance, each accounting for 28 percent of total consumption. Petroleum was consumed primarily in the transportation end-use sector, the vast majority of coal was used in electricity generation, and natural gas was broadly consumed in all end-use sectors except transportation (see Figure 3-5) (EIA 2006a).

Figure 3-3

2005 U.S. Energy Consumption by Energy Source

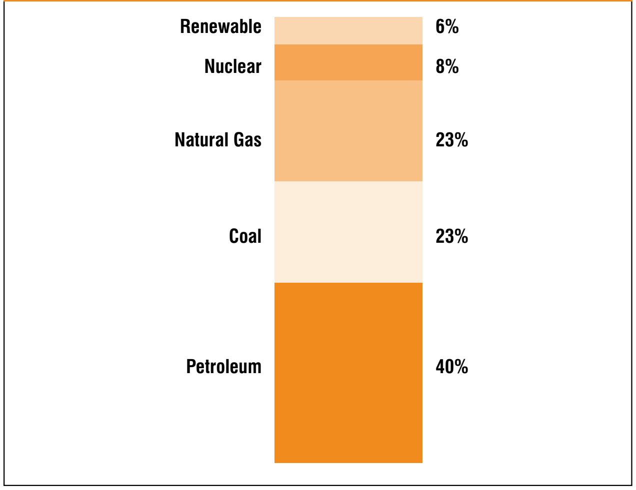
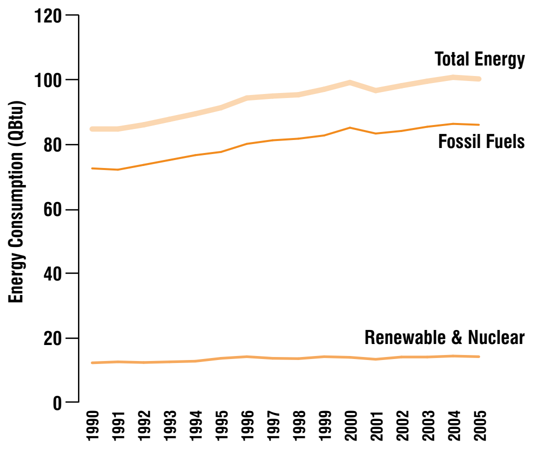


Figure 3-4

U.S. Energy Consumption (Quadrillion Btu)



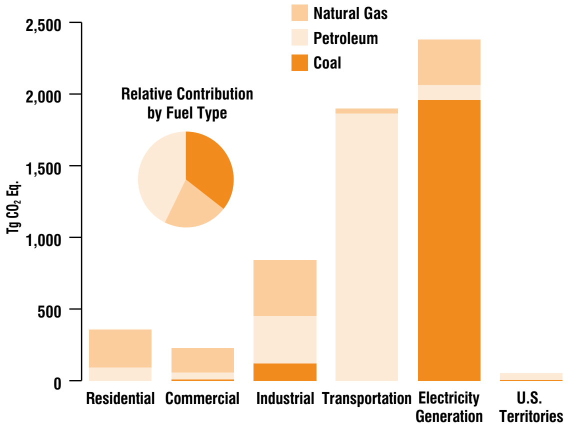
Note: Expressed as gross calorific values.

Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process, the C stored in the fuels is oxidized and emitted as CO_2 and smaller amounts of other gases, including CH_4, CO, and NMVOCs.[4] These other C-containing non-CO_2 gases are emitted as a by-product of incomplete fuel combustion, but are, for the most part, eventually oxidized to CO_2 in the atmosphere. Therefore, it is assumed that all the C in fossil fuels used to produce energy is eventually converted to atmospheric CO_2.

For the purpose of international reporting, the Intergovernmental Panel on Climate Change (IPCC) (IPCC/UNEP/OECD/IEA 1997) recommends that particular adjustments be made to national fuel consumption statistics. Certain fossil fuels can be manufactured into plastics, asphalt, lubricants, or other products. A portion of the C consumed for these non-energy products can be stored (i.e., sequestered) indefinitely. To account for the fact that the C in these fuels ends up in products instead of being combusted (i.e., oxidized and released into the atmosphere), consumption of fuels for non-energy purposes is estimated and subtracted from total fuel consumption estimates. Emissions from non-energy uses of fuels are estimated in the Carbon Emitted and Stored in Products from Non-Energy Uses of Fossil Fuels section in this chapter.

Figure 3-5

2005 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type



Note: The electricity generation sector also includes emissions of less than 0.01 Tg CO_2 Eq. from geothermal-based electricity generation.

---

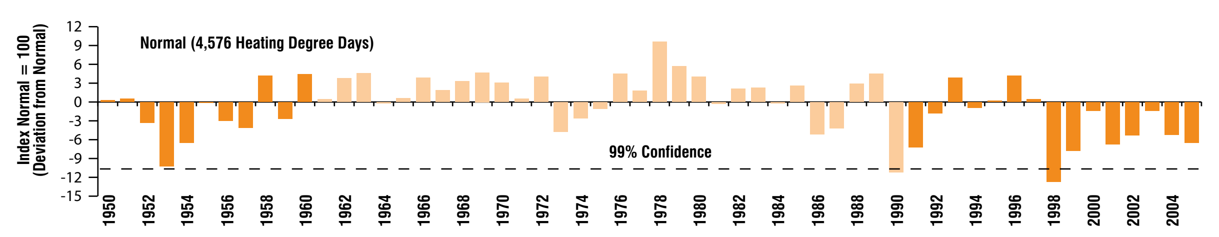
[4] See the sections entitled Stationary Combustion and Mobile Combustion in this chapter for information on non-CO_2 gas emissions from fossil fuel combustion.

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

In 2005, weather conditions became warmer in both the winter and summer. The winter was slightly milder than usual, with heating degree days in the United States 5 percent below normal (see Figure 3-6). Warmer winter conditions led to a decrease in demand for heating fuels. Summer temperatures were substantially warmer than usual, with cooling degree days 15 percent above normal (see Figure 3-7) (EIA 2006f),[5] thereby increasing the demand for electricity.

Figure 3-6

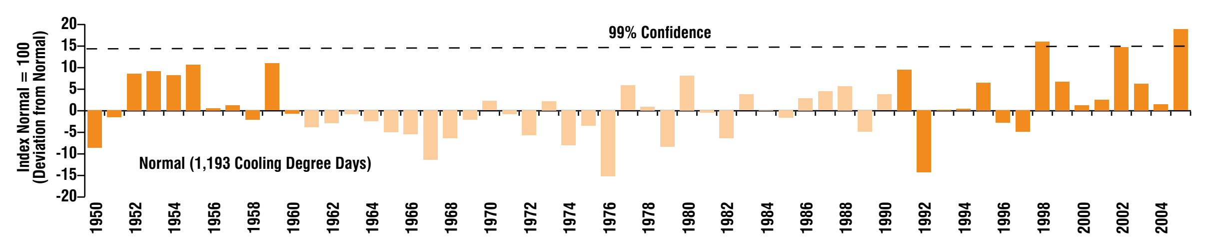
Annual Deviations from Normal Heating Degree Days for the United States (1950–2005)



Note: Climatological normal data are highlighted. Statistical confidence interval for "normal" climatology period of 1961 through 1990.

Figure 3-7

Annual Deviations from Normal Cooling Degree Days for the United States (1950–2005)

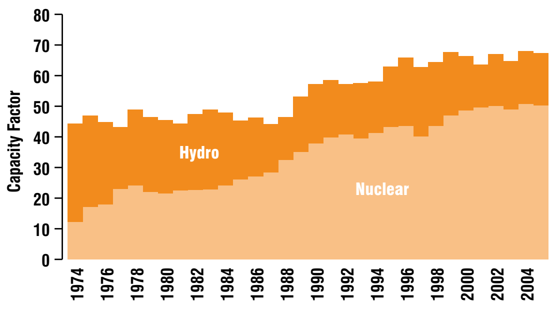


Note: Climatological normal data are highlighted. Statistical confidence interval for "normal" climatology period of 1961 through 1990.

Although no new U.S. nuclear power plants have been constructed in recent years, the utilization (i.e., capacity factors[6]) of existing plants in 2005 remained high at slightly over 89 percent. Electricity output by hydroelectric power plants decreased in 2005 by approximately 1 percent. Electricity generated by nuclear plants in 2005 provided almost 3 times as much of the energy consumed in the United States as hydroelectric plants (EIA 2006a). Aggregate nuclear and hydroelectric power plant capacity factors since 1973 are shown in Figure 3-8.

Figure 3-8

Aggregate Nuclear and Hydroelectric Power Plant Capacity Factors in the United States (1974–2005)



---

[5] 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).

[6] The capacity factor is defined as the ratio of the electrical energy produced by a generating unit for a given period of time to the electrical energy that could have been produced at continuous full-power operation during the same period (EIA 2006a).

Table 3-5: CO_2 Emissions from International Bunker Fuels (Tg CO_2 Eq.)*

Vehicle Mode	1990	1995	2000	2001	2002	2003	2004	2005
Aviation	45.7	50.2	59.9	58.7	61.1	58.8	62.2	62.6
Marine	68.0	50.4	41.3	38.9	28.0	24.9	34.9	34.6
Total	**113.7**	**100.6**	**101.1**	**97.6**	**89.1**	**83.7**	**97.2**	**97.2**

*See International Bunker Fuels section for additional detail.
Note: Totals may not sum due to independent rounding.

According to the UNFCCC reporting guidelines, CO_2 emissions from the consumption of fossil fuels for aviation and marine international transport activities (i.e., international bunker fuels) should be reported separately, and not included in national emission totals. Estimates of international bunker fuel emissions for the United States are provided in Table 3-5.

End-Use Sector Consumption

An alternative method of presenting CO_2 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. For the discussion below, electricity generation emissions have been distributed to each end-use sector based upon the sector's share of national electricity consumption. This method of distributing emissions assumes that each sector consumes electricity generated from an equally carbon-intensive mix of fuels and other energy sources. After the end-use sectors are discussed, emissions from electricity generation are addressed separately. Emissions from U.S. territories are also calculated separately due to a lack of end-use-specific consumption data. Table 3-6 and Figure 3-9 summarize CO_2 emissions from direct fossil fuel combustion and pro-rated electricity generation emissions from electricity consumption by end-use sector.

Figure 3-9

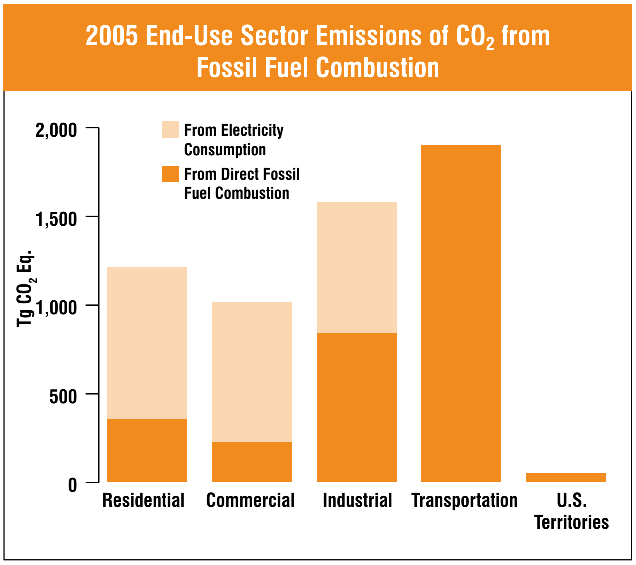


Table 3-6: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005
Transportation	**1,467.0**	**1,593.3**	**1,787.8**	**1,761.5**	**1,815.7**	**1,814.8**	**1,868.9**	**1,897.9**
Combustion	1,464.0	1,590.2	1,784.4	1,758.2	1,812.3	1,810.5	1,864.5	1,892.8
Electricity	3.0	3.0	3.4	3.3	3.4	4.3	4.4	5.2
Industrial	**1,539.8**	**1,595.8**	**1,660.1**	**1,596.6**	**1,575.5**	**1,595.1**	**1,615.2**	**1,575.2**
Combustion	857.1	882.7	875.0	869.9	857.7	858.3	875.6	840.1
Electricity	682.7	713.1	785.1	726.7	717.8	736.8	739.6	735.1
Residential	**929.9**	**995.4**	**1,131.5**	**1,124.8**	**1,147.9**	**1,179.1**	**1,175.9**	**1,208.7**
Combustion	340.3	356.4	373.5	363.9	362.4	383.8	369.9	358.7
Electricity	589.6	639.0	758.0	760.9	785.5	795.3	806.0	849.9
Commercial	**759.2**	**810.6**	**969.3**	**979.7**	**973.8**	**984.2**	**999.1**	**1,016.8**
Combustion	224.3	226.4	232.3	225.1	225.7	236.6	233.3	225.8
Electricity	534.9	584.2	736.9	754.6	748.0	747.6	765.8	791.0
U.S. Territories	**28.3**	**35.0**	**36.2**	**49.0**	**44.3**	**51.3**	**54.0**	**52.5**
Total	**4,724.1**	**5,030.0**	**5,584.9**	**5,511.7**	**5,557.2**	**5,624.5**	**5,713.0**	**5,751.2**
Electricity Generation	**1,810.2**	**1,939.3**	**2,283.5**	**2,245.5**	**2,254.7**	**2,284.0**	**2,315.8**	**2,381.2**

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.

Transportation End-Use Sector

Using this allocation method, the transportation end-use sector accounted for 1,897.9 Tg CO_2 in 2005, or approximately 33 percent of total CO_2 emissions from fossil fuel combustion, the largest share of any end-use economic sector.[7] Between 1990 and 2005, transportation CO_2 emissions increased by 431.0 Tg CO_2, representing approximately 41 percent of the growth in energy-related CO_2 emissions from all sectors. Almost all of the energy consumed in the transportation sector was petroleum-based, including motor gasoline, diesel fuel, jet fuel, and residual oil.

Table 3-7 provides a detailed breakdown of CO_2 emissions by fuel category and vehicle type for the transportation end-use sector. As detailed in the table, overall transportation CO_2 emissions increased by 29 percent from 1990 to 2005, representing an average annual increase of 1.8 percent. Between 2004 and 2005 transportation CO_2 emissions increased by 1.6 percent.

Transportation fuel consumption is broadly affected by travel activity and the amount of energy vehicles use to move people and goods by various travel modes. In the short-term, changes in transportation energy consumption and CO_2 emissions primarily reflect variation in travel activity that accompanies year-to-year economic fluctuations. Long-term factors, especially the cost of fuel, can impact travel patterns and vehicle energy efficiency. Since 1990, there has been a significant increase in vehicle miles traveled (VMT) by light-duty trucks, freight trucks, and aircraft. At the same time, the fuel economy of light-duty trucks and freight trucks has remained roughly constant. By contrast, commercial aircraft have become noticeably more fuel efficient and have operated with an increasing percentage of seats occupied.

As shown in Table 3-7, automobiles and light-duty trucks (consuming both gasoline and diesel) accounted for approximately 61 percent of transportation CO_2 emissions in 2005. From 1990 to 2005, CO_2 emissions from automobiles and light-duty trucks increased roughly 25 percent (236.2 Tg CO_2). Over this period, automobile and light-duty truck VMT increased by 39 percent, outweighing a small increase in overall fleet fuel economy. Much of the small increase in overall fleet fuel economy resulted from the retirement of older, less fuel efficient vehicles. Figure 3-10 presents the overall sales-weighted fuel economy of new vehicles sold in the United States over the 1990 to 2005 time period. The trend for new-vehicle fuel economy reflects a substantial increase in the sales of light-duty trucks when compared to the generally declining sales of automobiles (Figure 3-11).

Carbon dioxide emissions from freight trucks[8] increased by 69 percent (157.7 Tg CO_2 Eq.) from 1990 to 2005, representing the largest emissions rate increase of any major transportation mode. Fuel economy for the freight truck fleet was relatively constant over this period, while truck VMT increased by 51 percent. Aircraft[9] CO_2 emissions increased by approximately 3.4 percent (6.1 Tg CO_2 Eq.) between 1990 and 2005, reflecting both an increase in emissions from

Figure 3-10

Sales-Weighted Fuel Economy of New Automobiles and Light-Duty Trucks, 1990–2005

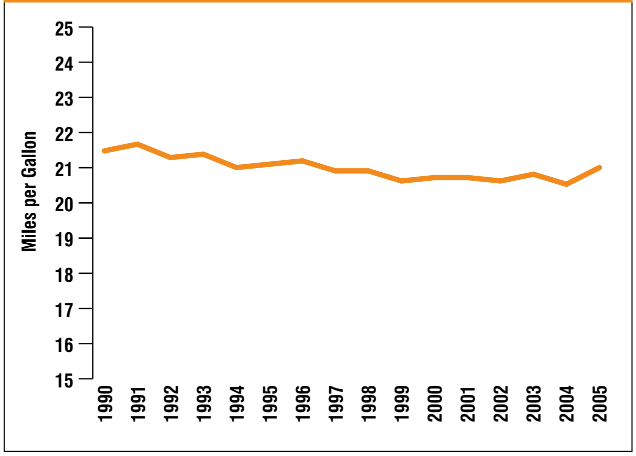
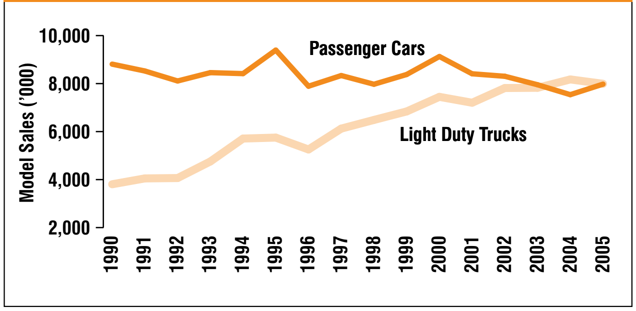


Figure 3-11

Sales of New Automobiles and Light-Duty Trucks, 1990–2005



---

[7] Note that electricity generation is the largest emitter of CO_2 when electricity is not distributed among end-use sectors.

[8] Includes "other trucks" fueled by gasoline, diesel and LPG.

[9] Includes consumption of jet fuel and aviation gasoline. Does not include aircraft bunkers, which are not accounted for in national emission totals.

Table 3-7: CO_2 Emissions from Fossil Fuel Combustion in the Transportation End-Use Sector (Tg CO_2 Eq.)[a]

Fuel/Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005
Gasoline	**961.7**	**1,029.7**	**1,121.9**	**1,127.1**	**1,155.8**	**1,159.5**	**1,180.8**	**1,182.4**
Automobiles	607.3	591.7	628.4	631.1	645.8	624.9	624.3	610.4
Light-Duty Trucks	302.1	386.4	441.6	445.3	458.8	488.5	509.8	524.9
Other Trucks[b]	37.9	35.5	35.3	34.3	34.8	29.9	30.3	30.6
Buses	0.3	0.4	0.4	0.3	0.3	0.3	0.4	0.4
Motorcycles	1.7	1.7	1.8	1.7	1.6	1.6	1.7	1.8
Boats (Recreational)	12.4	14.0	14.4	14.4	14.4	14.3	14.2	14.3
Distillate Fuel Oil (Diesel)	**272.7**	**325.1**	**401.0**	**401.6**	**415.1**	**421.8**	**447.3**	**462.3**
Automobiles	7.8	7.7	3.6	3.7	3.7	4.2	4.3	4.4
Light-Duty Trucks	11.3	14.7	17.3	17.0	17.5	21.9	23.4	25.0
Other Trucks[b]	188.3	234.9	307.5	308.5	322.7	324.8	337.5	353.4
Buses	7.9	8.6	10.2	9.3	8.8	9.6	13.8	14.0
Locomotives	35.1	39.2	41.7	41.8	41.5	42.4	44.8	45.2
Ships & Boats	10.7	10.9	14.4	16.0	15.7	12.9	16.5	13.6
Ships (Bunkers)	11.6	9.2	6.3	5.3	5.1	6.0	7.1	6.8
Jet Fuel[c]	**222.6**	**222.1**	**253.8**	**242.8**	**236.8**	**231.5**	**239.8**	**246.3**
Commercial Aircraft	136.3	142.8	164.2	152.6	145.7	143.9	147.2	156.5
Military Aircraft	34.3	23.8	20.5	22.5	20.4	19.9	21.0	17.6
General Aviation Aircraft	6.3	5.3	9.2	9.1	9.5	8.8	9.3	9.6
Aircraft (Bunkers)	45.7	50.2	59.9	58.7	61.1	58.8	62.2	62.6
Aviation Gasoline	**3.1**	**2.7**	**2.5**	**2.4**	**2.3**	**2.1**	**2.2**	**2.4**
General Aviation Aircraft	3.1	2.7	2.5	2.4	2.3	2.1	2.2	2.4
Residual Fuel Oil	**80.1**	**71.7**	**69.9**	**46.1**	**53.3**	**45.0**	**58.3**	**63.7**
Ships & Boats[d]	23.7	30.5	34.9	12.6	30.5	26.2	30.4	36.3
Ships (Bunkers)[d]	56.4	41.2	35.0	33.6	22.8	18.8	27.9	27.4
Natural Gas	**36.1**	**38.4**	**35.7**	**34.9**	**37.2**	**33.4**	**32.3**	**31.8**
Automobiles	+	0.1	+	+	+	+	+	+
Light Trucks	+	+	+	+	+	+	+	+
Buses	+	0.1	0.4	0.5	0.6	0.7	0.7	0.7
Pipeline	36.1	38.2	35.2	34.4	36.6	32.7	31.5	31.1
LPG	**1.4**	**1.1**	**0.7**	**0.8**	**0.8**	**1.0**	**1.1**	**1.1**
Light Trucks	0.5	0.5	0.3	0.3	0.3	0.4	0.4	0.4
Other Trucks[b]	0.8	0.5	0.4	0.5	0.5	0.6	0.7	0.7
Buses	+	+	+	+	+	+	+	+
Electricity	**3.0**	**3.0**	**3.4**	**3.3**	**3.4**	**4.3**	**4.4**	**5.2**
Rail	3.0	3.0	3.4	3.3	3.4	4.3	4.4	5.2
Total (Including Bunkers)[e]	**1,580.7**	**1,693.9**	**1,888.9**	**1,859.1**	**1,904.8**	**1,898.5**	**1,966.0**	**1,995.1**
Total (Excluding Bunkers)[e]	**1,467.0**	**1,593.3**	**1,787.8**	**1,761.5**	**1,815.7**	**1,814.8**	**1,868.9**	**1,897.9**

Note: Totals may not sum due to independent rounding.

[a] This table does not include emissions from non-transportation mobile sources, such as agricultural equipment and construction 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] Due to a change in methodology for estimating jet fuel consumption by aircraft type, the amount of jet fuel assigned to commercial aircraft is higher than in previous inventories; the “other aircraft” category has also been eliminated as a result of this change in methodology.

[d] Fluctuations in emission estimates from the combustion of residual fuel oil are currently unexplained, but may be related to data collection problems.

[e] 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.

\+ Less than 0.05 Tg CO_2 Eq.

commercial aircraft emissions and a decrease in domestic military aircraft emissions. While CO_2 emissions from commercial aircraft grew by approximately 14.8 percent (20.2 Tg CO_2 Eq.) from 1990 to 2005, passenger miles traveled increased by 69 percent over the same period, reflecting improvements in the fuel efficiency of planes and an increasing percentage of occupied seats per plane. For further information on all greenhouse gas emissions from transportation sources, please refer to Table A-108 in Annex 3.2.

Table 3-7 provides a detailed breakdown of CO_2 emissions by fuel category and vehicle type for the transportation end-use sector. Fifty-seven percent of the emissions from this end-use sector in 2005 were the result of the combustion of motor gasoline in automobiles and light-duty trucks. Other trucks and jet aircraft were also significant contributors, respectively accounting for 20 and 12 percent of CO_2 emissions from the transportation end-use sector.[10] For information on CO_2 emissions from off-road equipment and vehicles (i.e., non-transportation mobile sources), please refer to Table A-107 in Annex 3.2.

Industrial End-Use Sector

The industrial end-use sector accounted for 27 percent of CO_2 emissions from fossil fuel combustion. On average, 53 percent of these emissions resulted from the direct consumption of fossil fuels for steam and process heat production. The remaining 47 percent was associated with their consumption of electricity for uses such as motors, electric furnaces, ovens, and lighting.

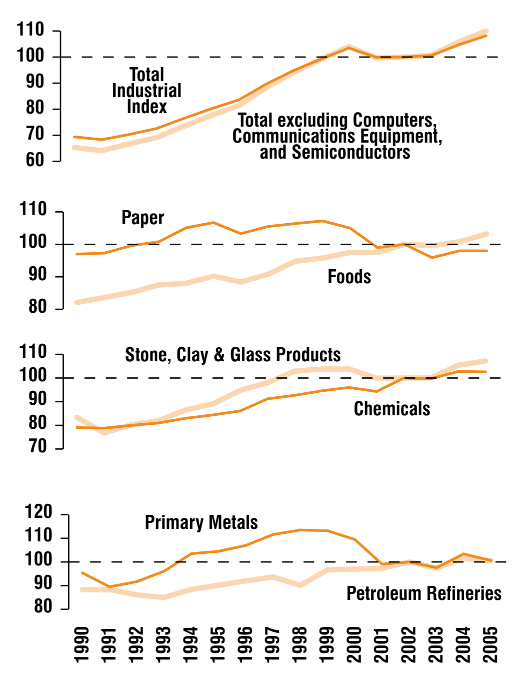
The industrial end-use sector includes activities such as manufacturing, construction, mining, and agriculture. The largest of these activities in terms of energy consumption is manufacturing, of which six industries—Petroleum Refineries, Chemicals, Primary Metals, Paper, Food, and Nonmetallic Mineral Products—represent the vast majority of the energy use (EIA 2006a and 2005b).

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 is also affected by weather conditions.[11] 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 affect on industrial emissions.

From 2004 to 2005, total industrial production and manufacturing output increased by 3.3 and 4.0 percent, respectively (FRB 2006). Over this period, output increased for Paper, Food, and Nonmetallic Mineral Products, but declined for Petroleum Refineries, Chemicals, and Primary Metals (see Figure 3-12).

Figure 3-12

Industrial Production Indices (Index 2002=100)



Despite the growth in industrial output (56 percent) and the overall U.S. economy (55 percent) from 1990 to 2005, CO_2 emissions from the industrial end-use sector increased by only 2.3 percent. A number of factors are believed to have caused this disparity between rapid 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) improvements in energy efficiency. In 2005, CO_2 emissions from fossil fuel combustion and electricity use within the industrial end-use sectors were 1,575.2 Tg CO_2 Eq., or 2.5 percent below 2004 emissions.

Residential and Commercial End-Use Sectors

The residential and commercial end-use sectors accounted for an average 21 and 18 percent, respectively, of CO_2 emissions from fossil fuel combustion. Both end-use sectors were heavily reliant on electricity for meeting energy needs, with electricity consumption for lighting, heating, air conditioning, and operating appliances contributing to about 70 and 78 percent of emissions from the residential and commercial end-use sectors, respectively. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and

---

[10] These percentages include emissions from bunker fuels.

[11] 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.

cooking needs. Coal consumption was a minor component of energy use in both of these end-use sectors. In 2005, CO_2 emissions from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 1,208.7 Tg CO_2 Eq. and 1,016.8 Tg CO_2 Eq., respectively.

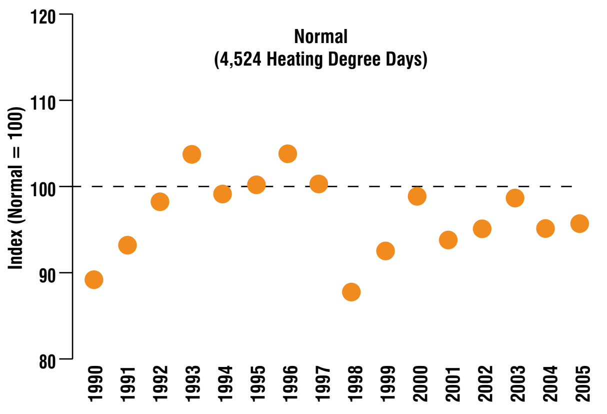
Emissions from the residential and commercial sectors have generally been increasing since 1990, and are often correlated with short-term fluctuations in energy consumption caused by weather conditions, rather than prevailing economic conditions (see Table 3-6). In the long-term, both end-use sectors 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 over 73 percent of the direct (not including electricity) fossil fuel emissions from the residential and commercial sectors. In 2005, natural gas emissions decreased by 1 and 2 percent, respectively, in each of these sectors, due to warmer conditions in the United States (see Figure 3-13).

Electricity sales to the residential and commercial end-use sectors in 2005 increased by 5 and 3 percent, respectively, from 2004. This trend can largely be attributed to the growing economy (3.2 percent), which led to increased demand for electricity. Increased air conditioning-related electricity consumption in these sectors was also attributable to the warmer summer (see Figure 3-14). Electricity-related emissions in both the residential and commercial sectors rose due to increased consumption; total emissions from the residential sector increased by 2.8 percent in 2005, with emissions from the commercial sector 1.8 percent higher than in 2004.

Figure 3-13

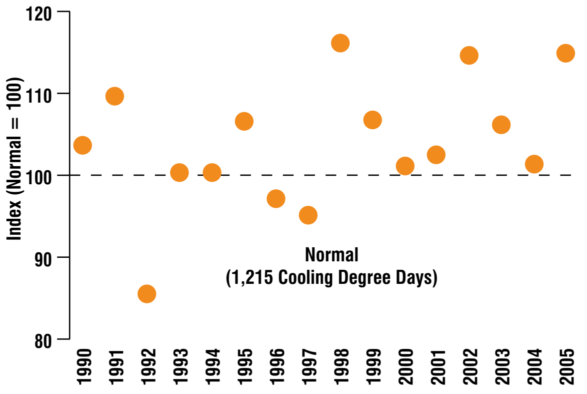
Heating Degree Days[12]



Note: Excludes Alaska and Hawaii

Figure 3-14

Cooling Degree Days[13]



Note: Excludes Alaska and Hawaii

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. Electricity generation also accounted for the largest share of CO_2 emissions from fossil fuel combustion, approximately 41 percent in 2005. 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 3-15).

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) categorizes 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

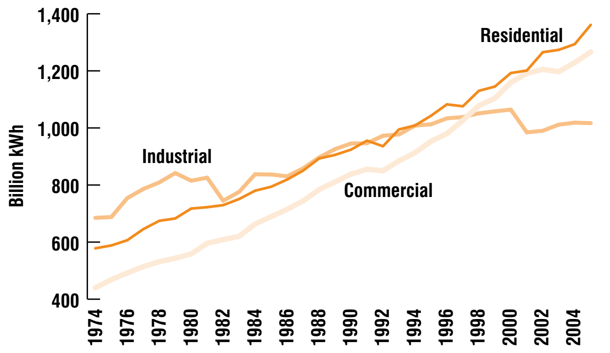
---

[12] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65 °F. Excludes Alaska and Hawaii. Normals are based on data from 1971 through 2000.

[13] Degree days are relative measurements of outdoor air temperature. Cooling degree days are deviations of the mean daily temperature above 65 °F. Excludes Alaska and Hawaii. Normals are based on data from 1971 through 2000.

Figure 3-15

Electricity Generation Retail Sales by End-Use Sector



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

of electricity,[14] while the other sectors consist of those producers that indicate their primary business is other than the production of electricity.

In 2005, the amount of electricity generated (in kWh) increased by 2.4 percent, largely due to the growing economy, expanding industrial production, and warmer summer conditions. However, CO_2 emissions increased by 2.8 percent, as a larger share of electricity was generated by coal. Coal and natural gas consumption for electricity generation increased by 2.1 percent and 7.5 percent, respectively, in 2005, and nuclear power decreased by 1.1 percent. As a result of the increase in coal consumption, C intensity from direct fossil fuel combustion increased slightly overall in 2005 (see Table 3-9). Coal is consumed primarily by the electric power

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 emitted as a product from their combustion. Useful energy, however, is generated in the United States from many other sources that do not emit CO_2 in the energy conversion process, such as renewable (i.e., hydropower, biofuels, geothermal, solar, and wind) and nuclear sources.[15]

Energy-related CO_2 emissions can be reduced by not only lowering total energy consumption (e.g., through conservation measures) 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.[16] 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. Other sources of energy, however, may be directly or indirectly C neutral (i.e., 0 Tg CO_2 Eq./Btu). Energy generated from nuclear and many renewable sources do not result in direct emissions of CO_2. Biofuels such as wood and ethanol are also considered to be C neutral; although these fuels do emit CO_2, in the long run the CO_2 emitted from biomass consumption does not increase atmospheric CO_2 concentrations if the biogenic C emitted is offset by the growth of new biomass.[17] The overall C intensity of the U.S. economy is thus dependent upon the quantity and combination of fuels and other energy sources employed to meet demand.

Table 3-8 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 or wood for heat. 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.

---

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

[15] Small quantities of CO_2, however, are released from some geologic formations tapped for geothermal energy. These emissions are included with fossil fuel combustion emissions from the electricity generation. Carbon dioxide emissions may also be generated from upstream activities (e.g., manufacture of the equipment) associated with fossil fuel and renewable energy activities, but are not accounted for here.

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

[17] Net carbon fluxes from changes in biogenic carbon reservoirs in wooded or croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.

Box 3-2: Carbon Intensity of U.S. Energy Consumption (continued)

Table 3-8: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (Tg CO_2 Eq./QBtu)

Sector	1990	1995	2000	2001	2002	2003	2004	2005
Residential[a]	57.3	56.6	56.7	56.9	56.6	56.8	56.9	56.7
Commercial[a]	59.6	57.8	57.3	57.6	57.1	57.4	57.6	57.5
Industrial[a]	63.8	62.7	62.6	63.5	63.0	63.4	63.5	64.0
Transportation[a]	71.0	71.0	71.0	71.0	71.0	71.0	71.1	71.1
Electricity Generation[b]	86.7	86.0	85.6	85.1	85.0	85.7	85.4	85.0
U.S. Territories[c]	74.1	74.1	73.2	73.6	73.7	74.1	74.0	74.1
All Sectors[c]	**72.7**	**72.2**	**72.6**	**72.7**	**72.5**	**72.8**	**72.9**	**73.1**

[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.

In contrast to Table 3-8, Table 3-9 presents C intensity values that incorporate energy consumed from all sources (i.e., fossil fuels, renewables, and nuclear). In addition, the emissions related to the generation of electricity have been attributed to both electricity generation and the end-use sectors in which that electricity was eventually consumed.[18] This table, therefore, provides a more complete picture of the actual C intensity of each end-use sector per unit of energy consumed. The transportation end-use sector in Table 3-9 emerges as the most C intensive when all sources of energy are included, due to its almost complete reliance on petroleum products and relatively minor amount of biomass-based fuels used, such as ethanol. The "other end-use sectors" (i.e., residential, commercial, and industrial) use significant quantities of biofuels such as wood, thereby lowering the overall C intensity. The C intensity of the electricity generation sector differs greatly from the scenario in Table 3-8, where only the energy consumed from the direct combustion of fossil fuels was included. This difference is due almost entirely to the inclusion of electricity generation from nuclear and hydropower sources, which do not emit CO_2.

Table 3-9: Carbon Intensity from all Energy Consumption by Sector (Tg CO_2 Eq./QBtu)

Sector	1990	1995	2000	2001	2002	2003	2004	2005
Transportation[a]	70.8	70.6	70.6	70.5	70.5	70.4	70.3	70.2
Other End-Use Sectors[a, b]	57.6	56.5	57.9	58.4	57.6	58.1	58.0	58.5
Electricity Generation[c]	59.0	57.9	59.9	60.0	58.9	59.6	59.4	59.8
All Sectors[d]	**61.1**	**60.3**	**61.4**	**61.8**	**61.3**	**61.6**	**61.5**	**61.9**

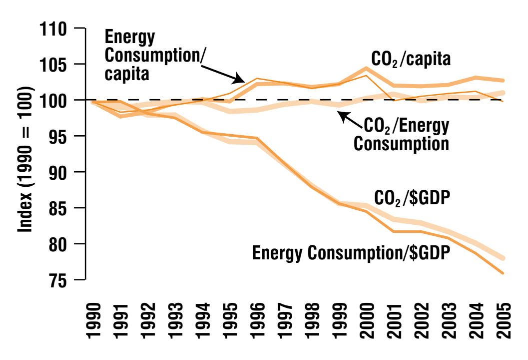
[a] Includes electricity (from fossil fuel, nuclear, and renewable sources) and direct renewable energy consumption.
[b] Other End-Use Sectors includes the residential, commercial, and industrial sectors.
[c] Includes electricity generation from nuclear and renewable sources.
[d] Includes nuclear and renewable energy consumption.
Note: Excludes non-energy fuel use emissions and consumption.

By comparing the values in Table 3-8 and Table 3-9, a few observations can be made. The use of renewable and nuclear energy sources has resulted in a significantly lower C intensity of the U.S. economy. Over the fifteen-year period of 1990 through 2005, however, the C intensity of U.S. energy consumption has been fairly constant, as the proportion of renewable and nuclear energy technologies have not changed significantly. Per capita energy consumption has fluctuated, but is now roughly equivalent to levels in 1990 (see Figure 3-16). 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 2006).

C intensity estimates were developed using nuclear and renewable energy data from EIA (2006a) and fossil fuel consumption data as discussed above and presented in Annex 2.1.

Figure 3-16

U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP



---

[18] In other words, the emissions from the generation of electricity are intentionally double counted by attributing them both to electricity generation and the end-use sector in which electricity consumption occurred.

sector in the United States, which accounted for 94 percent of total coal consumption for energy purposes in 2005. The amount of electricity generated from renewables decreased by 1.7 percent in 2005.

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 (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 unpublished supplemental tables on petroleum product detail (EIA 2006b). The United States does not include territories in its national energy statistics, so fuel consumption data for territories were collected separately from Grillot (2006).[19]

   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, and used in this inventory, are, instead, "bottom up" in nature. In other words, they are collected through surveys at the point of delivery or use and aggregated to determine national totals.[20]

   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 standard, which are to report energy statistics in terms of net calorific values (NCV) (i.e., lower heating values).[21]

2. *Subtract uses accounted for in the Industrial Processes chapter.* Portions of the fuel consumption data for six fuel categories—coking coal, 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 Gambogi (2006), EFMA (1995), U.S. Census Bureau (1991 through 1994), U.S. Census Bureau (2006), USITC (2006), U.S. Census Bureau (2005), EIA (2005a), EIA (2001b), USAA (2006), USGS (1998 through 2002), USGS (1995), Corathers (2006), USGS (1991a through 2005a), USGS (1991b through 2005b), U.S. International Trade Commission (2006), U.S. International Trade Commission (2004), Onder and Bagdoyan (1993), and Johnson (2006).[22]

3. *Adjust for biofuels, conversion of fossil fuels, and exports of* CO_2. Fossil fuel consumption estimates are adjusted downward to exclude (1) fuels with biogenic origins, (2) fuels created from other fossil fuels, and (3) exports of CO_2. Fuels with biogenic origins are assumed to result in no net CO_2 emissions, and must be subtracted from fuel consumption estimates. These fuels include ethanol added to motor gasoline and biomass gas used as natural gas. Synthetic natural gas is created from

---

[19] 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 53 Tg CO_2 Eq. in 2005.

[20] 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.

[21] 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.

[22] See sections on Iron and Steel Production, Ammonia Manufacture, Petrochemical Production, Titanium Dioxide Production, Ferroalloy Production, Aluminum Production, and Silicon Carbide Production in the Industrial Processes chapter.

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.[23] 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 and biogas were collected from EIA (2006b) and data for synthetic natural gas were collected from EIA (2006e), and data for CO_2 exports were collected from the Dakota Gasification Company (2006), Fitzpatrick (2002), Erickson (2003), EIA (2001a), EIA (2004), EIA (2006e), and Kass (2005).

4. *Adjust Sectoral Allocation of Distillate Fuel Oil.* EPA had conducted a separate bottom-up analysis of transportation fuel consumption based on FHWA Vehicle Miles Traveled (VMT) that indicated that the amount of distillate consumption allocated to the transportation sector in the EIA statistics should be adjusted. Therefore, for these estimates, the transportation sector's distillate fuel consumption was adjusted higher to match the value obtained from the bottom-up analysis based on VMT. As the total distillate consumption estimate from EIA is 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 (2005), Benson (2002 through 2004), DOE (1993 through 2004), EIA (2006a), EIA (1991 through 2005), EPA (2004), and FHWA (1996 through 2006).

5. *Adjust for fuels consumed for non-energy uses.* U.S. aggregate energy statistics include consumption of fossil fuels for non-energy purposes. 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, 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 (2006b).

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).[24] 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 2006) supplied data on military jet fuel use. Commercial jet fuel use was obtained from BEA (1991 through 2006) and DOT (1991 through 2006); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2006). Consumption of these fuels was subtracted from the corresponding fuels in the transportation end-use sector. Estimates of international bunker fuel emissions are discussed further in the section entitled International Bunker Fuels.

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 2005* (EIA 2006c) and EIA's *Monthly Energy Review* and unpublished supplemental tables on petroleum product detail (EIA 2006b). They are presented in Annexes 2.1 and 2.2.

---

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

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

8. *Estimate CO_2 Emissions.* Total CO_2 emissions are the product of the adjusted energy consumption (from the previous methodology steps 1 through 6), the C content of the fuels consumed, and the fraction of C that is oxidized. The fraction oxidized was assumed to be 100 percent for petroleum, coal, and natural gas based on guidance in IPCC (2006) (see Annex 2.1).

9. *Allocate transportation emissions by vehicle type.* This report provides a more detailed accounting of emissions from transportation because it is such a large consumer of fossil fuels in the United States. For 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 highway vehicles, annual estimates of combined motor gasoline and diesel fuel consumption by vehicle category were obtained from FHWA (1996 through 2006); for each vehicle category, the percent gasoline, diesel, and other (e.g., CNG, LPG) fuel consumption are estimated using data from DOE (1993 through 2004).

   For non-highway vehicles, activity data were obtained from AAR (2005), BEA (1991 through 2006), Benson (2002 through 2004), DOE (1993 through 2004), DESC (2006), DOC (1991 through 2006), DOT (1991 through 2006), EIA (2006a), EIA (2006d), EIA (2006g), EIA (2002), EIA (1991 through 2005), EPA (2004), and FAA (2005).

   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) System for assessing Aviation's Global Emission (SAGE) model.[25] 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 (2006a) and USAF (1998).[26]

Uncertainty

For estimates of CO_2 from fossil fuel combustion, the amount of CO_2 emitted is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel. Therefore, a careful accounting of fossil fuel consumption by fuel type, average carbon contents of fossil fuels consumed, and production of fossil fuel-based products with long-term carbon storage should yield an accurate estimate of CO_2 emissions.

Nevertheless, there are uncertainties in the consumption data, carbon content of fuels and products, and carbon oxidation efficiencies. For example, given the same primary fuel type (e.g., coal, petroleum, or natural gas), the amount of carbon contained in the fuel per unit of useful energy can vary. For the United States, however, the impact of these uncertainties on overall CO_2 emission estimates is believed to be relatively small. See, for example, Marland and Pippin (1990).

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 2005.

---

[25] FAA's System for assessing Aviation's Global Emissions (SAGE) model develops aircraft fuel burn and emissions for all commercial flights globally in a given year. The SAGE model dynamically models aircraft performance, fuel burn, and emissions, and is based on actual flight-by-flight aircraft movements. See <http://www.faa.gov/about/office_org/headquarters_offices/aep/models/sage/>.

[26] 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.

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. In particular, residual fuel consumption data for marine vessels are highly uncertain, as shown by the large fluctuations in emissions that do not mimic changes in other variables such as shipping ton miles.

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

Table 3-10: 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	2005 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]	**2,093.6**	**2,024.6**	**2,290.6**	**-3%**	**+9%**
Residential	1.0	0.9	1.1	-5%	+15%
Commercial	8.0	7.6	9.2	-5%	+15%
Industrial	122.2	117.5	142.3	-4%	+16%
Transportation	NE	NE	NE	NA	NA
Electricity Generation	1,958.4	1,882.7	2,146.7	-4%	+10%
U.S. Territories	4.0	3.5	4.7	-12%	+19%
Natural Gas[b]	**1,170.0**	**1,179.5**	**1,245.4**	**1%**	**+6%**
Residential	262.8	255.4	281.2	-3%	+7%
Commercial	167.0	162.3	178.6	-3%	+7%
Industrial	387.0	395.9	435.7	2%	+13%
Transportation	31.8	30.9	34.1	-3%	+7%
Electricity Generation	320.1	311.0	336.5	-3%	+5%
U.S. Territories	1.3	1.1	1.5	-12%	+17%
Petroleum[b]	**2,487.2**	**2,355.4**	**2,628.1**	**-5%**	**+6%**
Residential	95.0	90.1	99.5	-5%	+5%
Commercial	50.9	48.6	52.9	-5%	+4%
Industrial	330.9	283.9	387.0	-14%	+17%
Transportation	1,861.0	1,739.2	1,979.1	-7%	+6%
Electric Utilities	102.3	98.6	108.1	-4%	+6%
U.S. Territories	47.2	43.7	52.3	-7%	+11%
Total (excluding Geothermal)[b]	**5,750.8**	**5,656.3**	**6,060.1**	**-2%**	**+5%**
Geothermal	**0.4**	**NE**	**NE**	**NE**	**NE**
Total (including Geothermal)[b,c]	**5,751.2**	**5,656.3**	**6,060.1**	**-2%**	**+5%**

NA (Not Applicable)
NE (Not Estimated)

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

[b] The low and high estimates for total emissions were calculated separately through simulations and, hence, the low and high emission estimates for the sub-source categories do not sum to total emissions.

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

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 inventory 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 150 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.[27] 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.[28]

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

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-10. Fossil fuel combustion CO_2 emissions in 2005 were estimated to be between 5,656.3 and 6,060.1 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 2 percent below to 5 percent above the 2005 emission estimate of 5,751.2 Tg CO_2 Eq.

QA/QC and Verification

A source-specific QA/QC plan for CO_2 from fossil fuel combustion was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology used for estimating CO_2 emissions from fossil fuel combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated to determine whether any corrective actions were needed. Minor corrective actions were taken.

Recalculations Discussion

The most significant change impacting fuel combustion estimates in the current Inventory was updating the C oxidation factor for all fuel types to 100 percent. This change was made according to IPCC (2006) and impacted emission estimates for all fuel types for all years.

An additional adjustment for silicon carbide used for petroleum coke manufacturing was added to the current Inventory as a source that is accounted for in the Industrial Processes chapter. This was reallocated to the Industrial Processes chapter, as the silicon carbide was consumed during non-energy related industrial activity.

The Energy Information Administration (EIA 2006b) updated energy consumption data for all years. These revisions primarily impacted the emission estimates for 2004. EIA (2006b) no longer reports a small amount of consumption of other liquids in the electricity generation sector, which represented a change from the previous Inventory.

Overall, changes resulted in an average annual increase of 36.9 Tg CO_2 Eq. (0.7 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2004.

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.

---

[27] 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.

[28] 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.

[29] Although, in general, random uncertainties are the main focus of statistical uncertainty analysis, when the uncertainty estimates are elicited from experts, their estimates include both random and systematic uncertainties. Hence, both these types of uncertainties are represented in this uncertainty analysis.

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 coke (manufactured from coking coal). The non-energy applications are equally diverse, and include 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 61 percent of the total C consumed for non-energy purposes was stored in products, and not released to the atmosphere; the remaining 39 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 Municipal Solid Waste Combustion 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 these affect the mass of C in non-energy applications.

As shown in Table 3-11, fossil fuel emissions in 2005 from the non-energy uses of fossil fuels were 142.3 Tg CO_2 Eq., which constituted approximately 3 percent of overall fossil fuel emissions, approximately the same proportion as in 1990. In 2005, the consumption of fuels for non-energy uses (after the adjustments described above) was 5,492 TBtu, an increase of 22 percent since 1990 (see Table 3-12). About 66.3 Tg of the C (243.1 Tg CO_2 Eq.) in these fuels was stored, while the remaining 38.8 Tg C (142.4 Tg CO_2 Eq.) was emitted. The proportion of C emitted as CO_2 has remained about constant since 1990, at about 36 to 40 percent of total non-energy consumption (see Table 3-11).

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 (2006) (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 3-12 and Table 3-13 have been adjusted to subtract non-energy uses that are included in the source categories of the Industrial Processes chapter.[30] Consumption values were also adjusted to subtract exports of intermediary chemicals.

For the remaining non-energy uses, the quantity of C stored was estimated by multiplying the potential emissions

Table 3-11: CO_2 Emissions from Fossil Fuel Consumption for Non-Energy Use (Tg CO_2 Eq.)

Storage/Emissions	1990	1995	2000	2001	2002	2003	2004	2005
Potential Emissions	312.8	346.7	385.5	364.9	368.4	356.4	396.6	385.5
C Stored	195.6	213.6	244.5	233.5	233.1	225.1	246.4	243.1
Emissions as a % of Potential	37%	38%	37%	36%	37%	37%	38%	37%
Emissions	**117.2**	**133.1**	**141.0**	**131.3**	**135.3**	**131.3**	**150.2**	**142.3**

---

[30] 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.

by a storage factor. For several fuel types—petrochemical feedstocks (including natural gas for non-fertilizer uses, LPG, pentanes plus, naphthas, other oils, still gas, special naphtha, and industrial other coal), asphalt and road oil, lubricants, and waxes—U.S. data on C stocks and flows were used to develop C storage factors, calculated 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 Municipal Solid Waste Combustion 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.

Lastly, emissions were estimated by subtracting the C stored from the potential emissions (see Table 3-11). 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 volatile organic compound, solvent, and non-combustion CO emissions, Toxics Release Inventory (TRI) releases, hazardous waste incineration, and energy recovery. 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 1995, 2001), *National Air Quality*

Table 3-12: Adjusted Consumption of Fossil Fuels for Non-Energy Uses (TBtu)

Sector/Use	1990	1995	2000	2001	2002	2003	2004	2005
Industry	**4,223.7**	**4,771.7**	**5,261.2**	**5,045.2**	**5,032.3**	**4,864.3**	**5,295.4**	**5,208.2**
Industrial Coking Coal	0.0	43.8	62.8	25.5	46.4	72.0	214.7	136.6
Industrial Other Coal	8.2	11.3	12.4	11.3	12.0	11.9	11.9	11.9
Natural Gas to Chemical Plants, Other Uses	278.4	330.3	421.3	408.6	364.6	348.8	340.2	365.8
Asphalt & Road Oil	1,170.2	1,178.2	1,275.7	1,256.9	1,240.0	1,219.5	1,303.9	1,323.2
LPG	1,119.1	1,484.7	1,604.6	1,539.0	1,565.4	1,437.7	1,435.9	1,441.6
Lubricants	186.3	177.8	189.9	174.0	171.9	159.0	161.0	160.2
Pentanes Plus	77.3	285.3	228.7	199.8	166.1	158.3	156.4	146.0
Naphtha (<401 °F)	325.7	350.6	592.8	489.4	564.2	573.4	687.5	678.5
Other Oil (>401 °F)	677.2	612.7	554.3	525.9	456.2	501.0	547.5	515.1
Still Gas	21.3	40.1	12.6	35.8	57.8	59.0	63.5	67.7
Petroleum Coke	81.0	44.1	47.8	128.1	110.2	79.3	169.8	145.0
Special Naphtha	100.9	66.9	94.4	77.9	99.5	75.7	47.2	60.9
Distillate Fuel Oil	7.0	8.0	11.7	11.7	11.7	11.7	11.7	11.7
Waxes	33.3	40.6	33.1	36.3	32.2	31.0	30.8	31.4
Miscellaneous Products	137.8	97.1	119.2	124.9	134.2	126.0	113.4	112.8
Transportation	**176.0**	**167.9**	**179.4**	**164.3**	**162.4**	**150.1**	**152.1**	**151.3**
Lubricants	176.0	167.9	179.4	164.3	162.4	150.1	152.1	151.3
U.S. Territories	**86.7**	**90.8**	**165.5**	**80.3**	**138.6**	**127.9**	**136.6**	**132.2**
Lubricants	0.7	2.0	16.4	0.0	1.5	9.3	10.0	9.6
Other Petroleum (Misc. Prod.)	86.0	88.8	149.1	80.3	137.2	118.6	126.6	122.6
Total	**4,486.4**	**5,030.5**	**5,606.1**	**5,289.8**	**5,333.3**	**5,142.4**	**5,584.1**	**5,491.7**

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 3-13: 2005 Adjusted Non-Energy Use Fossil Fuel Consumption, Storage, and Emissions

Sector/Fuel Type	Adjusted Non-Energy Use[a] (TBtu)	Carbon Content (Tg C)	Storage Factor	Carbon Stored (Tg C)	Carbon Emissions (Tg C)	Carbon Emissions (Tg CO_2 Eq.)
Industry	**5,208.2**	**99.4**	-	**65.8**	**33.7**	**123.4**
Industrial Coking Coal	136.6	4.2	0.10	0.4	3.8	14.0
Industrial Other Coal	11.9	0.3	0.61	0.2	0.1	0.4
Natural Gas to Chemical Plants	365.8	5.3	0.61	3.2	2.0	7.5
Asphalt & Road Oil	1,323.2	27.3	1.00	27.3	0.0	0.0
LPG	1,441.6	24.2	0.61	14.9	9.4	34.3
Lubricants	160.2	3.2	0.09	0.3	2.9	10.8
Pentanes Plus	146.0	2.7	0.61	1.6	1.0	3.8
Naphtha (<401 °F)	678.5	12.3	0.61	7.6	4.8	17.4
Other Oil (>401 °F)	515.1	10.3	0.61	6.3	4.0	14.6
Still Gas	67.7	1.2	0.61	0.7	0.5	1.7
Petroleum Coke	145.0	4.0	0.50	2.0	2.0	7.4
Special Naphtha	60.9	1.2	0.61	0.7	0.5	1.7
Distillate Fuel Oil	11.7	0.2	0.50	0.1	0.1	0.4
Waxes	31.4	0.6	0.58	0.4	0.3	1.0
Miscellaneous Products	112.8	2.3	0.00	0.0	2.3	8.4
Transportation	**151.3**	**3.1**	-	**0.3**	**2.8**	**10.2**
Lubricants	151.3	3.1	0.09	0.3	2.8	10.2
U.S. Territories	**132.2**	**2.6**	-	**0.3**	**2.4**	**8.7**
Lubricants	9.6	0.2	0.09	0.0	0.2	0.6
Other Petroleum (Misc. Prod.)	122.6	2.5	0.10	0.2	2.2	8.1
Total	**5,491.7**	**105.1**		**66.3**	**38.8**	**142.3**

- Not applicable.

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

Note: Totals may not sum due to independent rounding.

and Emissions Trends Report (EPA 2006a), *Toxics Release Inventory, 1998* (2000a), *Biennial Reporting System* (EPA 2004a, 2006b), and pesticide sales and use estimates (EPA 1998, 1999, 2002, 2004b); the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 1994, 1997, 2001, 2005); the National Petrochemical & Refiners Association (NPRA 2001); the National Asphalt Pavement Association (Connolly 2000); the Emissions Inventory Improvement Program (EIIP 1998, 1999); the U.S. Census Bureau (1999, 2003, 2004); the American Plastics Council (APC 2000, 2001, 2003, 2005, 2006; Eldredge-Roebuck 2000); the Society of the Plastics Industry (SPI 2000); Bank of Canada (2006); Financial Planning Association (2006); INEGI (2006); Statistics Canada (2006); the United States International Trade Commission (2006); the Pesticide Action Network (PAN 2002); Gosselin, Smith, and Hodge (1984); the Rubber Manufacturers' Association (RMA 2002, 2006; STMC 2003); the International Institute of Synthetic Rubber Products (IISRP 2000, 2003); the Fiber Economics Bureau (FEB 2001, 2003, 2005, 2006); the *Material Safety Data Sheets* (Miller 1999); the Chemical Manufacturer's Association (CMA 1999); and the American Chemistry Council (ACC 2005, 2006.) Specific data sources are listed in full detail in Annex 2.3.

Uncertainty

An uncertainty analysis was conducted to quantify the uncertainty surrounding the estimates of emissions and storage factors from non-energy uses. This analysis, performed using @RISK software and the IPCC-recommended Tier 2 methodology (Monte Carlo 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), 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 3-14 (emissions) and Table 3-15 (storage factors). Carbon emitted from non-energy uses of fossil fuels in 2005 was estimated to be between 113.1 and 153.7 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 21 percent below to 8 percent above the 2005 emission estimate of 142.3 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.

In Table 3-15, 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

Table 3-14: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Non-Energy Uses of Fossil Fuels (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	81.9	65.4	98.1	-20%	+20%
Asphalt	CO_2	0.0	0.2	0.7	NA	NA
Lubricants	CO_2	21.6	17.9	25.0	-17%	+16%
Waxes	CO_2	1.0	0.7	1.5	-25%	+55%
Other	CO_2	37.9	17.4	40.1	-54%	+6%
Total	**CO_2**	**142.3**	**113.1**	**153.7**	**-21%**	**+8%**

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

Table 3-15: Tier 2 Quantitative Uncertainty Estimates for Storage Factors of Non-Energy Uses of Fossil Fuels (Percent)

Source	Gas	2005 Storage Factor (%)	Uncertainty Range Relative to Inventory Factor[a] (%)		(%, Relative)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	61%	59%	63%	-4%	+3%
Asphalt	CO_2	100%	99%	100%	-1%	+0%
Lubricants	CO_2	9%	4%	18%	-57%	+90%
Waxes	CO_2	58%	44%	69%	-25%	+20%
Other	CO_2	22%	20%	64%	-10%	+189%

[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).

quantified. More details on the uncertainty analysis are provided in Annex 2.3.

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. 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.

Recalculations Discussion

The methodology of the current Inventory reflects three corrections and two minor changes. Plastics data from the American Plastics Council includes some Mexican and Canadian production in addition to U.S. production. In the previous Inventory, the plastics geography correction was not correctly accounting for Mexican and Canadian production from 2002 through 2004. This correction caused an increase in the quantity of C emitted by 0.64 Tg C, 0.98 Tg C, and 1.02 Tg C compared to the previously reported estimates for 2002 though 2004.

As noted earlier, 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. For the current Inventory, for the first time, silicon carbide production is reported as a specific industrial process. To avoid double-counting of C emissions in the NEU section and the Industrial Processes chapter, the quantity of petroleum coke used as an input to silicon carbide was deducted from the potential emissions covered in this chapter.

In addition, in the previous Inventory, the cleanser consumption data was not properly accounting for data over the whole time series. The update in the current Inventory resulted in an increase in exports throughout the time series and decreased C emissions across the time series. Also, in the uncertainty analysis, Industrial Other Coal was previously being counted as an Other rather than a Feedstock. The calculations presented are now correctly accounting for Industrial Other Coal.

Additionally, the oxidation factor for MECS data was increased from 99 percent to 100 percent to be consistent throughout the Energy and Industrial Processes chapters. This change caused an increase in the quantity of C emitted by 0.10 to 0.20 Tg C compared to the previous Inventory.

Planned Improvements

There are several improvements planned for the future:

- Updating the analysis to comply with IPCC (2006). These changes will affect both the non-energy use and industrial processes sections.
- 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).

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 the remaining fuels (petroleum coke, 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.

3.3. Stationary Combustion (excluding CO_2) (IPCC Source Category 1A)

Stationary combustion encompasses all fuel combustion activities from fixed sources (versus mobile combustion). Other than CO_2, which was addressed in the previous section, gases from stationary combustion include the greenhouse gases CH_4 and N_2O and the indirect greenhouse gases NO_x, CO, and NMVOCs.[31] Emissions of these gases from stationary combustion sources depend upon fuel characteristics, size and vintage, along with combustion technology, pollution control equipment, and ambient environmental conditions. Emissions also vary with operation and maintenance practices.

N_2O and NO_x 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. Carbon monoxide emissions from stationary combustion are generally a function of the efficiency of combustion; they are highest when less oxygen is present in the air-fuel mixture than is necessary for complete combustion. These conditions are most likely to occur during start-up, shutdown and during fuel switching (e.g., the switching of coal grades at a coal-burning electric utility plant). CH_4 and NMVOC emissions from stationary combustion are primarily a function of the CH_4 and NMVOC content of the fuel and combustion efficiency.

Emissions of CH_4 decreased 13 percent overall since 1990 to 6.9 Tg CO_2 Eq. (330 Gg) in 2005. This decrease in CH_4 emissions was primarily due to lower wood consumption in the residential sector. Conversely, N_2O emissions rose 12 percent since 1990 to 13.8 Tg CO_2 Eq. (45 Gg) in 2005. The largest source of N_2O emissions was coal combustion by electricity generators, which alone accounted for 65 percent of total N_2O emissions from stationary combustion in 2005. Overall, however, stationary combustion is a small source of CH_4 and N_2O in the United States.

Table 3-16 and Table 3-17 provide CH_4 and N_2O emission estimates in Tg CO_2 Eq.; Table 3-18 and Table 3-19 present these estimates in Gg of each gas.

Methodology

CH_4 and N_2O emissions were estimated by multiplying fossil fuel and wood consumption data by emission factors (by sector and fuel type). National coal, natural gas, fuel oil, and wood consumption data were grouped by sector: industrial, commercial, residential, electric power, and U.S. territories. For the CH_4 and N_2O estimates, 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

Table 3-16: CH_4 Emissions from Stationary Combustion (Tg CO_2 Eq.)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005
Electric Power	**0.6**	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Coal	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Fuel Oil	0.1	+	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	0.1
Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Industrial	**2.1**	**2.3**	**2.3**	**2.1**	**2.0**	**2.0**	**2.1**	**1.9**
Coal	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Fuel Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	0.8	0.9	0.9	0.8	0.8	0.8	0.8	0.7
Wood	0.9	1.0	1.0	0.9	0.8	0.8	0.9	0.7
Commercial	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.1
Natural Gas	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Wood	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Residential	**4.4**	**4.0**	**3.5**	**3.1**	**3.1**	**3.3**	**3.4**	**3.4**
Coal	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Fuel Oil	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Natural Gas	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Wood	3.5	3.1	2.6	2.2	2.3	2.4	2.5	2.5
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
Natural Gas	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+
Total	**8.0**	**7.8**	**7.4**	**6.8**	**6.8**	**7.0**	**7.1**	**6.9**

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

---

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

Table 3-17: N_2O Emissions from Stationary Combustion (Tg CO_2 Eq.)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005
Electric Power	**7.6**	**8.0**	**9.3**	**9.1**	**9.1**	**9.4**	**9.4**	**9.6**
Coal	7.1	7.6	8.8	8.5	8.6	8.8	8.8	9.0
Fuel Oil	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Natural Gas	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Wood	0.2	0.1	0.2	0.1	0.2	0.2	0.2	0.2
Industrial	**3.2**	**3.3**	**3.3**	**3.1**	**3.0**	**2.9**	**3.1**	**2.8**
Coal	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6
Fuel Oil	0.6	0.5	0.5	0.5	0.5	0.5	0.6	0.6
Natural Gas	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Wood	1.7	1.9	1.9	1.7	1.6	1.6	1.7	1.5
Commercial	**0.4**	**0.4**	**0.4**	**0.3**	**0.3**	**0.4**	**0.4**	**0.3**
Coal	0.1	0.1	+	+	+	+	+	+
Fuel Oil	0.2	0.1	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	0.1
Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Residential	**1.1**	**1.0**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Natural Gas	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1
Wood	0.7	0.6	0.5	0.4	0.4	0.5	0.5	0.5
U.S. Territories	**0.1**	**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	0.1
Natural Gas	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+
Total	**12.3**	**12.8**	**14.0**	**13.5**	**13.4**	**13.7**	**13.9**	**13.8**

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

Table 3-18: CH_4 Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005
Electric Power	**27**	**27**	**33**	**32**	**32**	**34**	**34**	**35**
Coal	16	18	20	20	20	20	20	21
Fuel Oil	4	2	3	4	3	4	4	4
Natural Gas	3	4	5	5	5	5	5	6
Wood	4	4	4	4	4	5	5	5
Industrial	**101**	**110**	**108**	**99**	**97**	**96**	**99**	**89**
Coal	16	15	14	14	13	13	14	13
Fuel Oil	6	5	5	6	5	6	6	6
Natural Gas	37	42	42	38	39	38	38	35
Wood	41	47	47	41	40	39	42	35
Commercial	**42**	**43**	**44**	**42**	**42**	**44**	**44**	**43**
Coal	1	1	1	1	1	1	1	1
Fuel Oil	9	7	7	7	6	7	8	7
Natural Gas	13	15	16	15	15	16	15	15
Wood	19	21	20	19	20	20	20	20
Residential	**210**	**190**	**165**	**147**	**150**	**158**	**160**	**160**
Coal	9	5	3	4	4	4	4	3
Fuel Oil	14	13	15	15	14	15	15	14
Natural Gas	21	24	24	23	24	25	24	24
Wood	165	148	122	105	108	114	117	120
U.S. Territories	**2**	**2**	**2**	**3**	**3**	**3**	**3**	**3**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	2	2	2	3	3	3	3	3
Natural Gas	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+
Total	**382**	**373**	**351**	**324**	**324**	**334**	**340**	**330**

+ Does not exceed 0.5 Gg
Note: Totals may not sum due to independent rounding.

Table 3-19: N_2O Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005
Electric Power	**24**	**26**	**30**	**29**	**29**	**30**	**30**	**31**
Coal	23	25	28	28	28	28	28	29
Fuel Oil	1	+	1	1	1	1	1	1
Natural Gas	+	+	1	1	1	+	1	1
Wood	+	+	1	+	1	1	1	1
Industrial	**10**	**11**	**11**	**10**	**10**	**9**	**10**	**9**
Coal	2	2	2	2	2	2	2	2
Fuel Oil	2	1	2	2	2	2	2	2
Natural Gas	1	1	1	1	1	1	1	1
Wood	5	6	6	5	5	5	6	5
Commercial	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	1	+	+	+	+	+	+	+
Natural Gas	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+
Residential	**4**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	1	1	1	1	1	1	1	1
Natural Gas	+	+	+	+	+	+	+	+
Wood	2	2	2	1	1	2	2	2
U.S. Territories	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Coal	+	+	+	+	+	+	+	+
Fuel Oil	+	+	+	+	+	+	+	+
Natural Gas	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+
Total	**40**	**41**	**45**	**44**	**43**	**44**	**45**	**45**

+ Does not exceed 0.5 Gg
Note: Totals may not sum due to independent rounding.

detail (EIA 2006a). Wood consumption data for the United States was obtained from EIA's *Annual Energy Review* (EIA 2006b). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were provided separately by Grillot (2006).[32] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[33] Construction and agricultural fuel use was obtained from EPA (2004). 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.

Emission factors for the four end-use sectors were provided by the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997). U.S. territories' emission factors were estimated using the U.S. emission factors for the primary sector in which each fuel was combusted.

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

CH_4 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 Tier 2 uncertainty estimation methodology, Monte Carlo Simulation technique, with @RISK software.

---

[32] 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.

[33] 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.

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. A total of 115 input variables were simulated for the uncertainty analysis of this source category (85 from the CO_2 emissions from fossil fuel combustion inventory estimation model and 30 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.[34] For these variables, the uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[35] 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 3-20. Stationary combustion CH_4 emissions in 2005 (*including* biomass) were estimated to be between 4.8 and 14.7 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 30 percent below to 112 percent above the 2005 emission estimate of 6.9 Tg CO_2 Eq.[36] Stationary combustion N_2O emissions in 2005 (*including* biomass) were estimated to be between 10.8 and 39.9 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 22 percent below to 189 percent above the 2005 emissions estimate of 13.8 Tg CO_2 Eq.

The uncertainties associated with the emission estimates of CH_4 and N_2O are greater than those associated with estimates of CO_2 from fossil fuel combustion, which mainly rely on the carbon content of the fuel combusted. Uncertainties in both CH_4 and N_2O estimates are due to the fact that emissions are estimated based on emission factors representing only a limited subset of combustion conditions. For the indirect greenhouse gases, uncertainties are partly due to assumptions concerning combustion technology types, age of equipment, emission factors used, and activity data projections.

QA/QC and Verification

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.

Table 3-20: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Stationary Combustion, Including Biomass (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	6.9	4.8	14.7	-30%	+112%
Stationary Combustion	N_2O	13.8	10.8	39.9	-22%	+189%

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

---

[34] 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.

[35] 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.

[36] 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.

Recalculations Discussion

Historical CH_4 and N_2O emissions from stationary sources (excluding CO_2) were revised due to several changes. Slight changes to emission estimates for sectors are due to revised data from EIA (2006a). This revision is explained in greater detail in the section on CO_2 Emissions from Fossil Fuel Combustion within this sector. Wood consumption data from EIA (2006b) were revised for the commercial/institutional and residential sectors. The combination of the methodological and historical data changes resulted in an average annual increase of 0.2 Tg CO_2 Eq. (2.0 percent) in CH_4 emissions from stationary combustion and an average annual increase of 0.1 Tg CO_2 Eq. (0.2 percent) in N_2O emissions from stationary combustion for the period 1990 through 2004.

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.

3.4. Mobile Combustion (excluding CO_2) (IPCC Source Category 1A)

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 are closely related to fuel characteristics, air-fuel mixes, combustion temperatures, and the use of pollution control equipment. N_2O, in particular, can be formed by the catalytic processes used to control NO_x, CO, and hydrocarbon emissions. Carbon monoxide emissions from mobile combustion are significantly affected by combustion efficiency and the presence of post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. These emissions occur especially in idle, low speed, and cold start conditions. CH_4 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).

Emissions from mobile combustion were estimated by transport mode (e.g., highway, air, rail), fuel type (e.g. motor gasoline, diesel fuel, jet fuel), and vehicle type (e.g. passenger cars, light-duty trucks). Road transport accounted for the majority of mobile source fuel consumption, and hence, the majority of mobile combustion emissions. Table 3-21 and Table 3-22 provide CH_4 and N_2O emission estimates in Tg CO_2 Eq.; Table 3-23 and Table 3-24 present these estimates in Gg of each gas.[37]

Mobile combustion was responsible for a small portion of national CH_4 emissions (0.5 percent) but was the second largest source of U.S. N_2O emissions (8 percent). From 1990 to 2005, mobile source CH_4 emissions declined by 45 percent, to 2.6 Tg CO_2 Eq. (125 Gg), due largely to control technologies employed on highway vehicles since the mid-1990s to reduce CO, NO_x, NMVOC, and CH_4 emissions. Mobile source emissions of N_2O decreased by 13 percent, to 38.0 Tg CO_2 Eq. 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 31 percent decrease in mobile source N_2O emissions from 1998 to 2005. As a result, N_2O emissions in 2005 were 13 percent lower than in 1990, at 38.0 Tg CO_2 Eq. (123 Gg) (see Figure 3-17). Overall, CH_4 and N_2O emissions were predominantly from gasoline-fueled passenger cars and light-duty trucks.

Methodology

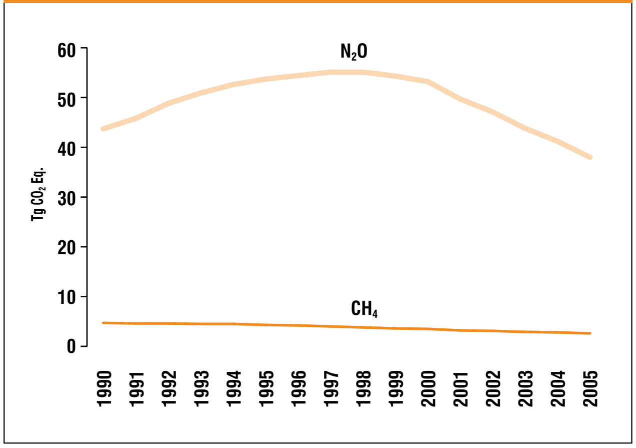
Estimates of CH_4 and N_2O emissions from mobile combustion were calculated by multiplying emission factors by measures of activity for each fuel and vehicle type (e.g., light-duty gasoline trucks). Activity data included vehicle

---

[37] See Annex 3.2 for a complete time series of emission estimates for 1990 through 2005.

Figure 3-17

Mobile Source CH_4 and N_2O Emissions



miles traveled (VMT) for highway (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 emissions from mobile combustion and the emission factors used in the calculations is provided in Annex 3.2.

EPA (2006c), EPA (2005) and EPA (2003) provide emission estimates of NO_x, CO, and NMVOCs for eight categories of highway vehicles,[38] aircraft, and seven categories of non-highway vehicles.[39] These emission estimates primarily reflect EPA data, which, in final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. The methodology used to develop these estimates can be found on EPA's Air Pollutant Emission Trends website, at <http://www.epa.gov/ttn/chief/trends/index.html>.

Highway Vehicles

Estimates of CH_4 and N_2O emissions from gasoline and diesel highway vehicles are based on VMT and emission factors by vehicle type, fuel type, model year, and control technology. Emission estimates from alternative fuel vehicles (AFVs)[40] are based on VMT and emission factors by vehicle and fuel type.

Emission factors for gasoline and diesel highway vehicles utilizing Tier 2 and Low Emission Vehicle (LEV)

Table 3-21: CH_4 Emissions from Mobile Combustion (Tg CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	1995	2000	2001	2002	2003	2004	2005
Gasoline Highway	**4.2**	**3.8**	**2.8**	**2.6**	**2.4**	**2.2**	**2.1**	**1.9**
Passenger Cars	2.6	2.1	1.6	1.5	1.4	1.2	1.2	1.1
Light-Duty Trucks	1.4	1.4	1.1	1.0	1.0	0.9	0.8	0.8
Heavy-Duty Vehicles	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Motorcycles	+	+	+	+	+	+	+	+
Diesel Highway	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Passenger Cars	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	+	+	+	+	+	+	+	+
Alternative Fuel Highway	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Non-Highway	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Ships and Boats	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Locomotives	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Farm Equipment	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Construction Equipment	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other[b]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**4.7**	**4.3**	**3.5**	**3.2**	**3.1**	**2.9**	**2.8**	**2.6**

+ Less than 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

[a] See Annex 3.2 for definitions of highway vehicle types.

[b] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment.

---

[38] These categories included: gasoline passenger cars, diesel passenger cars, light-duty gasoline trucks less than 6,000 pounds in weight, light-duty gasoline trucks between 6,000 and 8,500 pounds in weight, light-duty diesel trucks, heavy-duty gasoline trucks and buses, heavy-duty diesel trucks and buses, and motorcycles.

[39] These categories included: locomotives, marine vessels, farm equipment, construction equipment, other off-highway liquid fuel (e.g. recreational vehicles and lawn and garden equipment), and other off-highway gaseous fuel (e.g., other off-highway equipment running on compressed natural gas).

[40] 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 bifuel or dual fuel vehicles that may be partially powered by gasoline or diesel.

Table 3-22: N_2O Emissions from Mobile Combustion (Tg CO_2 Eq.)

Fuel Type/Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005
Gasoline Highway	**40.1**	**49.8**	**48.8**	**45.5**	**42.8**	**39.5**	**36.7**	**33.4**
Passenger Cars	25.4	26.9	24.7	23.2	21.9	20.3	18.8	17.0
Light-Duty Trucks	14.1	22.1	23.3	21.4	20.0	18.2	17.0	15.6
Heavy-Duty Vehicles	0.6	0.7	0.9	0.9	0.9	0.9	0.9	0.8
Motorcycles	+	+	+	+	+	+	+	+
Diesel Highway	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Passenger Cars	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Alternative Fuel Highway	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Non-Highway	**3.4**	**3.6**	**4.0**	**3.8**	**3.9**	**3.9**	**4.0**	**4.1**
Ships and Boats	0.4	0.4	0.5	0.3	0.5	0.4	0.5	0.5
Locomotives	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4
Farm Equipment	1.7	1.7	1.9	1.8	1.7	1.7	1.7	1.8
Construction Equipment	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.4
Aircraft	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.5
Other*	0.4	0.5	0.5	0.6	0.6	0.6	0.6	0.6
Total	**43.7**	**53.7**	**53.2**	**49.7**	**47.1**	**43.8**	**41.2**	**38.0**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.
*"Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment.

Table 3-23: CH_4 Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005
Gasoline Highway	**201**	**180**	**135**	**124**	**115**	**106**	**99**	**92**
Passenger Cars	125	101	76	70	65	59	56	51
Light-Duty Trucks	65	69	53	49	45	42	39	37
Heavy-Duty Vehicles	10	9	5	5	4	4	4	3
Motorcycles	1	1	1	1	1	1	1	1
Diesel Highway	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Passenger Cars	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	1	1	1	1	1	1	1	1
Alternative Fuel Highway	**+**	**+**	**1**	**1**	**2**	**2**	**2**	**2**
Non-Highway	**24**	**26**	**28**	**27**	**28**	**28**	**29**	**30**
Ships and Boats	3	4	5	3	4	4	5	5
Locomotives	3	3	3	3	3	3	4	4
Farm Equipment	7	7	7	7	7	6	7	7
Construction Equipment	4	5	5	6	6	6	6	7
Aircraft	2	3	3	3	3	4	4	4
Other*	3	3	4	4	4	4	4	4
Total	**226**	**207**	**165**	**154**	**146**	**136**	**131**	**125**

+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.
*"Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment.

technologies were developed by ICF (2006b); all other gasoline and diesel highway 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 GHGs depending on the driving segment. These driving

Table 3-24: N_2O Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005
Gasoline Highway	**129**	**161**	**158**	**147**	**138**	**127**	**118**	**108**
Passenger Cars	82	87	80	75	71	66	61	55
Light-Duty Trucks	45	71	75	69	65	59	55	50
Heavy-Duty Vehicles	2	2	3	3	3	3	3	3
Motorcycles	+	+	+	+	+	+	+	+
Diesel Highway	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Passenger Cars	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+
Heavy-Duty Vehicles	1	1	1	1	1	1	1	1
Alternative Fuel Highway	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Non-Highway	**11**	**12**	**13**	**12**	**13**	**12**	**13**	**13**
Ships and Boats	1	1	2	1	2	1	2	2
Locomotives	1	1	1	1	1	1	1	1
Farm Equipment	6	5	6	6	6	5	6	6
Construction Equipment	1	1	1	1	1	1	1	1
Aircraft	1	1	1	1	2	2	2	2
Other*	1	2	2	2	2	2	2	2
Total	**141**	**173**	**172**	**160**	**152**	**141**	**133**	**123**

+ Less than 0.5 Gg

Note: Totals may not sum due to independent rounding.

*"Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment.

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 to approximate average driving characteristics.

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 2005 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in *Highway Statistics* (FHWA 1996 through 2006). VMT was 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 2006) and information on total motor vehicle fuel consumption by fuel type from FHWA (1996 through 2006). VMT for AFVs were taken from Browning (2003). The age distributions of the U.S. vehicle fleet were obtained from EPA (2006e) and EPA (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 highway vehicles were obtained from EPA's Office of Transportation and Air Quality (EPA 2006a, 2006b, 2000, 1998, and 1997) and Browning (2005). These technologies and standards are defined in Annex 3.2, and were compiled from EPA (1993), EPA (1994a), EPA (1994b), EPA (1998), EPA (1999a), and IPCC/UNEP/OECD/IEA (1997).

These emission estimates were obtained from preliminary data (EPA 2006c), 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.

Non-Highway Vehicles

To estimate emissions from non-highway 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).[41] Activity data were obtained from AAR (2006), APTA (2006), BEA (1991 through 2005), Benson (2002 through 2004), DOE (1993 through 2006), DESC (2006), DOC (1991 through 2006), DOT (1991 through 2006), EIA (2006a), EIA (2006b), EIA (2004), EIA (2002), EIA (1991 through 2006), EPA (2006e), Esser (2003 through 2004), FAA (2006a and 2006b), Lou (2002), and Whorton (2006). Emission factors for non-highway modes were taken from IPCC/UNEP/OECD/IEA (1997).

Uncertainty

This section discusses the uncertainty of the emission estimates for CH_4 and N_2O. Uncertainty was analyzed separately for highway vehicles and non-highway vehicles due to differences in their characteristics and their contributions to total mobile source emissions.

A quantitative uncertainty analysis was conducted for the highway portion of the mobile source sector using the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo Simulation technique, using @RISK software. The uncertainty analysis was performed on 2005 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 two major sets of input variables: (1) vehicle miles traveled (VMT) data, by vehicle and fuel type and (2) emission factor data, by vehicle, fuel, and control technology type.

The emission factors for highway vehicles used in the Inventory were obtained from ICF (2006b) and ICF (2004). These factors were based on laboratory testing of vehicles. While the controlled testing environment simulates real driving conditions, emission results from such testing can only approximate real world conditions and emissions. For some vehicle and control technology types, the testing did not yield statistically significant results within the 95 percent confidence interval, requiring expert judgment to be used in developing the emission factors. In those cases, the emission factors were developed based on comparisons of fuel consumption between similar vehicle and control technology categories.

The estimates of VMT for highway vehicles by vehicle type in the United States were provided by FHWA (1996 through 2006), and were generated through the cooperation of FHWA and state and local governments. While the uncertainty associated with total U.S. VMT is believed to be low, the uncertainty within individual source categories was assumed to be higher given uncertainties associated with apportioning total VMT into individual vehicle categories, by fuel type, by technology type, and equipment age.

A significant amount of uncertainty is associated with the emission estimates for non-road sources. A primary cause is a large degree of uncertainty regarding emission factors. The IPCC *Good Practice Guidance* reports that CH_4 emissions from aviation and marine sources may be uncertain by a factor of two, while N_2O emissions may be uncertain by an order of magnitude for marine sources and several orders of magnitude for aviation. No information is provided on the uncertainty of emission factors for other non-highway sources.

Fuel consumption data have a lower uncertainty than emission factors, though large uncertainties do exist for individual sources.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-25. Mobile combustion CH_4 emissions in 2005 were estimated to be between 2.5 and 2.8 Tg CO_2 Eq. at a 95 percent confidence level (or in 19 out of 20 Monte Carlo Simulations). This indicates a range of 6 percent below to 6 percent above the 2005 emission estimate of 2.6 Tg CO_2 Eq. Also at a 95 percent confidence level, mobile combustion N_2O emissions in 2005 were estimated to be between 31.0 and 45.0 Tg CO_2 Eq., indicating a range

---

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

Table 3-25: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Mobile Combustion (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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
Mobile Sources	CH_4	2.6	2.5	2.8	-6%	+6%
Mobile Sources	N_2O	38.0	31.0	45.0	-18%	+19%

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

of 18 percent below to 19 percent above the 2005 emission estimate of 38.0 Tg CO_2 Eq.

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.

QA/QC and Verification

A source-specific QA/QC plan for mobile 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 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. A number of adjustments were made to the historical data used in calculating emissions in the current Inventory.

For highway sources, vehicle age distributions for 1999 to the present were revised based on new data obtained from EPA's MOVES model (EPA 2006e). Diesel fractions for light trucks and medium-heavy trucks for 1998 through 2003 were updated based on data obtained from the Transportation Energy Data Book (DOE 2006). The highway vehicle emissions estimation procedures now include a new gasoline vehicle emission control technology, Tier 2, and updated emissions factors for LEVs (ICF 2006b). These changes resulted in a reduction in gasoline highway vehicle emissions from 1996 onward, and most notably since 2002. In addition, revisions were made to both the light-duty and heavy-duty alternative fuel vehicle (AFV) emissions factors (ICF 2006a), which resulted in an increase in N_2O emissions and a decrease in CH_4 from AFVs. Lastly, VMT and fuel consumption estimates for non-highway vehicles were revised for 2004 based on updated data from FHWA's *Highway Statistics* (FHWA 1996 through 2006).

Several improvements and updates were also made in the calculation of emissions from non-road vehicles. Commercial aircraft energy consumption estimates now come from the Federal Aviation Administration's (FAA) System for Assessing Aviation's Global Emissions (SAGE) database (FAA 2006b), rather than from the Bureau of Transportation Statistics. This change increased estimates of fuel consumption and emissions attributed to commercial aircraft, but does not affect the total aircraft emissions figures, since the "Other Aviation" category was eliminated. Class II and III railroad diesel use estimates for 2002 and 2004 were obtained from the American Short Line and Regional Railroad Association (Whorton 2006), instead of the Upper Great Plains Institute. EPA's updated NONROAD model was used to recalculate fuel consumption for non-highway mobile sources.

As a result of these changes, average estimates of CH_4 and N_2O emissions from mobile combustion were slightly higher—showing an increase of no more than 0.32 Tg CO_2 Eq. (less than 0.6 percent) each year—for the period 1990 through 2000. In contrast, emissions estimates were lower in every year between 2001 and 2004, compared to last year's inventory. Specifically, estimates decreased 1.16 Tg CO_2 Eq. (2.4 percent) in 2003 and 1.83 Tg CO_2 Eq. (4 percent) in 2004.

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) *Improve estimation of VMT and fuel consumption by vehicle type (e.g., passenger car, light-duty truck, heavy-duty truck, bus):* Potential improvements in the breakdown of VMT and fuel consumption by vehicle type could be developed based on further investigation of the methodologies and data sources used. Estimates of motor vehicle travel and fuel consumption by vehicle type are taken from FHWA's Highway Statistics (FHWA 1996 to 2006), which in turn are based on data from the Highway Performance Monitoring System, fuel tax receipts, Vehicle Inventory and Use Survey (VIUS), and other sources. FHWA annually updates only the most recent year of historical VMT and fuel consumption estimates (for instance, only the 2004 estimates in 2005 Highway Statistics are recalculated, while 1990–2003 remain constant). Additional data might help to develop improved estimates of historical VMT and fuel consumption by vehicle type going back through 1990. Moreover, the shares of VMT associated with each vehicle type reported by FHWA are quite different from estimates used in EPA's MOBILE model, and these differences should be investigated.

2) *Improve the process of apportioning VMT by vehicle type to each fuel type:* The current inventory process for estimating VMT by vehicle/fuel type category involves apportioning VMT by vehicle type to each fuel type on the basis of fuel consumption. While this is a reasonable simplification, this approach implicitly assumes the same average fuel economy for gasoline and diesel vehicles. A more accurate apportionment of VMT by fuel type for light-duty trucks and medium/heavy-duty trucks could potentially be developed using data on vehicle travel from the Vehicle Inventory and Use Survey (U.S. Census Bureau 2000) and other publications, or using VMT breakdowns by vehicle/fuel type combinations from the MOBILE6 or MOVES models.

3) *Continue the Reconciliation of Fuel Consumption Estimates used for Calculating N_2O/CH_4 and CO_2:* Estimates of transportation fuel consumption by fuel type from EIA are used as the basis for estimating CO_2 emissions from the transportation sector. These estimates are then apportioned to mode and vehicle category based on "bottom up" estimates of fuel consumption from sources such as FHWA's *Highway Statistics* (FHWA 1996 through 2006) and DOE's *Transportation Energy Data Book* (DOE 1993 through 2006). These sources are also used to develop N_2O and CH_4 estimates. The EPA fuel consumption estimates, however, differ from the estimates derived using "bottom up" sources. For this Inventory, estimates of distillate fuel consumption have been reconciled. Potential improvements include reconciling additional fuel consumption estimates from EIA and other data sources, and revising the current process of allocating CO_2 emissions to particular vehicle types.

4) *Continue to examine ways to utilize EPA's MOVES model in the development of the Inventory estimates, including use for uncertainty analysis:* Although the inventory uses some of the underlying data from MOVES, such as vehicle age distributions by model year, MOVES is not used directly in calculating mobile source emissions. The use of MOVES should be further explored.

3.5. 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. All 115 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 2005, 13 coal mines collected CH_4 from degasification systems and sold this gas to a pipeline, thus reducing emissions to the atmosphere. In addition, one coal mine used CH_4 from its degasification system to heat mine ventilation air on site. Two of the coal mines that sold gas to pipelines also used CH_4 to generate electricity or 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

Table 3-26: CH_4 Emissions from Coal Mining (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Underground Mining	62.1	49.2	39.1	38.1	35.4	35.8	37.9	35.6
Liberated	67.6	61.6	53.9	54.5	52.7	51.3	53.9	50.6
Recovered & Used	(5.6)	(12.4)	(14.8)	(16.5)	(17.4)	(15.5)	(16.0)	(15.0)
Surface Mining	10.4	8.9	8.8	9.2	8.8	8.4	8.6	8.9
Post-Mining (Underground)	7.7	6.9	6.7	6.8	6.4	6.4	6.6	6.4
Post-Mining (Surface)	1.7	1.4	1.4	1.5	1.4	1.4	1.4	1.4
Total	**81.9**	**66.5**	**55.9**	**55.5**	**52.0**	**52.1**	**54.5**	**52.4**

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

Table 3-27: CH_4 Emissions from Coal Mining (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Underground Mining	2,955	2,343	1,860	1,812	1,684	1,707	1,803	1,696
Liberated	3,220	2,935	2,565	2,596	2,511	2,443	2,565	2,408
Recovered & Used	(265)	(592)	(704)	(784)	(827)	(736)	(762)	(712)
Surface Mining	497	425	417	438	420	402	411	425
Post-Mining (Underground)	367	328	317	323	304	305	315	305
Post-Mining (Surface)	81	69	68	71	68	65	67	69
Total	**3,899**	**3,165**	**2,662**	**2,644**	**2,476**	**2,480**	**2,597**	**2,494**

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

mining is released during processing, storage, and transport of the coal.

Total CH_4 emissions in 2005 were estimated to be 52.4 Tg CO_2 Eq. (2,494 Gg), a decline of 36 percent since 1990 (see Table 3-26 and Table 3-27). Of this amount, underground mines accounted for 68 percent, surface mines accounted for 17 percent, and post-mining emissions accounted for 15 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. CH_4 emissions increased slightly in 2003 due to additional gas drainage being vented to the atmosphere and a reduction in CH_4 recovery. Although overall emissions declined, recovery decreased again in 2005 with reduced production from pre-drainage wells, increased use of horizontal gob wells that are vented to the atmosphere, and temporary closure of a major project due to a mine fire. Surface mine emissions and post-mining emissions remained relatively constant from 1990 to 2005.

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[42] 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-four mines using these systems, depending on available data. For example,

---

[42] 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.

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 2005, thirteen active coal mines sold recovered CH_4 into the local gas pipeline networks, while one coal mine used recovered CH_4 on site. 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 3-28) (EIA 2006), 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 (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 3-28: Coal Production (Thousand Metric Tons)

Year	Underground	Surface	Total
1990	384,250	546,818	931,068
1995	359,477	577,638	937,115
2000	338,173	635,592	973,765
2001	345,305	676,142	1,021,446
2002	324,219	667,619	991,838
2003	320,047	651,251	971,297
2004	333,449	674,551	1,008,000
2005	334,404	691,460	1,025,864

Uncertainty

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 liberated and 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, and thus the avoided emissions, may increase if the drainage area is found to be larger 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 3-29. Coal

Table 3-29: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Coal Mining (Tg CO_2 Eq. and Percent)

Source	Gas	2005 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal Mining	CH_4	52.4	49.8	58.7	-5%	+12%

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

mining CH_4 emissions in 2005 were estimated to be between 49.8 and 58.7 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 5 percent below to 12 percent above the 2005 emission estimate of 52.4 Tg CO_2 Eq.

Recalculations Discussion

In 2005, recalculations of emissions avoided at three Jim Walter Resources (JWR) coal mines in Alabama were performed because the mining company provided mine maps describing mined-out areas for each month from 2000 through 2005. In previous Inventories, emissions-avoided calculations for any pre-drainage wells at JWR coal mines were based on publicly-available data records from the Alabama State Oil & Gas Board. Also in previous Inventories, emission reductions were calculated for pre-drainage wells that were located inside the mine plan boundaries and were declared "shut-in" by the O&G Board. In recent years, JWR had mined-through numerous pre-drainage wells that were subsequently converted to gob wells for further coal mine degasification. Because they were never shut in, emissions avoided were not calculated.

The mine maps provided by JWR allowed for a more accurate accounting as to when and which pre-drainage wells should be included in the emissions avoided calculations. As a result, recalculations were performed on years 2000 through 2004. The most pronounced changes to the Inventory were made in the years 2003 through 2004, where corrections led to an overall reduction of emissions in 2003 and 2004 by 2.7 and 1.8 Tg CO_2 Eq., respectively. Minor changes were made to JWR emissions avoided for 1995 through 1996 as well.

For the current Inventory, recalculations were performed on all years, with negligible changes in 1994, 1996, and 1998 through 2002, as QA/QC of databases uncovered that emissions avoided had been miscalculated. Some recalculations were done in 2003 on Alabama mines but were not linked retroactively. These recalculations either led to no change in net emissions, or a change of 0.1 Tg CO_2 Eq. Emissions avoided for 2003 were adjusted downward as a major operator reported in 2004 that double-counting of some pre-drainage wells had previously occurred. Correction of this error led to a reduction in emissions avoided of 1.0 Tg CO_2 Eq., which contributed to the reduction in emissions in 2003 from 54.8 to 52.1 Tg CO_2 Eq.

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

All underground and surface coal mining liberates CH_4 as part of the normal mining operations. The amount of CH_4 liberated depends on the amount that resides in the coal ("*in situ*") and surrounding strata when mining occurs. The in-situ CH_4 content depends upon the amount of CH_4 created during the coal formation (i.e., coalification) process, and the geologic characteristics of the coal seams. During coalification, more deeply buried deposits tend to generate more CH_4 and retain more of the gas after uplift to minable depths. Deep underground coal seams generally have higher CH_4 contents than shallow coal seams or surface deposits.

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 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.

Table 3-30: CH_4 Emissions from Abandoned Underground Coal Mines (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Abandoned Underground Mines	6.0	8.9	8.8	8.1	7.7	7.5	7.3	7.0
Recovered & Used	0.0	0.7	1.5	1.5	1.6	1.5	1.5	1.4
Total	**6.0**	**8.2**	**7.3**	**6.7**	**6.1**	**5.9**	**5.8**	**5.5**

Note: Totals may not sum due to independent rounding.

Table 3-31: CH_4 Emissions from Abandoned Underground Coal Mines (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Abandoned Underground Mines	287	422	421	387	367	354	345	331
Recovered & Used	0	32	72	70	75	72	70	68
Total	**286**	**391**	**349**	**318**	**292**	**282**	**275**	**263**

Note: Totals may not sum due to independent rounding.

Gross abandoned mine CH_4 emissions ranged from 6.0 to 9.1 Tg CO_2 Eq. from 1990 through 2005, 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. 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 2005, with only two closures in 2005. By 2005, abandoned mine emissions declined to 5.5 Tg CO_2 Eq. (see Table 3-30 and Table 3-31).

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. 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, P_r, declines as described by the isotherm. The emission rate declines because the mine pressure (P_w) 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 mcf/d

q_i = Initial gas rate at time zero (t_o) in million cubic feet per day (mcfd)

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 are also affected by both 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).

$$q = q_i e^{(-Dt)}$$

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 440 abandoned mines closing after 1972 produced emissions greater than 100 mcfd when active. Further, the status of 264 of the 440 mines (or 60 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 40 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).

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, throughout the 20th century. 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 ventilation data for the total CH_4 liberation rate for fourteen mines that closed between 1992 and 2005. 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

Table 3-32: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Abandoned Underground Coal Mines ($Tg CO_2$ Eq. and Percent)

Source	Gas	2005 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	5.5	4.6	6.5	-16%	+18%

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

multiplied by 1.22 and 1.02 to account for all U.S. abandoned mine emissions. From 1993 through 2005, 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 3-32. Abandoned coal mines CH_4 emissions in 2005 were estimated to be between 4.6 and 6.5 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 16 percent below to 18 percent above the 2005 emission estimate of 5.5 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 40 percent of the mines), with a ±50 percent uncertainty.

Recalculations Discussion

Quality assurance/quality control of the calculation spreadsheets for the 1990 through 2004 inventory years revealed an equation link that contained a minor error. The error was tracked back to the 1998 calculation worksheet and carried through 2004. The equation was corrected and the emissions recalculated for 1998 through 2004. In addition, a few other minor data corrections were completed during the recalculation process.

3.7. Natural Gas Systems (IPCC Source Category 1B2b)

The U.S. natural gas system encompasses hundreds of thousands of wells, hundreds of processing facilities, and over a million miles of transmission and distribution pipelines. Overall, natural gas systems emitted 111.1 Tg CO_2 Eq. (5,292 Gg) of CH_4 in 2005, an 11 percent decrease over 1990 emissions (see Table 3-33 and Table 3-34), and 28.2 Tg CO_2 Eq. (28,185 Gg) of non-energy CO_2 in 2005, a 16 percent decrease over 1990 emissions (see Table 3-35 and Table 3-36). Improvements in management practices and technology, along with the replacement of older equipment, have helped to stabilize emissions.

CH_4 and non-energy 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

Table 3-33. CH_4 Emissions from Natural Gas Systems (Tg CO_2 Eq.)*

Stage	1990	1995	2000	2001	2002	2003	2004	2005
Field Production	31.8	36.6	38.5	41.2	42.4	40.9	38.0	35.2
Processing	14.8	14.9	14.5	14.7	14.1	13.5	13.5	11.9
Transmission and Storage	46.8	46.3	44.1	41.0	42.5	42.3	40.6	36.8
Distribution	31.0	30.3	29.4	28.6	25.9	27.0	26.9	27.4
Total	**124.5**	**128.1**	**126.6**	**125.4**	**125.0**	**123.7**	**119.0**	**111.1**

*Including CH_4 emission reductions achieved by the Natural Gas STAR program and NESHAP regulations.
Note: Totals may not sum due to independent rounding.

Table 3-34. CH_4 Emissions from Natural Gas Systems (Gg)*

Stage	1990	1995	2000	2001	2002	2003	2004	2005
Field Production	1,514	1,745	1,832	1,963	2,021	1,949	1,811	1,675
Processing	706	709	692	698	673	645	643	564
Transmission and Storage	2,230	2,205	2,102	1,950	2,025	2,013	1,934	1,751
Distribution	1,477	1,442	1,401	1,360	1,231	1,284	1,281	1,303
Total	**5,927**	**6,101**	**6,027**	**5,971**	**5,951**	**5,891**	**5,669**	**5,292**

*Including CH_4 emission reductions achieved by the Natural Gas STAR program and NESHAP regulations.
Note: Totals may not sum due to independent rounding.

Table 3-35. Non-energy CO_2 Emissions from Natural Gas Systems (Tg CO_2 Eq.)

Stage	1990	1995	2000	2001	2002	2003	2004	2005
Field Production	5.9	9.1	6.0	6.3	6.5	6.3	6.3	6.4
Processing	27.8	24.6	23.3	22.4	23.1	22.0	21.8	21.7
Transmission and Storage	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Distribution	+	+	+	+	+	+	+	+
Total	**33.7**	**33.8**	**29.4**	**28.8**	**29.6**	**28.4**	**28.2**	**28.2**

Note: Totals may not sum due to independent rounding.

Table 3-36. Non-energy CO_2 Emissions from Natural Gas Systems (Gg)

Stage	1990	1995	2000	2001	2002	2003	2004	2005
Field Production	5,876	9,083	5,955	6,307	6,462	6,341	6,309	6,350
Processing	27,752	24,621	23,333	22,387	23,066	22,002	21,780	21,736
Transmission and Storage	58	60	61	59	62	61	62	60
Distribution	43	42	41	40	40	40	40	39
Total	**33,729**	**33,807**	**29,390**	**28,793**	**29,630**	**28,445**	**28,190**	**28,185**

Note: Totals may not sum due to independent rounding.

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-energy 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. Fugitive emissions and emissions from pneumatic devices account for the majority of CH_4 emissions. Flaring emissions account for the majority of the non-energy CO_2 emissions. Emissions from field production accounted for approximately 32 percent of CH_4 emissions and about 23 percent of non-energy CO_2 emissions from natural gas systems in 2005.

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-energy CO_2 emissions come from acid gas removal units, which are designed to remove CO_2 from natural gas. Processing plants account for about 11 percent of CH_4 emissions and approximately 77 percent of non-energy 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 34 percent of emissions from natural gas systems, while CO_2 emissions from transmission and storage account for less than 1 percent of the non-energy 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 1,034,000 miles of distribution mains in 2005, an increase from just over 888,000 miles in 1990 (OPS 2006b). Distribution system emissions, which account for approximately 25 percent of CH_4 emissions from natural gas systems and less than 1 percent of non-energy CO_2 emissions, result mainly from fugitive emissions from gate stations and non-plastic piping (cast iron, steel).[43] 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 2005 were 12 percent lower than 1990 levels.

Methodology

The primary basis for estimates of CH_4 and non-energy-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 and activity factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system. The same activity factors were used to estimate both CH_4 and non-energy CO_2 emissions. However, the CH_4 emission factors were adjusted for CO_2 content when estimating fugitive and vented non-energy CO_2 emissions. 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 and activity factors. For other years, a set of industry activity factor drivers was developed that can be used to update activity factors. 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.

See Annex 3.4 for more detailed information on the methodology and data used to calculate CH_4 and non-energy CO_2 emissions from natural gas systems.

Activity factor data were taken from the following sources: American Gas Association (AGA 1991–1998); American Petroleum Institute (API 2005); Minerals and Management Service (MMS 2006a-e); Monthly Energy Review (EIA 2006e); Natural Gas Liquids Reserves Report (EIA 2005); Natural Gas Monthly (EIA 2006c,d,f); the Natural Gas STAR Program annual emissions savings (EPA 2006); Oil and Gas Journal (OGJ 1997–2006); Office of Pipeline Safety (OPS 2006a-b) and other Energy Information Administration publications (EIA 2004, 2006a,b,g); World Oil Magazine (2006a-b). Data for estimating emissions from hydrocarbon production tanks is incorporated (EPA 1999). Coalbed CH_4 well activity factors were taken from the

---

[43] The percentages of total emissions from each stage may not sum to 100 percent due to independent rounding.

Wyoming Oil and Gas Conservation Commission (Wyoming 2006) and the Alabama State Oil and Gas Board (Alabama 2006). Other state well data was taken from: American Association of Petroleum Geologists (AAPG 2004); Brookhaven College (Brookhaven 2004); Kansas Geological Survey (Kansas 2006); Montana Board of Oil and Gas Conservation (Montana 2006); Oklahoma Geological Survey (Oklahoma 2006); Morgan Stanley (Morgan Stanley 2005); Rocky Mountain Production Report (Lippman 2003); New Mexico Oil Conservation Division (New Mexico 2006a,b); Texas Railroad Commission (Texas 2006a-d); Utah Division of Oil, Gas and Mining (Utah 2006). Emission factors were taken from EPA/GRI (1996). GRI's Unconventional Natural Gas and Gas Composition Databases (GRI 2001) were used to adapt the CH_4 emission factors into non-energy related CO_2 emission factors. Additional information about CO_2 content in transmission quality natural gas was obtained via the internet from numerous U.S. transmission companies to help further develop the non-energy CO_2 emission factors.

Uncertainty

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 results presented below provide with 95 percent certainty the range within which emissions from this source category are likely to fall.

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 3-37. Natural gas systems CH_4 emissions in 2005 were estimated to be between 82.2 and 144.4 Tg CO_2 Eq. at a 95 percent confidence level. Natural gas systems non-energy CO_2 emissions in 2005 were estimated to be between 20.8 and 36.6 Tg CO_2 Eq. at a 95 percent confidence level.

Recalculations Discussion

Significant changes were made to the emission calculations in the Production sector. The first change implemented was to incorporate a variable CH_4 content of the natural gas produced in the United States to the emission factors of the production sector. In the past, CH_4 content for the emission factors was kept constant for each year and different National Energy Modeling System (NEMS) regions. For the revised method, the CH_4 content is first estimated in two base years, 1990 and 1995, using GRI and GTI data source estimates, respectively. Then the CH_4 content for other years in the time series 1990 through 2005 are driven by the natural gas production for each state and year. Each NEMS region's CH_4 content is calculated separately to reflect the differences in the reservoir basins around the country. The net effect of this restructuring on the historical emission estimates is an average 3 percent increase in emissions. The varying CH_4 content in each region added another source of uncertainty to the uncertainty analysis.

The second change to the production sector of the Inventory was replacement of activity factors for five sources: separators, heaters, pneumatic devices, chemical injection pumps and compressors. The new activity factors were developed by re-organizing the original GRI activity

Table 3-37: 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	2005 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
Natural Gas Systems	CH_4	111.1	82.2	144.4	-26%	+30%
Natural Gas Systems[b]	CO_2	28.2	20.8	36.6	-26%	+30%

[a] Range of emission estimates predicted by Monte Carlo Stochastic 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.

factor data into the new NEMS production regions. The net effect of this change is a 2 percent decrease in 2004 emission estimates.

Another change in the estimates for the current Inventory is the accounting of CH_4 emission reductions from U.S. EPA National Emissions Standards for Hazardous Air Pollutants (NESHAP) regulations, which is the civil enforcement of the Maximum Achievable Control Technology or MACT standard. These federal regulations were enacted in 1999 and require a 95 percent reduction of emissions from dehydrator vents and condensate tanks with throughputs above the threshold levels set by the regulation. The inventory methodology now incorporates these emission reductions when describing the total emissions from natural gas systems. Overall, the net effect on the historical CH_4 emission estimates from this change is less than an average 1 percent decrease in emissions since 1999.

Finally, the Inventory now contains estimates for non-energy related (vented, fugitive, flared) CO_2 emissions from the natural gas industry. The estimation uses the same activity and emission factors as the CH_4 emission estimates but adjusts the emission factors using the ratio of CO_2/CH_4 content of the natural gas. Efforts were made to ensure that there was no double-accounting of CO_2 emissions from other systems reported elsewhere in the U.S. Inventory.

The combination of these methodological and historical data changes resulted in an average annual decrease of 0.3 Tg CO_2 Eq. (0.3 percent) in CH_4 emissions from natural gas systems for the period 1990 through 2004.

Planned Improvements

One improvement being contemplated involves a trend analysis for the time series. As discussed above, the natural gas systems inventory now reflects changing emissions factors based on changing CH_4 content in natural gas in different NEMS regions. The uncertainty analysis, for the sake of simplicity, currently assumes a constant uncertainty across all years in the emissions time series. A trend analysis reflecting changing uncertainty in the time series will be conducted to more closely follow the IPCC Guidelines. Additional improvements include developing region specific emission and activity factors and incorporating any new data that becomes available from new studies in the future into the emissions model.

3.8. Petroleum Systems (IPCC Source Category 1B2a)

CH_4 emissions from petroleum systems are primarily associated with crude oil production, transportation, and refining operations. During each of these activities, CH_4 is released to the atmosphere as fugitive emissions, vented emissions, emissions from operational upsets, and emissions from fuel combustion. Total CH_4 emissions from petroleum systems in 2005 were 28.5 Tg CO_2 Eq. (1,357 Gg). Since 1990, emissions have declined by 17 percent, due to a decline in domestic oil production and industry efforts to reduce emissions (see Table 3-38 and Table 3-39). The emission increase exhibited between 2004 and 2005 resulted from an increase in the number of offshore platforms (primarily shallow water, but also deep water). The various sources of emissions are detailed below.

Production Field Operations. Production field operations account for over 97 percent of total CH_4 emissions from petroleum systems. Vented CH_4 from field operations account for approximately 91 percent of the emissions from the production sector, fugitive emissions account for 3.5 percent, combustion emissions 5.3 percent, and process upset emissions, slightly over one-tenth of a percent. The most dominant sources of vented emissions are offshore oil platforms (shallow and deep water platforms), field storage tanks and natural-gas-powered pneumatic devices (low bleed and high bleed). These five sources alone emit over 86 percent of the production field operations emissions. Offshore platform emissions are a combination of fugitive, vented, and combustion emissions from all equipment housed on the platform for both oil and associated gas on those labeled as oil platforms. Emissions from storage 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 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. Two additional large sources, chemical injection pumps and gas engines, together account for nine percent of emissions from the production sector. The remaining five percent of the emissions are distributed among 26 additional activities within the four categories: vented, fugitive, combustion and process upset emissions.

Table 3-38: CH_4 Emissions from Petroleum Systems (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Production Field Operations	**33.8**	**30.5**	**27.1**	**26.7**	**26.1**	**25.1**	**24.7**	**27.8**
Pneumatic Device Venting	10.3	9.7	9.0	8.9	8.9	8.7	8.6	8.5
Tank Venting	3.8	3.4	3.2	3.2	3.2	3.2	3.0	2.8
Combustion & Process Upsets	1.9	1.7	1.6	1.6	1.6	1.5	1.5	1.5
Misc. Venting & Fugitives	17.4	15.1	12.8	12.5	12.0	11.3	11.2	14.5
Wellhead Fugitives	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4
Crude Oil Transportation	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Refining	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Total	**34.4**	**31.1**	**27.8**	**27.4**	**26.8**	**25.8**	**25.4**	**28.5**

Note: Totals may not sum due to independent rounding.

Table 3-39: CH_4 Emissions from Petroleum Systems (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Production Field Operations	**1,609**	**1,450**	**1,292**	**1,271**	**1,242**	**1,196**	**1,176**	**1,324**
Pneumatic Device Venting	489	463	428	425	424	412	408	406
Tank Venting	179	161	154	154	151	150	142	133
Combustion & Process Upsets	88	82	76	75	75	73	72	72
Misc. Venting & Fugitives	827	719	612	594	570	540	533	692
Wellhead Fugitives	26	25	22	22	23	22	21	21
Crude Oil Transportation	**7**	**6**	**5**	**5**	**5**	**5**	**5**	**5**
Refining	**25**	**25**	**28**	**27**	**27**	**27**	**28**	**28**
Total	**1,640**	**1,482**	**1,325**	**1,303**	**1,275**	**1,229**	**1,209**	**1,357**

Note: Totals may not sum due to independent rounding.

For more detailed, source-level, data on methane emissions in production field operations refer to Annex 3.5.

Crude Oil Transportation. Crude oil transportation activities account for less than one percent of total CH_4 emissions from the oil industry. Venting from tanks and marine vessel loading operations accounts for 65 percent of CH_4 emissions from crude oil transportation. Fugitive emissions, almost entirely from floating roof tanks, account for 18 percent. The remaining 17 percent is distributed among seven 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 slightly over two 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 87 percent of the emissions, while fugitive and combustion emissions account for approximately six and seven 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.

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 1999, EPA 1996). 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 very small compared to CH_4 emissions upstream of oil refineries.

The methodology for estimating CH_4 emissions from the 64 oil industry activities employs emission factors initially developed by EPA (1999) and activity factors that are based on two EPA studies (1996, 1999). Emissions are estimated for each activity by multiplying emission factors (e.g., emission rate per equipment item or per activity) by their corresponding activity factor (e.g., equipment count or frequency of activity). The report provides emission factors and activity factors for all activities except those related to offshore oil production. For offshore oil production, two emission factors were calculated using data collected over a one-year period for all federal offshore platforms (EPA 2005, MMS 2005c). 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 2005. The number of platforms in shallow water and the number of platforms in deep water are used as activity factors and are taken from Minerals Management Service statistics (MMS 2005a, b, d).

Activity factors for years 1990 through 2005 were collected from a wide variety of statistical resources. For some years, complete activity factor data were not available. In such cases, one of three approaches was employed. Where appropriate, the activity factor 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 factor for heater treaters, reported statistics for wells and production were used, along with the ratios developed for EPA (1996). In other cases, the activity factor was held constant from 1990 through 2005 based on EPA (1999). Lastly, the previous year's data were used when data for the current year were unavailable. See Annex 3.5 for additional detail.

Nearly all emission factors were taken from EPA (1995, 1996, 1999). The remaining emission factors were taken from EPA default values in (EPA 2005) and the consensus of industry peer review panels.

Among the more important references used to obtain activity factors are the Energy Information Administration annual and monthly reports (EIA 1990 through 2005, 1990 through 2006, 1995 through 2005, 1995 through 2006), *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, MMS reports (MMS 2001, 2005a,b,d), ICF analysis of MMS (EPA 2005, MMS 2005c), the *Oil & Gas Journal* (OGJ 2005-2006) and the United States Army Corps of Engineers (1995-2004).

Uncertainty

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 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 with 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 five major sources, which account for 86 percent of the total emissions, the uncertainty surrounding these five 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 3-40. Petroleum systems CH_4 emissions in 2005 were estimated to be between 21.7 and 70.7 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 24 percent below to 148 percent above the 2005 emission estimate of 28.5 Tg CO_2 Eq.

Table 3-40: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petroleum Systems (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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
Petroleum Systems	CH_4	28.5	21.7	70.7	-24%	+148%

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

Recalculations Discussion

Two types of activity factor and activity driver revisions were made in the 2005 Petroleum Systems emissions inventory. Some revisions were due to a change in data sources referenced, while some revisions were due to updating previous years' data with revised data from existing data sources. Overall changes resulted in an annual decrease of approximately 0.14 Tg CO_2 Eq. (0.6 percent) for 2003 and 0.26 Tg CO_2 Eq. (1 percent) for 2004, relative to the previous Inventory. For other years in the time series, the emission estimates increased by less than 0.1 percent.

Planned Improvements

A key improvement being contemplated is to include fugitive, vented, and combustion CO_2 emissions sources in the Petroleum Systems inventory.

3.9. Municipal Solid Waste Combustion (IPCC Source Category 1A5)

Combustion is used to manage about 7 to 17 percent of the municipal solid wastes (MSW) 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 2000b, Goldstein and Matdes 2001, Kaufman et al. 2004a, Simmons et al. 2006). Almost all combustion of MSW in the United States occurs at waste-to-energy facilities where useful energy is recovered, and thus emissions from waste combustion are accounted for in the Energy chapter. Combustion of municipal solid wastes results in conversion of the organic inputs to CO_2. According to IPCC guidelines, when the CO_2 emitted is of fossil origin, it is counted as a net anthropogenic emission of CO_2 to the atmosphere. Thus, the emissions from waste combustion 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. Tires (which contain rubber and carbon black) are also considered a "non-hazardous" waste and are included in the municipal solid waste combustion estimate, though waste disposal practices for tires differ from the rest of municipal solid waste (viz., most combustion occurs outside of MSW combustion facilities).

Approximately 34 million metric tons of municipal solid wastes were combusted in the United States in 2005 (Simmons et al. 2006). CO_2 emissions from combustion of municipal solid wastes rose 91 percent since 1990, to an estimated 20.9 Tg CO_2 Eq. (20,912 Gg) in 2005, as the volume of plastics and other fossil C-containing materials in MSW increased (see Table 3-43 and Table 3-44). Waste combustion is also a source of N_2O emissions (De Soete 1993). N_2O emissions from municipal solid waste combustion were estimated to be 0.4 Tg CO_2 Eq. (1 Gg N_2O) in 2005, and have not changed significantly since 1990.

Methodology

Emissions of CO_2 from MSW combustion include CO_2 generated by the combustion of plastics, synthetic fibers, and synthetic rubber, as well as the combustion of synthetic rubber and carbon black in tires. These emissions were estimated by multiplying the amount of each material combusted by the C content of the material and the fraction oxidized (98 percent). Plastics combusted in MSW were categorized into seven plastic resin types, each material

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 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 Manufacture and Urea Application sections of the Inventory report, respectively.

IPCC (2006) includes, 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. If site-specific monitoring and reporting data are not available, and the carbon capture and storage system cannot, therefore, be considered in a complete and consistent manner, the assumption is that the captured CO_2 is emitted. The assumption that, in the absence of site specific data, all CO_2 injected in storage sites is emitted is opposite from the current methodology implemented by the United States. The new methodology will not affect emission estimates for CO_2 consumption for non-EOR applications.

The United States initiated data collection efforts to incorporate this new methodology for the current Inventory report. However, time was not sufficient to fully implement this guidance and the estimates are not yet included in national totals. Preliminary estimates indicate that the amount of CO_2 emitted from EOR operations and pipelines is 35.2 Tg CO_2 Eq. (35,156 Gg CO_2) (see Table 3-41). 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. The United States is initiating a process to collect the necessary data to fully implement the 2006 IPCC Guidelines methodology for this source category in subsequent Inventory reports.

Table 3-41: Emissions of CO_2 from EOR Operations and Pipelines (Tg CO_2 Eq.)

Year	1990	1995	2000	2001	2002	2003	2004	2005
Acid Gas Removal Plants	4.8	3.7	2.3	2.9	2.9	3.0	3.7	6.0
Naturally Occurring CO_2	20.8	22.7	22.7	23.0	21.9	24.3	27.1	28.5
Ammonia Production Plants	0.0	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Pipelines Transporting CO_2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**25.6**	**27.0**	**25.6**	**26.6**	**25.5**	**28.0**	**31.5**	**35.2**

Table 3-42: Emissions of CO_2 from EOR Operations and Pipelines (Gg)

Year	1990	1995	2000	2001	2002	2003	2004	2005
Acid Gas Removal Plants	4,832	3,672	2,264	2,894	2,943	2,993	3,719	5,992
Naturally Occurring CO_2	20,752	22,687	22,649	23,015	21,854	24,273	27,085	28,481
Ammonia Production Plants	0	676	676	676	676	676	676	676
Pipelines Transporting CO_2	8	8	8	8	8	8	7	7
Total	**25,592**	**27,044**	**25,598**	**26,593**	**25,482**	**27,951**	**31,489**	**35,156**

Table 3-43: CO_2 and N_2O Emissions from Municipal Solid Waste Combustion (Tg CO_2 Eq.)

Gas/Waste Product	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**10.9**	**15.7**	**17.9**	**18.3**	**18.5**	**19.5**	**20.1**	**20.9**
Plastics	8.0	10.3	12.1	12.4	12.4	13.0	13.4	13.9
Synthetic Rubber in Tires	0.2	0.8	0.9	0.9	1.0	1.0	1.1	1.2
Carbon Black in Tires	0.2	1.1	1.2	1.2	1.2	1.3	1.4	1.6
Synthetic Rubber in MSW	1.3	1.6	1.7	1.8	1.8	1.9	1.9	1.9
Synthetic Fibers	1.2	1.8	2.1	2.1	2.2	2.3	2.3	2.4
N_2O	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total	**11.4**	**16.2**	**18.3**	**18.7**	**18.9**	**19.9**	**20.5**	**21.3**

Table 3-44: CO_2 and N_2O Emissions from Municipal Solid Waste Combustion (Gg)

Gas/Waste Product	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**10,950**	**15,712**	**17,889**	**18,344**	**18,513**	**19,490**	**20,115**	**20,912**
Plastics	7,976	10,347	12,068	12,378	12,365	12,984	13,381	13,852
Synthetic Rubber in Tires	191	841	893	895	952	1,010	1,108	1,207
Carbon Black in Tires	249	1,099	1,167	1,170	1,245	1,320	1,449	1,579
Synthetic Rubber in MSW	1,334	1,596	1,678	1,762	1,767	1,862	1,875	1,899
Synthetic Fibers	1,200	1,830	2,083	2,139	2,184	2,315	2,302	2,375
N_2O	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

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 number of scrap tires used for fuel and the synthetic rubber and carbon black content of the tires.

More detail on the methodology for calculating emissions from each of these waste combustion sources is provided in Annex 3.6.

For each of the methods used to calculate CO_2 emissions from municipal solid waste combustion, 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 material in MSW and its portion combusted were taken from the *Characterization of Municipal Solid Waste in the United States* (EPA 2000b, 2002, 2003, 2005a, 2006b) and detailed unpublished backup data for some years not shown in the reports (Schneider 2007). For synthetic rubber and carbon black in scrap tires, information was obtained from *U.S. Scrap Tire Markets in the United States 2005 Edition* (RMA 2006) and *Scrap Tires, Facts and Figures* (STMC 2000, 2001, 2002, 2003, 2006).

Average C contents for the "Other" plastics category, synthetic rubber in MSW, and synthetic fibers were calculated from 1998 production statistics, which divide their respective markets by chemical compound. Information about scrap tire composition was taken from the Scrap Tire Management Council's internet site (STMC 2006).

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

Combustion of MSW also results in emissions of N_2O. These emissions were calculated as a function of the total estimated mass of MSW combusted and an emission factor. The N_2O emission estimates are based on different data sources. As noted above, N_2O emissions are a function of total waste combusted in each year; for 1990 through 2005, these data were derived from the information published in *BioCycle* (Simmons et al. 2006). Data on total waste combusted was not available for 2005, so the value for 2005 was assumed to equal the most recent value available (2004). Table 3-45 provides data on MSW generation and percentage combustion for the total waste stream. The emission factor of N_2O emissions per quantity of MSW combusted is an average of values from IPCC's *Good Practice Guidance* (2000).

Table 3-45: Municipal Solid Waste Generation (Metric Tons) and Percent Combusted

Year	Waste Generation	Combusted (%)
1990	266,365,714	11.5
1995	296,390,405	10.0
2000	371,071,109	7.0
2001	353,086,962[a]	7.4[a]
2002	335,102,816	7.7
2003	343,482,645[b]	7.6[b]
2004	351,862,474	7.4
2005	351,862,474[c]	7.4[c]

[a] Interpolated between 2000 and 2002 values.
[b] Interpolated between 2002 and 2004 values.
[c] Assumed equal to 2004 value.

Uncertainty

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 MSW combustion. 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 combustion emission estimates arise from both the assumptions applied to the data and from the quality of the data. Key factors include MSW combustion rate; fraction oxidized; missing data on MSW composition; average C content of MSW 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 3-46. Municipal solid waste combustion CO_2 emissions in 2005 were estimated to be between 15.5 and 25.0 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 26 percent below to 19 percent above the 2005 emission estimate of 20.9 Tg CO_2 Eq. Also at a 95 percent confidence level, municipal solid waste combustion N_2O emissions in 2005 were estimated to be between 0.11 and 1.02 Tg CO_2 Eq. This indicates a range of 74 percent below to 153 percent above the 2005 emission estimate of 0.40 Tg CO_2 Eq.

QA/QC and Verification

A source-specific QA/QC plan was implemented for MSW Combustion. 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 MSW combustion. 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.

Table 3-46: Tier 2 Quantitative Uncertainty Estimates for CO_2 and N_2O from Municipal Solid Waste Combustion (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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
Municipal Solid Waste Combustion	CO_2	20.9	15.5	25.0	-26%	+19%
Municipal Solid Waste Combustion	N_2O	0.4	0.1	1.0	-74%	+153%

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

Planned Improvements

EPA will investigate additional data sources for calculating an N_2O emission factor for U.S. MSW combustion.

3.10. Energy Sources of Indirect Greenhouse Gas Emissions

In addition to the main greenhouse gases addressed above, many energy-related activities generate emissions of indirect greenhouse gases. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) from energy-related activities from 1990 to 2005 are reported in Table 3-47.

Methodology

These emission estimates were obtained from preliminary data (EPA 2006), 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

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.

3.11. 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 currently 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

Table 3-47: NO_x, CO, and NMVOC Emissions from Energy-Related Activities (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
NO_x	**21,024**	**20,631**	**18,537**	**17,714**	**17,569**	**16,753**	**15,886**	**15,385**
Mobile Combustion	10,920	10,622	10,310	9,819	10,319	9,911	9,520	9,145
Stationary Combustion	9,883	9,821	8,002	7,667	6,837	6,428	5,952	5,824
Oil and Gas Activities	139	100	111	113	316	317	317	318
Municipal Solid Waste Combustion	82	88	114	114	97	98	98	98
*International Bunker Fuels**	*1,985*	*1,540*	*1,334*	*1,266*	*988*	*900*	*1,179*	*1,155*
CO	**125,759**	**104,527**	**89,835**	**86,167**	**84,369**	**81,832**	**79,435**	**77,173**
Mobile Combustion	119,480	97,755	83,680	79,972	77,382	74,756	72,269	69,915
Stationary Combustion	5,000	5,383	4,340	4,377	5,224	5,292	5,361	5,431
Municipal Solid Waste Combustion	978	1,073	1,670	1,672	1,440	1,457	1,475	1,493
Oil and Gas Activities	302	316	146	147	323	327	331	335
*International Bunker Fuels**	*115*	*113*	*124*	*120*	*118*	*112*	*124*	*122*
NMVOCs	**12,620**	**10,538**	**8,953**	**8,610**	**9,131**	**8,827**	**8,538**	**8,263**
Mobile Combustion	10,932	8,745	7,230	6,872	6,608	6,302	6,011	5,734
Stationary Combustion	912	973	1,077	1,080	1,733	1,734	1,735	1,736
Oil and Gas Activities	554	582	389	400	546	547	547	548
Municipal Solid Waste Combustion	222	237	257	258	244	244	244	245
*International Bunker Fuels**	*59*	*48*	*44*	*42*	*35*	*32*	*40*	*40*

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

Intergovernmental Negotiating Committee in establishing the Framework Convention on Climate Change.[44] These decisions are reflected in the *Revised 1996 IPCC Guidelines*, as well as the 2006 IPCC GLs, 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/UNEP/OECD/IEA 1997).[45]

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.[46] 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.[47]

Emissions of CO_2 from aircraft are essentially a function of fuel use. CH_4 and N_2O emissions also depend upon engine characteristics, flight conditions, and flight phase (i.e., take-off, climb, cruise, decent, and landing). CH_4 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., Navy), fishing, and miscellaneous support ships (e.g., tugboats). For the purpose of estimating greenhouse gas emissions, international bunker fuels are solely related to cargo and passenger carrying vessels, which is the largest of the four categories, and military vessels. Two main types of fuels are used on sea-going vessels: distillate diesel fuel and residual fuel oil. CO_2 is the primary greenhouse gas emitted from marine shipping.

Overall, aggregate greenhouse gas emissions in 2005 from the combustion of international bunker fuels from both aviation and marine activities were 98.2 Tg CO_2 Eq., or 14 percent below emissions in 1990 (see Table 3-48 and Table 3-49). Although emissions from international flights departing from the United States have increased significantly (34 percent), emissions from international shipping voyages departing the United States have decreased by 50 percent 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.

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 (2006) and USAF (1998), and heat content for jet fuel was taken from EIA (2006). A complete description of the methodology and a listing of the various factors employed can be found

---

[44] 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).

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

[46] 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).

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

Table 3-48: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (Tg CO_2 Eq.)

Gas/Mode	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**113.7**	**100.6**	**101.1**	**97.6**	**89.1**	**83.7**	**97.2**	**97.2**
Aviation	45.7	50.2	59.9	58.7	61.1	58.8	62.2	62.6
Marine	68.0	50.4	41.3	38.9	28.0	24.9	34.9	34.6
CH_4	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aviation	+	+	+	+	+	+	+	+
Marine	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**1.0**	**0.9**	**0.9**	**0.9**	**0.8**	**0.8**	**0.9**	**0.9**
Aviation	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6
Marine	0.5	0.4	0.3	0.3	0.2	0.2	0.3	0.3
Total	**114.8**	**101.6**	**102.2**	**98.6**	**90.0**	**84.5**	**98.2**	**98.2**

+ Does not exceed 0.05 Tg CO_2 Eq.

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

Table 3-49: CO_2, CH_4 and N_2O Emissions from International Bunker Fuels (Gg)

Gas/Mode	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**113,683**	**100,627**	**101,125**	**97,563**	**89,101**	**83,690**	**97,177**	**97,191**
Aviation	45,731	50,202	59,853	58,696	61,120	58,806	62,241	62,598
Marine	67,952	50,425	41,272	38,866	27,981	24,884	34,937	34,593
CH_4	**8**	**6**	**6**	**5**	**4**	**4**	**5**	**5**
Aviation	1	1	2	2	2	2	2	2
Marine	7	5	4	4	3	2	3	3
N_2O	**3**	**3**	**3**	**3**	**3**	**2**	**3**	**3**
Aviation	1	2	2	2	2	2	2	2
Marine	2	1	1	1	1	1	1	1

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

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 were collected from three government agencies. Jet fuel consumed by U.S. flag air carriers for international flight segments was supplied by the Bureau of Transportation Statistics (DOT 1991 through 2006). It was assumed that 50 percent of the fuel used by U.S. flagged carriers for international flights—both departing and arriving in the United States—was purchased domestically for flights departing from the United States. In other words, only one-half of the total annual fuel consumption estimate was used in the calculations. Data on jet fuel expenditures by foreign flagged carriers departing U.S. airports was taken from unpublished data collected by the Bureau of Economic Analysis (BEA) under the U.S. Department of Commerce (BEA 1991 through 2006). Approximate average fuel prices paid by air carriers for aircraft on international flights was taken from DOT (1991 through 2006) and used to convert the BEA expenditure data to gallons of fuel consumed. 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 2006). 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 3-50. 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 1991 through 2006). Activity data on distillate diesel consumption by military vessels departing from U.S. ports were provided by DESC (2006). 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 3-51.

Uncertainty

Emission estimates related to the consumption of international bunker fuels are subject to the same uncertainties as those from domestic aviation and marine mobile combustion emissions; however, additional uncertainties result from the difficulty in collecting accurate fuel consumption activity data for international transport activities separate from domestic transport activities.[48] 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.

Particularly for aviation, the DOT (1991 through 2006) international flight segment fuel data used for U.S. flagged carriers does not include smaller air carriers and unfortunately defines flights departing to Canada and some flights to Mexico as domestic instead of international. As

Table 3-50: Aviation Jet Fuel Consumption for International Transport (Million Gallons)

Nationality	1990		1995		2000	2001	2002	2003	2004	2005
U.S. Carriers	1,954		2,221		2,737	2,619	2,495	2,418	2,465	2,760
Foreign Carriers	2,051		2,544		3,162	3,113	3,537	3,377	3,671	3,450
U.S. Military	862		581		480	524	482	473	498	462
Total	**4,867**		**5,347**		**6,380**	**6,255**	**6,515**	**6,268**	**6,634**	**6,673**

Note: Totals may not sum due to independent rounding.

Table 3-51: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990		1995		2000	2001	2002	2003	2004	2005
Residual Fuel Oil	4,781		3,495		2,967	2,846	1,937	1,597	2,363	2,320
Distillate Diesel Fuel & Other	617		573		290	204	158	137	167	241
U.S. Military Naval Fuels	522		334		329	318	348	459	530	471
Total	**5,920**		**4,402**		**3,586**	**3,368**	**2,443**	**2,193**	**3,059**	**3,032**

Note: Totals may not sum due to independent rounding.

---

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

for the BEA (1991 through 2006) data on foreign flagged carriers, there is some uncertainty as to the average fuel price, and to the completeness of the data. It was also not possible to determine what portion of fuel purchased by foreign carriers at U.S. airports was actually used on domestic flight segments; this error, however, is believed to be small.[49]

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.[50]

There is also concern as to the reliability of the existing DOC (1991 through 2006) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

QA/QC and Verification

A source-specific QA/QC plan for international bunker fuels was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CO_2, CH_4, and N_2O from international bunker fuels in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated. No corrective actions were necessary.

---

[49] Although foreign flagged air carriers are prevented from providing domestic flight services in the United States, passengers may be collected from multiple airports before an aircraft actually departs on its international flight segment. Emissions from these earlier domestic flight segments should be classified as domestic, not international, according to the IPCC.

[50] 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.

Recalculations Discussion

Historical activity data for aviation was slightly revised for both U.S. and foreign carriers. These changes were due to revisions to international fuel cost for foreign carriers and international jet fuel consumption for U.S. carriers, provided by DOT (1991 through 2006). The density for jet fuel was also revised to reflect data obtained from Chevron (2000) and ASTM (1989). This revision increased the heat content for aviation jet fuel by 2 percent for all years. The C content coefficient was also revised from 0.99 to 1 for all fuel types based on guidance in IPCC (2006). These historical data changes resulted in changes to the emission estimates for 1990 through 2004, which averaged to an annual increase in emissions from international bunker fuels of 0.1 Tg CO_2 Eq. (0.1 percent) in CO_2 emissions, annual increase of less than 0.1 Tg CO_2 Eq. (less than 0.2 percent) in CH_4 emissions, and annual increase of less than 0.1 Tg CO_2 Eq. (0.2 percent) in N_2O emissions.

3.12. 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. However, in the long run the CO_2 emitted from biomass consumption does not increase atmospheric CO_2 concentrations, assuming that the biogenic C emitted is offset by the uptake of CO_2 that results from the growth of new biomass. As a result, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel-based emissions and are not included in the U.S. totals. Net C fluxes from changes in biogenic C reservoirs in wooded or crop lands are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

In 2005, total CO_2 emissions from the burning of woody biomass in the industrial, residential, commercial, and electricity generation sectors were approximately 184.1 Tg CO_2 Eq. (184,067 Gg) (see Table 3-52 and Table 3-53). As the largest consumer of woody biomass, the industrial sector was responsible for 63 percent of the CO_2 emissions from this source. The residential sector was the second largest emitter, constituting 24 percent of the total, while the commercial and electricity generation sectors accounted for the remainder.

Biomass-derived fuel consumption in the United States consisted primarily of ethanol use in the transportation sector. 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. These fuels burn

Table 3-52: CO_2 Emissions from Wood Consumption by End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005
Industrial	135.3	155.1	153.6	135.4	131.1	128.0	138.5	116.2
Residential	59.8	53.6	44.3	38.2	39.2	41.2	42.3	43.3
Commercial	6.8	7.5	7.4	6.9	7.1	7.4	7.3	7.2
Electricity Generation	13.3	12.9	13.9	13.0	15.5	17.3	17.0	17.3
Total	**215.2**	**229.1**	**219.1**	**193.5**	**192.8**	**193.8**	**205.1**	**184.1**

Note: Totals may not sum due to independent rounding.

Table 3-53: CO_2 Emissions from Wood Consumption by End-Use Sector (Gg)

End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005
Industrial	135,348	155,075	153,559	135,415	131,079	127,970	138,522	116,238
Residential	59,808	53,621	44,340	38,153	39,184	41,247	42,278	43,309
Commercial	6,779	7,463	7,370	6,887	7,080	7,366	7,252	7,236
Electricity Generation	13,252	12,932	13,851	13,034	15,487	17,250	17,034	17,284
Total	**215,186**	**229,091**	**219,119**	**193,489**	**192,830**	**193,833**	**205,086**	**184,067**

Note: Totals may not sum due to independent rounding.

cleaner than gasoline (i.e., lower in NO_x and hydrocarbon emissions), and have been employed in urban areas with poor air quality. However, because ethanol is a hydrocarbon fuel, its combustion emits CO_2.

In 2005, the United States consumed an estimated 3.4 trillion Btu of ethanol, and as a result, produced approximately 22.4 Tg CO_2 Eq. (22,408 Gg) (see Table 3-54) 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.

Methodology

Woody biomass emissions were estimated by applying two EIA gross heat contents (Lindstrom 2006) to U.S. consumption data (EIA 2006) (see Table 3-55), provided in energy units for the industrial, residential, commercial, and electric generation sectors. One heat content (16.953114 MMBtu/MT wood and wood waste) was applied to the industrial sector's consumption, while the other heat content (15.432359 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 EIA emission factor of 17.99 Tg C/QBtu (Lindstrom 2006) to U.S. ethanol consumption estimates that were provided in energy units (EIA 2006) (see Table 3-56).

Table 3-54: CO_2 Emissions from Ethanol Consumption (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	4.2	4,155
1995	7.7	7,683
2000	9.2	9,188
2001	9.7	9,673
2002	11.5	11,520
2003	15.8	15,770
2004	19.7	19,740
2005	22.4	22,408

Table 3-55: Woody Biomass Consumption by Sector (Trillion Btu)

Year	Industrial	Residential	Commercial	Electricity Generation
1990	1,442	580	66	129
1995	1,652	520	72	125
2000	1,636	430	71	134
2001	1,443	370	67	126
2002	1,396	380	69	150
2003	1,363	400	71	167
2004	1,476	410	70	165
2005	1,238	420	70	168

Table 3-56: Ethanol Consumption (Trillion Btu)

Year	Trillion Btu
1990	63
1995	117
2000	139
2001	147
2002	175
2003	239
2004	299
2005	340

Uncertainty

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 increase 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.

Recalculations Discussion

Commercial wood consumption values were revised for the full time series, based on updated information from EIA's Commercial Building Energy Consumption Survey (EIA 2006). EIA (2006) also reported minor changes in wood consumption by the residential and industrial sectors for the full time series, and in ethanol consumption for 2001 through 2004.

Box 3-4: Formation of CO_2 through Atmospheric CH_4 Oxidation

CH_4 emitted to the atmosphere will eventually oxidize into CO_2, which remains in the atmosphere for up to 200 years. The global warming potential (GWP) of CH_4, however, does not account for the radiative forcing effects of the CO_2 formation that results from this CH_4 oxidation. The IPCC *Guidelines for Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) do not explicitly recommend a procedure for accounting for oxidized CH_4, but some of the resulting CO_2 is, in practice, included in the inventory estimates because of the intentional "double-counting" structure for estimating CO_2 emissions from the combustion of fossil fuels. According to the IPCC Guidelines, countries should estimate emissions of CH_4, CO, and NMVOCs from fossil fuel combustion, but also assume that these compounds eventually oxidize to CO_2 in the atmosphere. This is accomplished by using CO_2 emission factors that do not factor out carbon in the fuel that is released in the form of CH_4, CO, and NMVOC molecules. Therefore, the carbon in fossil fuel is intentionally double counted, as an atom in a CH_4 molecule and as an atom in a CO_2 molecule.[51] While this approach does account for the full radiative forcing effect of fossil fuel-related greenhouse gas emissions, the timing is not accurate because it may take up to 12 years for the CH_4 to oxidize and form CO_2.

There is no similar IPCC approach to account for the oxidation of CH_4 emitted from sources other than fossil fuel combustion (e.g., landfills, livestock, and coal mining). CH_4 from biological systems contains carbon that is part of a rapidly cycling biological system, and therefore any C created from oxidized CH_4 from these sources is matched with carbon removed from the atmosphere by biological systems–likely during the same or subsequent year. Thus, there are no additional radiative forcing effects from the oxidation of CH_4 from biological systems. For example, the C content of CH_4 from enteric fermentation is derived from plant matter, which itself was created through the conversion of atmospheric CO_2 to organic compounds.

The remaining anthropogenic sources of CH_4 (e.g., fugitive emissions from coal mining and natural gas systems, industrial process emissions) do increase the long-term CO_2 burden in the atmosphere, and this effect is not captured in the Inventory. The following tables provide estimates of the equivalent CO_2 production that results from the atmospheric oxidation of CH_4 from these remaining sources. The estimates for CH_4 emissions are gathered from the respective sections of this report, and are presented in Table 3-57. The CO_2 estimates are summarized in Table 3-58.

Table 3-57: CH_4 Emissions from Non-Combustion Fossil Sources (Gg)

Source	1990	1995	2000	2001	2002	2003	2004	2005
Coal Mining	3,899	3,165	2,662	2,644	2,476	2,480	2,597	2,494
Abandoned Underground Coal Mines	286	391	349	318	292	282	275	263
Natural Gas Systems	5,927	6,101	6,027	5,971	5,951	5,891	5,669	5,292
Petroleum Systems	1,640	1,482	1,325	1,303	1,275	1,229	1,209	1,357
Petrochemical Production	41	52	58	51	52	51	55	52
Silicon Carbide Production	1	1	1	+	+	+	+	+
Iron and Steel Production	63	62	57	51	48	49	50	45
Total	**11,858**	**11,254**	**10,479**	**10,339**	**10,094**	**9,982**	**9,855**	**9,504**

Note: These emissions are accounted for under their respective source categories. Totals may not sum due to independent rounding.
+ Does not exceed 0.5 Gg

---

[51] It is assumed that 100 percent of the CH_4 emissions from combustion sources are accounted for in the overall carbon emissions calculated as CO_2 for sources using emission factors and carbon mass balances. However, it may be the case for some types of combustion sources that the oxidation factors used for calculating CO_2 emissions do not accurately account for the full mass of carbon emitted in gaseous form (i.e., partially oxidized or still in hydrocarbon form).

Box 3-4: Formation of CO_2 through Atmospheric CH_4 Oxidation (continued)

Table 3-58: Formation of CO_2 through Atmospheric CH_4 Oxidation (Tg CO_2 Eq.)

Source	1990	1995	2000	2001	2002	2003	2004	2005
Coal Mining	10.7	8.7	7.3	7.3	6.8	6.8	7.1	6.9
Abandoned Underground Coal Mines	0.8	1.1	1.0	0.9	0.8	0.8	0.8	0.7
Natural Gas Systems	16.3	16.8	16.6	16.4	16.4	16.2	15.6	14.6
Petroleum Systems	4.5	4.1	3.6	3.6	3.5	3.4	3.3	3.7
Petrochemical Production	0.1	0.1	0.2	0.1	0.1	0.1	0.2	0.1
Silicon Carbide Production	+	+	+	+	+	+	+	+
Iron and Steel Production	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Total	**32.6**	**30.9**	**28.8**	**28.4**	**27.8**	**27.4**	**27.1**	**26.1**

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

The estimates of CO_2 formation are calculated by applying a factor of 44/16, which is the ratio of molecular weight of CO_2 to the molecular weight of CH_4. For the purposes of the calculation, it is assumed that CH_4 is oxidized to CO_2 in the same year that it is emitted. As discussed above, this is a simplification, because the average atmospheric lifetime of CH_4 is approximately 12 years.

CO_2 formation can also result from the oxidation of CO and NMVOCs. However, the resulting increase of CO_2 in the atmosphere is explicitly included in the mass balance used in calculating the storage and emissions from non-energy uses of fossil fuels, with the carbon components of CO and NMVOC counted as CO_2 emissions in the mass balance.[52]

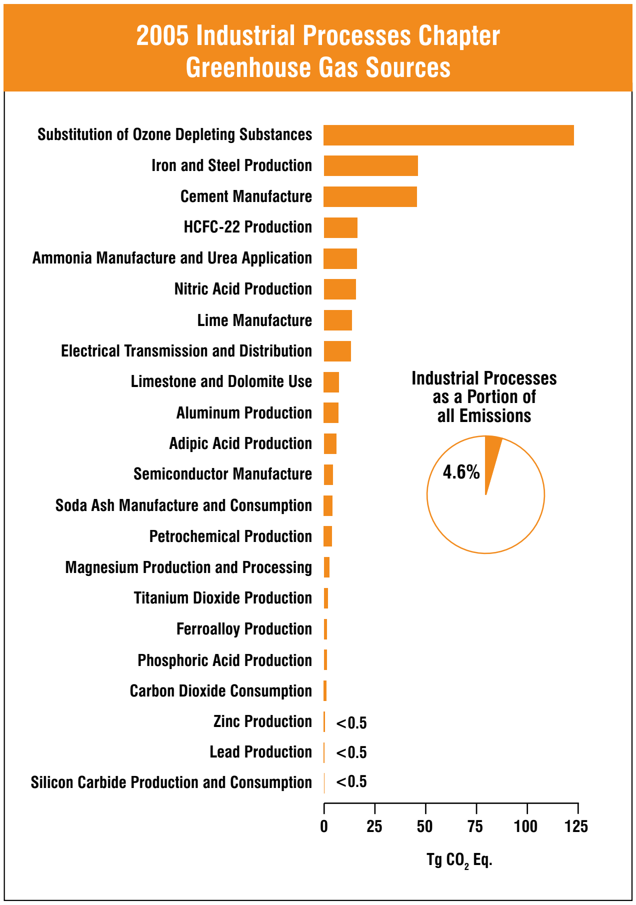
---

[52] See Annex 2.3 for a more detailed discussion on accounting for indirect emissions from CO and NMVOCs.

4. Industrial Processes

Greenhouse gas emissions are produced as a by-product 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), or nitrous oxide (N_2O). The processes addressed in this chapter include iron and steel production, cement manufacture, ammonia manufacture and urea application, lime manufacture, limestone and dolomite use (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash manufacture and use, titanium dioxide production, phosphoric acid production, ferroalloy production, CO_2 consumption, aluminum production, petrochemical production, silicon carbide production and consumption, lead production, zinc production, nitric acid production, and adipic acid production (see Figure 4-1).

Figure 4-1



2005 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 for the substitution of ozone depleting substances is growing rapidly, as 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, 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.

In 2005, industrial processes generated emissions of 333.6 teragrams of CO_2 equivalent (Tg CO_2 Eq.), or 5 percent of total U.S. greenhouse gas emissions. CO_2 emissions from all industrial processes were 146.8 Tg CO_2 Eq. (146,825 gigagrams [Gg]) in 2005, or 2 percent of total U.S. CO_2 emissions. CH_4 emissions from industrial processes resulted in emissions of approximately 2.0 Tg CO_2 Eq. (97 Gg) in 2005, which was less than 1 percent of U.S. CH_4 emissions. N_2O emissions from adipic acid and nitric acid production were 21.7 Tg CO_2 Eq. (70 Gg) in 2005, or 5 percent of total U.S. N_2O emissions. In 2005, combined emissions of HFCs, PFCs and SF_6 totaled 163.0 Tg CO_2 Eq. Overall, emissions from industrial processes increased by 11.2 percent from 1990 to 2005 despite decreases in emissions from several industrial processes, such as iron and steel, aluminum production, ammonia manufacture and urea application, HCFC-22 production, and electrical transmission and distribution. The increase in overall emissions was driven by a rise in the emissions originating from cement manufacture and, primarily, the emissions from the use of substitutes for ozone depleting substances.

Table 4-1 summarizes emissions for the Industrial Processes chapter in units of Tg CO_2 Eq., while unweighted native gas emissions in Gg are provided in Table 4-2.

In order to ensure the quality of the emission estimates from industrial processes, Tier 1 quality assurance and quality control (QA/QC) procedures and checks have been performed on all industrial process sources. Where

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

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**175.5**	**171.8**	**166.8**	**152.8**	**152.0**	**148.8**	**152.8**	**146.8**
Cement Manufacture	33.3	36.8	41.2	41.4	42.9	43.1	45.6	45.9
Iron and Steel Production	84.9	73.3	65.1	57.9	54.6	53.4	51.3	45.2
Ammonia Manufacture & Urea Application	19.3	20.5	19.6	16.7	17.8	16.2	16.9	16.3
Lime Manufacture	11.3	12.8	13.3	12.9	12.3	13.0	13.7	13.7
Limestone and Dolomite Use	5.5	7.4	6.0	5.7	5.9	4.7	6.7	7.4
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.1	4.1	4.1	4.2	4.2
Aluminum Production	6.8	5.7	6.1	4.4	4.5	4.5	4.2	4.2
Petrochemical Production	2.2	2.8	3.0	2.8	2.9	2.8	2.9	2.9
Titanium Dioxide Production	1.3	1.7	1.9	1.9	2.0	2.0	2.3	1.9
Ferroalloy Production	2.2	2.0	1.9	1.5	1.3	1.3	1.4	1.4
Phosphoric Acid Production	1.5	1.5	1.4	1.3	1.3	1.4	1.4	1.4
CO_2 Consumption	1.4	1.4	1.4	0.8	1.0	1.3	1.2	1.3
Zinc Production	0.9	1.0	1.1	1.0	0.9	0.5	0.5	0.5
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Production and Consumption	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2
CH_4	**2.2**	**2.4**	**2.5**	**2.2**	**2.1**	**2.1**	**2.2**	**2.0**
Petrochemical Production	0.9	1.1	1.2	1.1	1.1	1.1	1.2	1.1
Iron and Steel Production	1.3	1.3	1.2	1.1	1.0	1.0	1.0	1.0
Ferroalloy Production	+	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+	+
N_2O	**33.0**	**37.1**	**25.6**	**20.8**	**23.1**	**22.9**	**21.8**	**21.7**
Nitric Acid Production	17.8	19.9	19.6	15.9	17.2	16.7	16.0	15.7
Adipic Acid Production	15.2	17.2	6.0	4.9	5.9	6.2	5.7	6.0
HFCs, PFCs, and SF_6	**89.3**	**103.5**	**143.8**	**133.8**	**143.0**	**142.7**	**153.9**	**163.0**
Substitution of Ozone Depleting Substances	0.3	32.2	80.9	88.6	96.9	105.5	114.5	123.3
HCFC-22 Production[a]	35.0	27.0	29.8	19.8	19.8	12.3	15.6	16.5
Electrical Transmission and Distribution[b]	27.1	21.8	15.2	15.1	14.3	13.8	13.6	13.2
Semiconductor Manufacture	2.9	5.0	6.3	4.5	4.4	4.3	4.7	4.3
Aluminum Production	18.5	11.8	8.6	3.5	5.2	3.8	2.8	3.0
Magnesium Production and Processing[b]	5.4	5.6	3.0	2.4	2.4	2.9	2.6	2.7
Total	**300.1**	**314.8**	**338.7**	**309.6**	**320.2**	**316.4**	**330.6**	**333.6**

\+ Does not exceed 0.05 Tg CO_2 Eq.

[a] HFC-23 emitted

[b] SF_6 emitted

Note: Totals may not sum due to independent rounding.

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

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**175,500**	**171,832**	**166,805**	**152,794**	**152,032**	**148,767**	**152,798**	**146,825**
Cement Manufacture	33,278	36,847	41,190	41,357	42,898	43,082	45,603	45,910
Iron and Steel Production	84,904	73,333	65,115	57,927	54,595	53,370	51,309	45,235
Ammonia Manufacture & Urea Application	19,306	20,453	19,616	16,719	17,766	16,173	16,894	16,321
Lime Manufacture	11,273	12,844	13,344	12,861	12,330	13,022	13,728	13,660
Limestone and Dolomite Use	5,533	7,359	5,960	5,733	5,885	4,720	6,702	7,397
Soda Ash Manufacture and Consumption	4,141	4,304	4,181	4,147	4,139	4,111	4,205	4,228
Aluminum Production	6,831	5,659	6,086	4,381	4,490	4,503	4,231	4,208
Petrochemical Production	2,221	2,750	3,004	2,787	2,857	2,777	2,895	2,897
Titanium Dioxide Production	1,308	1,670	1,918	1,857	1,997	2,013	2,259	1,921
Ferroalloy Production	2,152	2,036	1,893	1,459	1,349	1,305	1,419	1,392
Phosphoric Acid Production	1,529	1,513	1,382	1,264	1,338	1,382	1,395	1,383
CO_2 Consumption	1,415	1,423	1,416	825	978	1,310	1,199	1,324
Zinc Production	949	1,013	1,140	986	937	507	477	465
Lead Production	285	298	311	293	290	289	259	265
Silicon Carbide Production and Consumption	375	329	248	199	183	202	224	219
CH_4	**106**	**116**	**117**	**103**	**101**	**101**	**106**	**97**
Petrochemical Production	41	52	58	51	52	51	55	51
Iron and Steel Production	63	62	57	51	48	49	50	45
Ferroalloy Production	1	1	1	+	+	+	+	+
Silicon Carbide Production and Consumption	1	1	1	+	+	+	+	+
N_2O	**107**	**120**	**83**	**67**	**75**	**74**	**70**	**70**
Nitric Acid Production	58	64	63	51	56	54	52	51
Adipic Acid Production	49	56	19	16	19	20	19	19
HFCs, PFCs, and SF_6	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M	M
HCFC-22 Production[a]	3	2	3	2	2	1	1	1
Electrical Transmission and Distribution[b]	1	1	1	1	1	1	1	1
Semiconductor Manufacture	M	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M	M
Magnesium Production and Processing[b]	+	+	+	+	+	+	+	+
NO_x	**591**	**607**	**626**	**656**	**532**	**533**	**534**	**535**
CO	**4,125**	**3,959**	**2,217**	**2,339**	**1,710**	**1,730**	**1,751**	**1,772**
NMVOCs	**2,422**	**2,642**	**1,773**	**1,769**	**1,811**	**1,813**	**1,815**	**1,818**

+ Does not exceed 0.5 Gg

M (Mixture of gases)

[a] HFC-23 emitted

[b] SF_6 emitted

Note: Totals may not sum due to independent rounding.

performed, Tier 2 procedures focused on the emission factor and activity data sources and methodology used for estimating emissions, and will be described within the QA/QC and Verification Discussion of that source description. In addition to the national QA/QC plan, a more detailed plan was developed specifically for the CO_2 and CH_4 industrial processes sources. This plan was based on the U.S. strategy, but was tailored to include specific procedures recommended for these sources.

The general method employed to estimate emissions for industrial processes, as recommended by the IPCC, involves multiplying production data (or activity data) for each process by an emission factor per unit of production. The uncertainty in the emission estimates is therefore generally a function of a combination of the uncertainties surrounding the production and emission factor variables. Uncertainty of activity data and the associated probability density functions for industrial processes CO_2 sources were estimated based on expert assessment of available qualitative and quantitative information. Uncertainty estimates and probability density functions for the emission factors used to calculate emissions from this source were devised based on IPCC recommendations.

Activity data is obtained through a survey of manufacturers conducted by various organizations (specified within each source); the uncertainty of the activity data is a function of the reliability of plant-level production data and is influenced by the completeness of the survey response. The emission factors used were either derived using calculations that assume precise and efficient chemical reactions, or were based upon empirical data in published references. As a result, uncertainties in the emission coefficients can be attributed to, among other things, inefficiencies in the chemical reactions associated with each production process or to the use of empirically-derived emission factors that are biased; therefore, they may not represent U.S. national averages. Additional assumptions are described within each source.

The uncertainty analysis performed to quantify uncertainties associated with the 2005 inventory estimates from industrial processes continues a multi-year process for developing credible quantitative uncertainty estimates for these source categories using the IPCC Tier 2 approach. As the process continues, the type and the characteristics of the actual probability density functions underlying the input variables are identified and better characterized (resulting in development of more reliable inputs for the model, including accurate characterization of correlation between variables), based primarily on expert judgment. Accordingly, the quantitative uncertainty estimates reported in this section should be considered illustrative and as iterations of ongoing efforts to produce accurate uncertainty estimates. The correlation among data used for estimating emissions for different sources can influence the uncertainty analysis of each individual source. While the uncertainty analysis recognizes very significant connections among sources, a more comprehensive approach that accounts for all linkages will be identified as the uncertainty analysis moves forward.

4.1. Cement Manufacture (IPCC Source Category 2A1)

Cement manufacture 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.[1] Cement production, at the most recent estimation, accounted for about 2.4 percent of total global industrial and energy-related CO_2 emissions (IPCC 1996, USGS 2003). Cement is manufactured in 37 states and Puerto Rico. CO_2 emitted from the chemical process of cement production is the largest source of industrial CO_2 emissions in the United States.

During the cement production process, calcium carbonate ($CaCO_3$) is heated in a cement kiln at a temperature of about 1,300 °C (2,400 °F) to form lime (i.e., calcium oxide or CaO) and CO_2 in a process known as calcination or calcining. A very small amount of carbonates other than $CaCO_3$ is also present in the raw material; however, for calculation purposes all of the raw material is assumed to be $CaCO_3$. Next, the lime is combined with silica-containing materials to produce clinker (an intermediate product), with the earlier by-product CO_2 being released to the atmosphere. The clinker is then allowed to cool, mixed with a small amount of gypsum, and used to make portland cement. Additional CO_2 emissions result from the production of masonry cement, which accounts for approximately 6 percent of total clinker production, and is produced using lime and portland cement. However, this additional lime is already accounted for in the Lime Manufacture source category in this chapter; therefore, the additional emissions from making masonry cement from clinker are not counted in this source category's total. They are presented here for informational purposes only.

---

[1] 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.

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
1995	36.8	36,847
2000	41.2	41,190
2001	41.4	41,357
2002	42.9	42,898
2003	43.1	43,082
2004	45.6	45,603
2005	45.9	45,910

* Totals exclude CO_2 emissions from making masonry cement from clinker, which are accounted for under Lime Manufacture.

In 2005, U.S. clinker production—including Puerto Rico—totaled 88,783 thousand metric tons (Van Oss 2006). The resulting emissions of CO_2 from 2005 cement production were estimated to be 45.9 Tg CO_2 Eq. (45,910 Gg) (see Table 4-3). Emissions from masonry production from clinker raw material are accounted for under Lime Manufacture.

After falling in 1991 by two percent from 1990 levels, cement production emissions have grown every year since. Overall, from 1990 to 2005, emissions increased by 38 percent. Cement continues to be a critical component of the construction industry; therefore, the availability of public construction funding, as well as overall economic growth, have had considerable influence on cement production.

Methodology

CO_2 emissions from cement manufacture are created by the chemical reaction of carbon-containing minerals (i.e., calcining limestone). 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 64.6 percent (IPCC 2000) and a constant reflecting the mass of CO_2 released per unit of lime. This calculation yields an emission factor of 0.507 tons of CO_2 per ton of clinker produced, which was determined as follows:

$$EF_{\text{Clinker}} = 0.646\ \text{CaO} \times \left[\frac{44.01\ \text{g/mole}\ CO_2}{56.08\ \text{g/mole CaO}}\right]$$

$$= 0.507\ \text{tons}\ CO_2/\text{ton clinker}$$

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. Total cement production emissions were calculated by adding the emissions from clinker production to the emissions assigned to CKD (IPCC 2000).

Masonry cement requires additional lime over and above the lime used in clinker production. In particular, non-plasticizer additives such as lime, slag, and shale are added to the cement, increasing its weight by approximately five percent. Lime accounts for approximately 60 percent of this added weight. Thus, the additional lime is equivalent to roughly 2.86 percent of the starting amount of the product, since:

$$0.6 \times 0.05/(1 + 0.05) = 2.86\%$$

An emission factor for this added lime can then be calculated by multiplying this 2.86 percent by the molecular weight ratio of CO_2 to CaO (0.785) to yield 0.0224 metric tons of additional CO_2 emitted for every metric ton of masonry cement produced.

As previously mentioned, the CO_2 emissions from the additional lime added during masonry cement production are accounted for in the section on CO_2 emissions from Lime Manufacture. Thus, the activity data for masonry cement production are shown in this chapter for informational purposes only, and are not included in the cement emission totals.

The 1990 through 2005 activity data for clinker and masonry cement production (see Table 4-4) were obtained through a personal communication with Hendrick Van Oss (Van Oss 2006) of the USGS and through the USGS *Mineral Yearbook: Cement* (USGS 1993 through 2005). The data were compiled by USGS through questionnaires sent to domestic clinker and cement manufacturing plants.

Table 4-4: Cement Production (Gg)

Year	Clinker	Masonry
1990	64,355	3,209
1995	71,257	3,603
2000	79,656	4,332
2001	79,979	4,450
2002	82,959	4,449
2003	83,315	4,737
2004	88,190	5,000
2005	88,783	5,514

Uncertainty

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker and in the percentage of CKD recycled inside the clinker kiln. Uncertainty is also associated with the amount of lime added to masonry cement, but it is accounted for under the Lime Manufacture source category. The lime content of clinker varies from 64 to 66 percent. 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. Cement Manufacture CO_2 emissions were estimated to be between 40.1 and 52.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below and 14 percent above the emission estimate of 45.9 Tg CO_2 Eq.

Recalculations Discussion

The historical activity data used to calculate the emissions from cement production were updated for the year 2004. The change resulted in a decrease of 0.04 Tg CO_2 Eq. (less than one percent) in CO_2 emissions from cement production for that year.

4.2. Iron and Steel Production (IPCC Source Category 2C1)

In addition to being an energy intensive process, the production of iron and steel also generates process-related emissions of CO_2 and CH_4. Iron is produced by first reducing iron oxide (iron ore) with metallurgical coke in a blast furnace to produce pig iron (impure iron containing about 3 to 5 percent C by weight). Metallurgical coke is manufactured using coking coal as a raw material. Iron may be introduced into the blast furnace in the form of raw iron ore, pellets, briquettes, or sinter. Pig iron is used as a raw material in the production of steel, which contains about 4 percent C by weight. Pig iron is also used as a raw material in the production of iron products in foundries. The pig iron production process produces CO_2 emissions and fugitive CH_4 emissions.

The production of metallurgical coke from coking coal and the consumption of the metallurgical coke used as a reducing agent in the blast furnace are considered in the Inventory to be non-energy (industrial) processes, not energy (combustion) processes. 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. Coke oven gas and coal tar are C-containing by-products of the coke manufacturing process. Coke oven gas is

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

Source	Gas	2005 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 Manufacture	CO_2	45.9	40.1	52.1	-13%	+14%

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

generally burned as a fuel within the steel mill. Coal tar is used as a raw material to produce anodes used for primary aluminum production and other electrolytic processes, and also in the production of other coal tar products. The coke production process produces CO_2 emissions and fugitive CH_4 emissions.

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 prior to being charged into the blast furnace. The sintering process produces CO_2 emissions and fugitive CH_4 emissions.

The metallurgical coke is a reducing agent in the blast furnace. CO_2 is produced as the metallurgical coke used in the blast furnace process is oxidized and the iron ore is reduced. Steel is produced from pig iron in a variety of specialized steel-making furnaces. The majority of CO_2 emissions from the iron and steel process come from the use of coke in the production of pig iron, with smaller amounts evolving from the removal of C from pig iron used to produce steel. Some C is also stored in the finished iron and steel products.

Emissions of CO_2 and CH_4 from iron and steel production in 2005 were 45.2 Tg CO_2 Eq. (45,235 Gg) and 1.0 Tg CO_2 Eq. (45 Gg), respectively (see Table 4-6 and Table 4-7), totaling 46.2 Tg CO_2 Eq. Emissions have declined steadily from 1990 to 2005 due to restructuring of the industry, technological improvements, and increased scrap utilization. In 2005, domestic production of pig iron decreased by 12.0 percent and coal coke production decreased by 1.1 percent. Overall, domestic pig iron and coke production have declined since the 1990s. Pig iron production in 2005 was 21 percent lower than in 2000 and 24 percent below 1990 levels. Coke production in 2005 was 20 percent lower than in 2000 and 39 percent below 1990 levels. Overall, emissions from iron and steel productions have declined by 47 percent (40.0 Tg CO_2 Eq.) from 1990 to 2005.

Methodology

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). The total coking coal converted to coke in coke plants and the total amount of coke produced were identified. These data were used to estimate the emissions associated with producing coke from coking coal and attributed to the production of iron and steel. Additionally, the amount of coke consumed to produce pig iron and the emissions associated with this production were estimated. The C content of the coking coal and coke consumed in these processes were estimated by multiplying the energy consumption by material specific C-content coefficients. The C content coefficients used are presented in Annex 2.1.

Emissions from the re-use of scrap steel were also estimated by assuming that all the associated C content of the scrap steel, which has an associated C content of approximately 0.5 percent, are released during the scrap re-use process.

Lastly, emissions from C anodes, used during the production of steel in electric arc furnaces (EAFs), were also

Table 4-6: CO_2 and CH_4 Emissions from Iron and Steel Production (Tg CO_2 Eq.)

Gas	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	84.9	73.3	65.1	57.9	54.6	53.4	51.3	45.2
CH_4	1.3	1.3	1.2	1.1	1.0	1.0	1.0	1.0
Total	**86.2**	**74.6**	**66.3**	**59.0**	**55.6**	**54.4**	**52.3**	**46.2**

Table 4-7: CO_2 and CH_4 Emissions from Iron and Steel Production (Gg)

Gas	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	84,904	73,333	65,115	57,927	54,595	53,370	51,309	45,235
CH_4	63	62	57	51	48	49	50	45

estimated. Emissions of CO_2 were calculated by multiplying the annual production of steel in EAFs by an emission factor (4.4 kg CO_2/ton $steel_{EAF}$). It was assumed that the C anodes used in the production of steel in EAFs are composed of 80 percent petroleum coke and 20 percent coal tar pitch (DOE 1997). Since coal tar pitch is a by-product of the coke production process and its C-related emissions have already been accounted for earlier in the iron and steel emissions calculation as part of the process, the emissions were reduced by the amount of C in the coal tar pitch used in the anodes to avoid double counting.

Emissions associated with the production of coke from coking coal, pig iron production, the re-use of scrap steel, and the consumption of C anodes during the production of steel were summed.

Additionally, the coal tar pitch component of C anodes consumed during the production of aluminum is accounted for in the aluminum production section of this chapter. The emissions were reduced by the amount of coal tar pitch used in aluminum production to avoid double counting. The amount of coal tar pitch consumed for processes other than the aluminum production and as EAF anodes and net imports of coal tar were also estimated. A storage factor was applied to estimate emissions associated with other coal tar pitch consumption and net imports.

C storage was accounted for by assuming that all domestically manufactured steel had a C content of 0.5 percent. Furthermore, any pig iron that was not consumed during steel production, but fabricated into finished iron products, was assumed to have a C content of 4 percent.

The potential CO_2 emissions associated with C contained in pig iron used for purposes other than iron and steel production, stored in the steel product, stored as coal tar, and attributed to C anode consumption during aluminum production were summed and subtracted from the total emissions estimated above.

The production processes for coal coke, 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 emission factors taken from the 1995 IPCC Guidelines (IPCC/UNEP/OECD/IEA 1995) (see Table 4-8) to annual domestic production data for coal coke, sinter, and pig iron.

Table 4-8: CH_4 Emission Factors for Coal Coke, Sinter, and Pig Iron Production (g/kg)

Material Produced	g CH_4/kg produced
Coal Coke	0.5
Pig Iron	0.9
Sinter	0.5

Source: IPCC/UNEP/OECD/IEA 1997.

Data relating to the amount of coal consumed at coke plants, and for the production of coke for domestic consumption in blast furnaces, were taken from the Energy Information Administration (EIA), Quarterly Coal Report October through December (EIA 1998, 1999, 2000, 2001, 2002, 2003, 2004a) and January through March (EIA 2006c). Data on total coke consumed for pig iron production were taken from the American Iron and Steel Institute (AISI), *Annual Statistical Report* (AISI 2001, 2002, 2003, 2004, 2005, 2006). Scrap steel consumption data for 1990 through 2005 were obtained from *Annual Statistical Report* (AISI 1995, 2001, 2002, 2003, 2004, 2005, 2006) (see Table 4-9). Crude steel production, as well as pig iron use for purposes other than steel production, was also obtained from *Annual Statistical Report* (AISI 1996, 2001, 2002, 2004, 2005, 2006). C content percentages for pig iron and crude steel and the CO_2 emission factor for C anode emissions from steel production were obtained from IPCC *Good Practice Guidance* (IPCC 2000). Data on the non-energy use of coking coal were obtained from EIA's *Emissions of U.S. Greenhouse Gases in the United States* (EIA 2004b, 2006b). Information on coal tar net imports was determined using data from the U.S. Bureau of the Census's U.S. International Trade Commission's Trade Dataweb (U.S. Bureau of the Census 2006). Coal tar consumption for aluminum production data was estimated based on information gathered by EPA's Voluntary Aluminum Industrial Partnership (VAIP) program and data from USAA Primary Aluminum Statistics (USAA 2004, 2005, 2006) (see Aluminum Production in this chapter). Annual consumption of iron ore used in sinter production for 1990 through 2004 was obtained from the USGS *Iron Ore Yearbook* (USGS 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004) and for 2005 from the USGS Commodity Specialist (Jorgenson 2006). The CO_2 emission factor for C anode emissions from aluminum production was taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Estimates for the composition of

Table 4-9: Production and Consumption Data for the Calculation of CO_2 and CH_4 Emissions from Iron and Steel Production (Thousand Metric Tons)

Gas/Activity Data	1990	1995	2000	2001	2002	2003	2004	2005
CO_2								
Coal Consumption at Coke Plants	35,269	29,948	26,254	23,655	21,461	21,998	21,473	21,259
Coke Consumption for Pig Iron	25,043	22,288	19,307	17,236	15,959	15,482	15,068	13,848
Basic Oxygen Furnace Steel Production	56,216	56,721	53,965	47,359	45,463	45,874	47,714	42,705
Electric Arc Furnace Steel Production	33,510	38,472	47,860	42,774	46,125	47,804	51,969	52,194
CH_4								
Coke Production	25,054	21,545	18,877	17,191	15,221	15,579	15,340	15,167
Iron Ore Consumption for Sinter	12,239	12,575	10,784	9,234	9,018	8,984	8,047	8,313
Domestic Pig Iron Production for Steel	49,062	50,233	47,400	41,741	39,601	40,487	42,292	37,222

C anodes used during EAF steel and aluminum production were obtained from *Energy and Environmental Profile of the U.S. Aluminum Industry* (DOE 1997).

Uncertainty

The time series data sources for production of coal coke, sinter, pig iron, steel, and aluminum upon which the calculations are based are assumed to be consistent for the entire time series. The estimates of CO_2 emissions from the production and utilization of coke are based on consumption data, average C contents, and the fraction of C oxidized. Uncertainty is associated with the total U.S. coke consumption and coke consumed for pig iron production. These data are provided by different data sources (EIA and AISI) and comparisons between the two datasets for net imports, production, and consumption identified discrepancies; however, the data chosen are considered the best available. These data and factors produce a relatively accurate estimate of CO_2 emissions. However, there are uncertainties associated with each of these factors. For example, C oxidation factors may vary depending on inefficiencies in the combustion process, where varying degrees of ash or soot can remain unoxidized.

Simplifying assumptions were made concerning the composition of C anodes and the C contents of all pig iron and crude steel. It was also assumed that all coal tar used during anode production originates as a by-product of the domestic coking process. There is also uncertainty associated with the total amount of coal tar products produced and with the storage factor for coal tar. Uncertainty surrounding the CO_2 emission factor for C anode consumption in aluminum production was also estimated.

For the purposes of the CH_4 calculation it is assumed that none of the CH_4 is captured in stacks or vents and that all of the CH_4 escapes as fugitive emissions. 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 4-10. Iron and Steel CO_2 emissions were estimated to be between 40.4 and 57.2 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 11 percent below and 27 percent above the emission estimate of 45.2 Tg CO_2 Eq. Iron and Steel CH_4 emissions were estimated to be between 0.9 Tg CO_2 Eq.

Table 4-10: Tier 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Iron and Steel Production (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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
Iron and Steel Production	CO_2	45.2	40.4	57.2	-11%	+27%
Iron and Steel Production	CH_4	1.0	0.9	1.0	-8%	+8%

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

and 1.0 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below and 8 percent above the emission estimate of 1.0 Tg CO_2 Eq.

Recalculations Discussion

CO_2 emission estimates for the iron and steel source category were updated for the entire time series to reflect revisions to the coal tar import/export data and the C content of steel. These revisions resulted in a change in emissions of less than one percent throughout the time series.

Planned Improvements

Plans for improvements to the iron and steel source category are to include methodologies outlined in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). These methodologies involve the inclusion of energy-related emissions in the iron and steel emission estimates as well as emissions associated with metallurgical coke production, sinter production, pellet production, and direct reduced iron ore production in addition to iron and steel production.

4.3. Ammonia Manufacture and Urea Application (IPCC Source Category 2B1)

Emissions of CO_2 occur during the production of synthetic ammonia, primarily through the use of natural gas 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 nitrogen production plant located in Kansas is producing ammonia from petroleum coke feedstock. In some plants the CO_2 produced is captured and used to produce urea. 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. 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. CO_2 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.

The conversion process for conventional steam reforming of CH_4, including 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 in the production of ammonia is emitted directly to the atmosphere. Both ammonia and CO_2 are used as raw materials in the production of urea [$CO(NH_2)_2$], which is another type of nitrogenous fertilizer that contains C as well as N. The chemical reaction that produces urea is:

$$2\ NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

The C in the urea that is produced and assumed to be subsequently applied to agricultural land as a nitrogenous fertilizer is ultimately released into the environment as CO_2; therefore, the CO_2 produced by ammonia production and subsequently used in the production of urea does not change overall CO_2 emissions. However, the CO_2 emissions are allocated to the ammonia and urea production processes according to the amount of ammonia and urea produced.

Net emissions of CO_2 from ammonia manufacture in 2005 were 9.2 Tg CO_2 Eq. (9,197 Gg), and are summarized in Table 4-11 and Table 4-12. Emissions of CO_2 from urea application in 2005 totaled 7.1 Tg CO_2 Eq. (7,124 Gg), and are summarized in Table 4-11 and Table 4-12.

Table 4-11: CO_2 Emissions from Ammonia Manufacture and Urea Application (Tg CO_2 Eq.)

Source	1990	1995	2000	2001	2002	2003	2004	2005
Ammonia Manufacture	12.6	13.5	12.1	9.3	10.5	8.8	9.6	9.2
Urea Application	6.8	6.9	7.5	7.4	7.3	7.4	7.3	7.1
Total	**19.3**	**20.5**	**19.6**	**16.7**	**17.8**	**16.2**	**16.9**	**16.3**

Note: Totals may not sum due to independent rounding.

Table 4-12: CO_2 Emissions from Ammonia Manufacture and Urea Application (Gg)

Source	1990	1995	2000	2001	2002	2003	2004	2005
Ammonia Manufacture	12,553	13,546	12,128	9,321	10,501	8,815	9,571	9,197
Urea Application	6,753	6,907	7,488	7,398	7,266	7,358	7,323	7,124
Total	**19,306**	**20,453**	**19,616**	**16,719**	**17,766**	**16,173**	**16,894**	**16,321**

Note: Totals may not sum due to independent rounding.

Methodology

The calculation methodology for non-combustion CO_2 emissions from production of nitrogenous fertilizers from natural gas feedstock is based on a CO_2 emission factor published by the European Fertilizer Manufacturers Association (EFMA). 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 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. For each ton of urea produced, 8.8 of every 12 tons of CO_2 are consumed and 6.8 of every 12 tons of ammonia are consumed. The CO_2 emissions reported for ammonia production are therefore reduced by a factor of 0.73 multiplied by total annual domestic urea production, and that amount of CO_2 emissions is allocated to urea fertilizer application. Total CO_2 emissions resulting from nitrogenous fertilizer production do not change as a result of this calculation, but some of the CO_2 emissions are attributed to ammonia production and some of the CO_2 emissions are attributed to urea application.

The calculation of the total non-combustion CO_2 emissions from nitrogenous fertilizers accounts for CO_2 emissions from the application of imported and domestically produced urea. For each ton of imported urea applied, 0.73 tons of CO_2 are emitted to the atmosphere. The amount of imported urea applied is calculated based on the net of urea imports and exports.

All 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 (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 tons 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 tons CO_2/metric ton NH_3, with 1.2 metric tons CO_2/metric ton NH_3 as a typical value. 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 tons 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). Ammonia and urea production data (see Table 4-13) were obtained from Coffeyville Resources (Coffeyville 2005, 2006) and the Census Bureau of the U.S. Department of

Table 4-13: Ammonia Production, Urea Production, and Urea Net Imports (Gg)

Year	Ammonia Production	Urea Production	Urea Net Imports
1990	15,425	8,124	1,086
1995	15,788	7,363	2,055
2000	14,342	6,969	3,241
2001	11,092	6,080	4,008
2002	12,577	7,038	2,870
2003	10,279	5,783	4,250
2004	10,939	5,755	4,230
2005	10,143	5,268	4,447

Commerce (U.S. Census Bureau 1991, 1992, 1993, 1994, 1998, 1999, 2000, 2001a, 2001b, 2002a, 2002b, 2002c, 2003, 2004, 2005, 2006) as reported in *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports. Import and export 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 2005 (U.S. Census Bureau 1998, 1999, 2000, 2001a, 2001b, 2002a, 2002b, 2002c, 2003, 2004, 2005, 2006), 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 4-13).

Uncertainty

The uncertainties presented in this section are primarily due to how accurately the emission factor used represents an average across all ammonia plants using natural gas feedstock. 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; and the assumption that 100 percent of the urea production and net imports are used as fertilizer or in otherwise emissive uses. It is also assumed that ammonia and urea are produced at collocated plants from the same natural gas raw material.

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 4-14. Ammonia Manufacture and Urea Application CO_2 emissions were estimated to be between 15.0 and 17.6 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below and 8 percent above the emission estimate of 16.3 Tg CO_2 Eq.

Recalculations Discussion

Estimates of CO_2 emissions from ammonia manufacture and urea application for the years 2002 and 2003 were revised to reflect updated data from the U.S. Census Bureau Current Industrial Report. These changes resulted in a decrease in CO_2 emissions from urea manufacture of 0.7 Tg CO_2 Eq. (10 percent) for 2002 and an increase of 0.9 Tg CO_2 Eq. (13 percent) for 2003.

Planned Improvements

Plans for improvements to the ammonia-manufacture and urea-application source category include updating emission factors to include both fuel and feedstock CO_2 emissions, incorporating CO_2 capture and storage, and attributing urea application to the Agriculture sector. Methodologies will

Table 4-14: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Manufacture and Urea Application (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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 Manufacture and Urea Application	CO_2	16.3	15.0	17.6	-8%	+8%

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

also be updated if additional ammonia-production plants are found to use hydrocarbons other than natural gas for ammonia production.

4.4. Lime Manufacture (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 (FGD) systems at coal-fired electric power plants, construction, and water purification. Lime has historically ranked fifth in total production of all chemicals in the United States. 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. CO_2 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)[2] production. It is also important to note that, for certain applications, lime reabsorbs CO_2 during use (see Uncertainty, below).

Lime production in the United States—including Puerto Rico—was reported to be 19,984 thousand metric tons in 2005 (USGS 2006). This resulted in estimated CO_2 emissions of 13.7 Tg CO_2 Eq. (or 13,660 Gg) (see Table 4-15 and Table 4-16).

The contemporary lime market is distributed across five end-use categories as follows: metallurgical uses, 36 percent; environmental uses, 28 percent; chemical and industrial uses, 21 percent; construction uses, 14 percent; and refractory dolomite, 1 percent. In the construction sector, hydrated lime is still used to improve durability in plaster, stucco, and mortars. In 2005, the amount of hydrated lime used for traditional building increased slightly from 2004 levels to 493 metric tons (USGS 2006).

Table 4-15: Net CO_2 Emissions from Lime Manufacture (Tg CO_2 Eq.)

Year	Tg CO_2 Eq.
1990	11.3
1995	12.8
2000	13.3
2001	12.9
2002	12.3
2003	13.0
2004	13.7
2005	13.7

Table 4-16: CO_2 Emissions from Lime Manufacture (Gg)

Year	Potential	Recovered*	Net Emissions
1990	11,766	(493)	11,273
1995	13,741	(896)	12,844
2000	14,577	(1,233)	13,344
2001	13,978	(1,118)	12,861
2002	13,381	(1,051)	12,330
2003	14,171	(1,149)	13,022
2004	14,853	(1,125)	13,728
2005	14,831	(1,171)	13,660

* For sugar refining and precipitated calcium carbonate production.
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Lime production in 2005 slightly increased over 2004, the third annual increase in production after four years of decline. Overall, from 1990 to 2005, lime production has increased by 26 percent. The increase in production is attributed in part to growth in demand for environmental applications, especially flue gas desulfurization technologies. In 1993, EPA completed regulations under the Clean Air Act capping sulfur dioxide (SO_2) emissions from electric utilities. Lime scrubbers’ high efficiencies and increasing affordability have allowed the flue gas desulfurization end-use to expand significantly over the years. Phase II of the Clean Air Act Amendments, which went into effect on January 1, 2000, remains the driving force behind the growth in the flue gas desulfurization market (USGS 2003).

---

[2] Precipitated calcium carbonate is a specialty filler used in premium-quality coated and uncoated papers.

Methodology

During the calcination stage of lime manufacture, 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. 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). The emission factors were calculated as follows:

For high-calcium lime:

$$[(44.01 \text{ g/mole } CO_2) \div (56.08 \text{ g/mole CaO})] \times (0.95 \text{ CaO/lime}) = 0.75 \text{ g } CO_2\text{/g lime}$$

For dolomitic lime:

$$[(88.02 \text{ g/mole } CO_2) \div (96.39 \text{ g/mole CaO})] \times (0.95 \text{ CaO/lime}) = 0.87 \text{ g } CO_2\text{/g lime}$$

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 $[Ca(OH)_2 \cdot Mg(OH)_2]$ (IPCC 2000). These factors set the chemically combined water content to 24.3 percent for high-calcium hydrated lime, and 27.3 percent for dolomitic hydrated lime.

Lime production in the United States was 19,984 thousand metric tons in 2005 (USGS 2006), resulting in potential CO_2 emissions of 14.8 Tg CO_2 Eq. Some of the CO_2 generated during the production process, however, was recovered for use in sugar refining and PCC production. Combined lime manufacture by these producers was 1,964 thousand metric tons in 2005. It was assumed that approximately 80 percent of the CO_2 involved in sugar refining and PCC was recovered, resulting in actual CO_2 emissions of 13.7 Tg CO_2 Eq.

Lime production data (high-calcium- and dolomitic-quicklime, high-calcium- and dolomitic-hydrated, and dead-burned dolomite) for 1990 through 2005 (see Table 4-17) were obtained from USGS (1992 through 2005). Natural hydraulic lime, which is produced from CaO and hydraulic calcium silicates, is not produced in the United States (USGS 2005). Total lime production was adjusted to account for the water content of hydrated lime and is presented with lime consumption by sugar refining and PCC production in Table 4-18 (USGS 1992 through 2005). The CaO and $CaO \cdot MgO$ contents of lime were obtained from the IPCC *Good Practice Guidance* (IPCC 2000). 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. For sugar refining and PCC, it was assumed that 100 percent of lime manufacture and consumption was

Table 4-18: Adjusted Lime Production and Lime Use for Sugar Refining and PCC (Gg)

Year	High-Calcium	Dolomitic	Use for Sugar Refining and PCC
1990	12,514	2,809	826
1995	14,700	3,207	1,503
2000	15,473	3,506	2,067
2001	15,137	3,105	1,874
2002	14,536	2,934	1,762
2003	15,520	2,998	1,926
2004	15,820	3,526	1,887
2005	15,781	3,535	1,964

Table 4-17: 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
1995	13,165	2,635	2,027	363	308
2000	14,300	3,000	1,550	421	200
2001	13,600	2,580	2,030	447	200
2002	13,400	2,420	1,500	431	200
2003	13,900	2,460	2,140	464	200
2004	14,200	3,020	2,140	421	200
2005	14,100	2,990	2,220	474	200

high-calcium, based on communication with the National Lime Association (Males 2003).

Uncertainty

The uncertainties contained in these estimates can be attributed to slight differences in the chemical composition of these products. 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 manufacture lime with exactly the same properties.

In addition, a portion of the CO_2 emitted during lime manufacture 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). CO_2 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 are required to quantify the amount of CO_2 that is reabsorbed.[3]

In some cases, lime is generated from calcium carbonate by-products at pulp mills and water treatment plants.[4] 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 Inventory totals.[5]

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.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-19. Lime CO_2 emissions were estimated to be between 12.6 and 14.8 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below and 8 percent above the emission estimate of 13.7 Tg CO_2 Eq.

Recalculations Discussion

Corrections were made to the chemically combined water content percentages of high-calcium hydrated lime and

Table 4-19: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Manufacture (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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 Manufacture	CO_2	13.7	12.6	14.8	-8%	+8%

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

---

[3] 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).

[4] Some carbide producers may also regenerate lime from their calcium hydroxide by-products, which does not result in emissions of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) [$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$], not calcium carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2$ + heat $\rightarrow CaO + H_2O$] and no CO_2 is released.

[5] Based on comments submitted by and personal communication with Dr. Sergio F. Galeano, Georgia-Pacific Corporation.

dolomitic hydrated lime. This change resulted in a 0.2 percent increase in emissions on average throughout the time series. Estimates of CO_2 from lime manufacture for the year 2004 were revised to reflect updated data from the USGS. These changes resulted in a decrease in CO_2 emissions from lime manufacture of less than one percent for 2004.

Planned Improvements

Future inventories are anticipated to include emissions associated with lime kiln dust (LKD) in the lime emission estimates. Research will be conducted to determine the availability of LKD data in the United States for inclusion in the emission estimates.

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

Limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$)[6] are basic raw materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy, glass manufacture, 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 United States, and significant quantities are extracted for industrial applications. For some of these applications, limestone is sufficiently heated during the process and generates CO_2 as a by-product. Examples of such applications include limestone used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization systems for utility and industrial plants, or as a raw material in glass manufacturing and magnesium production.

In 2005, approximately 12,522 thousand metric tons of limestone and 3,953 thousand metric tons of dolomite were consumed during production for these applications. Overall, usage of limestone and dolomite resulted in aggregate CO_2 emissions of 7.4 Tg CO_2 Eq. (7,397 Gg) (see Table 4-20 and Table 4-21). Emissions in 2005 increased 10 percent from the previous year and have increased 34 percent overall from 1990 through 2005.

Table 4-20: CO_2 Emissions from Limestone & Dolomite Use (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Flux Stone	3.0	4.0	2.8	2.5	2.4	2.1	4.1	3.3
Glass Making	0.2	0.5	0.4	0.1	0.1	0.3	0.4	0.4
FGD	1.4	1.7	1.8	2.6	2.8	1.9	1.9	3.0
Magnesium Production	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0
Other Miscellaneous Uses	0.8	1.1	0.9	0.5	0.7	0.4	0.4	0.7
Total	**5.5**	**7.4**	**6.0**	**5.7**	**5.9**	**4.7**	**6.7**	**7.4**

Notes: Totals may not sum due to independent rounding. Other miscellaneous uses include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

Table 4-21: CO_2 Emissions from Limestone & Dolomite Use (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Flux Stone	2,999	4,004	2,830	2,514	2,405	2,072	4,112	3,265
Limestone	2,554	3,077	1,810	1,640	1,330	904	2,023	1,398
Dolomite	446	927	1,020	874	1,075	1,168	2,088	1,867
Glass Making	217	533	368	113	61	337	350	427
Limestone	189	410	368	113	61	337	350	406
Dolomite	28	122	0	0	0	0	0	21
FGD	1,433	1,663	1,774	2,551	2,766	1,932	1,871	2,985
Magnesium Production	64	41	73	53	0	0	0	0
Other Miscellaneous Uses	819	1,119	916	501	652	380	369	721
Total	**5,533**	**7,359**	**5,960**	**5,733**	**5,885**	**4,720**	**6,702**	**7,397**

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.

---

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

Methodology

CO_2 emissions were calculated by multiplying the quantity of limestone or dolomite consumed by the average C content, approximately 12.0 percent for limestone and 13.2 percent for dolomite (based on stoichiometry). This assumes that all C is oxidized and released. 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.

Traditionally, the production of magnesium metal was the only other 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.

Consumption data for 1990 through 2005 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 4-22) were obtained from personal communication with Deborah Weaver of the USGS (Weaver 2006) and in the USGS *Minerals Yearbook: Crushed Stone Annual Report* (USGS 1993, 1995a, 1995b, 1996a, 1997a, 1998a, 1999a, 2000a, 2001a, 2002a, 2003a, 2004a, 2005a). The production capacity data for 1990 through 2005 of dolomitic magnesium metal (see Table 4-23) also came from the USGS (1995c, 1996b, 1997b, 1998b, 1999b, 2000b, 2001b, 2002b, 2003b, 2004b, 2005b, 2006). The last plant in the United States that used the dolomitic production process for magnesium metal closed in 2001. The USGS does not mention this process in the 2005 *Minerals Yearbook: Magnesium*; therefore, it is assumed that this process continues to be non-existent in the United States (USGS 2006). 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

Table 4-23: Dolomitic Magnesium Metal Production Capacity (Metric Tons)

Year	Production Capacity
1990	35,000
1995	22,222
2000	40,000
2001	29,167
2002	0
2003	0
2004	0
2005	0

Note: Production capacity for 2002, 2003, 2004, and 2005 amounts to zero because the last U.S. production plant employing the dolomitic process shut down mid-2001 (USGS 2002b, 2003b, 2004b, 2005b, 2006).

Table 4-22: Limestone and Dolomite Consumption (Thousand Metric Tons)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Flux Stone	6,738	8,935	6,249	5,558	5,275	4,501	8,971	7,086
Limestone	5,804	6,995	4,114	3,727	3,023	2,055	4,599	3,176
Dolomite	933	1,941	2,135	1,831	2,252	2,466	4,373	3,910
Glass Making	489	1,189	836	258	139	765	796	966
Limestone	430	933	836	258	139	765	796	923
Dolomite	59	256	0	0	0	0	0	43
FGD	3,258	3,779	4,031	5,798	6,286	4,390	4,253	6,785
Other Miscellaneous Uses	1,835	2,543	2,081	1,138	1,483	863	840	1,638
Total	**12,319**	**16,445**	**13,197**	**12,751**	**13,183**	**10,520**	**14,859**	**16,475**

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.

Table 4-24: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Limestone and Dolomite Use (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	7.4	6.9	7.9	-6%	+6%

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

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.

Finally, 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.[7]

Uncertainty

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. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process, the kind of ore processed, and the final use of the slag. 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. 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. Also, some of the limestone reported as "limestone" is believed to actually be dolomite, which has a higher C content. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. Lastly, the uncertainty of the estimates for limestone used in glass making is especially high. 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. However, since glass making accounts for a small percent of consumption, its contribution to the overall emissions estimate is low.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-24. Limestone and Dolomite Use CO_2 emissions were estimated to be between 6.9 and 7.9 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 6 percent below and 6 percent above the emission estimate of 7.4 Tg CO_2 Eq.

Planned Improvements

Future improvements to the limestone and dolomite source category involve research into the availability of limestone and dolomite end-use data. If sufficient data are available, limestone and dolomite used as process materials in source categories to be included in future inventories (e.g., glass production, other process use of carbonates) may be removed and the emission estimates included there.

4.6. Soda Ash Manufacture 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

---

[7] This approach was recommended by USGS.

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 three states produce natural soda ash: Wyoming, California, and Colorado. Of these three states, only net emissions of CO_2 from Wyoming were calculated due to specifics regarding the production processes employed in each state.[8] During the production process used in Wyoming, trona ore is treated to produce soda ash. CO_2 is generated as a by-product of this reaction, and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed.

In 2005, CO_2 emissions from the manufacture of soda ash from trona were approximately 1.7 Tg CO_2 Eq. (1,655 Gg). Soda ash consumption in the United States generated 2.6 Tg CO_2 Eq. (2,573 Gg) in 2005. Total emissions from soda ash manufacture and consumption in 2005 were 4.2 Tg CO_2 Eq. (4,228 Gg) (see Table 4-25 and Table 4-26). Emissions have fluctuated since 1990. These fluctuations were strongly related to the behavior of the export market and the U.S. economy. Emissions in 2005 increased by approximately 0.5 percent from the previous year, and have increased overall by approximately 2 percent since 1990.

Table 4-25: CO_2 Emissions from Soda Ash Manufacture and Consumption (Tg CO_2 Eq.)

Year	Manufacture	Consumption	Total
1990	1.4	2.7	4.1
1995	1.6	2.7	4.3
2000	1.5	2.7	4.2
2001	1.5	2.6	4.1
2002	1.5	2.7	4.1
2003	1.5	2.6	4.1
2004	1.6	2.6	4.2
2005	1.7	2.6	4.2

Note: Totals may not sum due to independent rounding.

Table 4-26: CO_2 Emissions from Soda Ash Manufacture and Consumption (Gg)

Year	Manufacture	Consumption	Total
1990	1,431	2,710	4,141
1995	1,607	2,698	4,304
2000	1,529	2,652	4,181
2001	1,500	2,648	4,147
2002	1,470	2,668	4,139
2003	1,509	2,602	4,111
2004	1,607	2,598	4,205
2005	1,655	2,573	4,228

Note: Totals may not sum due to independent rounding.

The United States represents about one-fourth of total world soda ash output. The approximate distribution of soda ash by end-use in 2005 was glass making, 49 percent; chemical production, 27 percent; soap and detergent manufacturing, 10 percent; distributors, 5 percent; flue gas desulfurization, 2 percent; water treatment, 1 percent; pulp and paper production, 1 percent; and miscellaneous, 4 percent (USGS 2006).

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 over the next five years. (USGS 2006).

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. CO_2 and water are generated as by-products of the calcination process. CO_2

---

[8] 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 by-product, the CO_2 is recovered and recycled for use in the carbonation stage and is not emitted.

In Colorado, the lone producer of sodium bicarbonate no longer mines trona in the state. Instead, $NaHCO_3$ is 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 include the feedstocks mined in Wyoming and shipped to Colorado. In this way, the sodium bicarbonate production that takes place in Colorado is accounted for in the Wyoming numbers.

emissions from the calcination of trona can be estimated based on the following chemical reaction:

$$\underset{\text{[trona]}}{2(Na_3H(CO_3)_2 \cdot 2H_2O)} \rightarrow \underset{\text{[soda ash]}}{3Na_2CO_3} + 5H_2O + CO_2$$

Based on this formula, approximately 10.27 metric tons of trona are required to generate one metric ton of CO_2. Thus, the 17 million metric tons of trona mined in 2005 for soda ash production (USGS 2006) resulted in CO_2 emissions of approximately 1.7 Tg CO_2 Eq. (1,655 Gg).

Once manufactured, 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 4-27) were taken from USGS (1994 through 2006). Soda ash manufacture and consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Table 4-27: Soda Ash Manufacture and Consumption (Gg)

Year	Manufacture*	Consumption
1990	14,700	6,530
1995	16,500	6,500
2000	15,700	6,390
2001	15,400	6,380
2002	15,100	6,430
2003	15,500	6,270
2004	16,500	6,260
2005	17,000	6,200

* Soda ash manufactured from trona ore only.

Uncertainty

Emission estimates from soda ash manufacture 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 4-28. Soda Ash Manufacture and Consumption CO_2 emissions were estimated to be between 3.9 and 4.5 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 4.2 Tg CO_2 Eq.

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.

4.7. 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

Table 4-28: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Manufacture and Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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 Manufacture and Consumption	CO_2	4.2	3.9	4.5	-7%	+7%

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

Table 4-29: CO_2 Emissions from Titanium Dioxide Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.3	1,308
1995	1.7	1,670
2000	1.9	1,918
2001	1.9	1,857
2002	2.0	1,997
2003	2.0	2,013
2004	2.3	2,259
2005	1.9	1,921

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 petroleum coke is manufactured specifically for this purpose

Emissions of CO_2 in 2005 were 1.9 Tg CO_2 Eq. (1,921 Gg), a decrease of 18 percent from the previous year and an increase of 47 percent since 1990. The trend upward, due to increasing production within the industry, was disrupted in 2005 as a result of Hurricane Katrina (see Table 4-29), which disrupted production of TiO_2 pigment in Mississippi (USGS 2006).

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 U.S. production capacity for each process. As of 2004, the last remaining sulfate-process plant in the United States had closed. As a result, all U.S. current TiO_2 production results from 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 petroleum coke used in the process is 90 percent C and 10 percent inert materials.

The emission factor for the TiO_2 chloride process was taken from the report, *Everything You've Always Wanted to Know about Petroleum Coke* (Onder and Bagdoyan 1993). Titanium dioxide production data and the percentage of total TiO_2 production capacity that is chloride process for 1990 through 2005 (see Table 4-30) were obtained from a personal communication with Deborah Kramer, USGS Commodity Specialist, of the USGS (Kramer 2006) and through the *Minerals Yearbook: Titanium Annual Report* (USGS 1991 through 2005). Percentage chloride-process data were not available for 1990 through 1993, and 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). The composition data for petroleum coke were obtained from Onder and Bagdoyan (1993).

Table 4-30: Titanium Dioxide Production (Gg)

Year	Gg
1990	979
1995	1,250
2000	1,400
2001	1,330
2002	1,410
2003	1,420
2004	1,540
2005	1,310

Uncertainty

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 4-31. Titanium dioxide production CO_2 emissions were estimated to be between 1.6 and 2.2 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below and 16 percent above the emission estimate of 1.9 Tg CO_2 Eq.

Table 4-31: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	2.2	-16%	+16%

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

Planned Improvements

Future improvements to TiO_2 production methodology 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.

4.8. Ferroalloy Production (IPCC Source Category 2C2)

CO_2 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:

$$Fe_2O_3 + 2\ SiO_2 + 7C \rightarrow 2FeSi + 7CO$$

While most of the C contained in the process materials is released to the atmosphere as CO_2, a percentage is also

Table 4-32: CO_2 and CH_4 Emissions from Ferroalloy Production (Tg CO_2 Eq.)

Year	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	2.2	2.0	1.9	1.5	1.3	1.3	1.4	1.4
CH_4	+	+	+	+	+	+	+	+
Total	**2.2**	**2.0**	**1.9**	**1.5**	**1.4**	**1.3**	**1.4**	**1.4**

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

Table 4-33: CO_2 and CH_4 Emissions from Ferroalloy Production (Gg)

Year	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	2,152	2,036	1,893	1,459	1,349	1,305	1,419	1,392
CH_4	0.7	0.6	0.5	0.4	0.4	0.4	0.4	0.4

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 2005 were 1.4 Tg CO_2 Eq. (1,392 Gg) (see Table 4-32 and Table 4-33), which is a 2 percent decrease from the previous year and a 35 percent reduction since 1990. Emissions of CH_4 from ferroalloy production in 2005 were 0.01 Tg CO_2 Eq. (0.4 Gg), which is a 1 percent decrease from the previous year and a 43 percent decrease since 1990.

Methodology

Emissions of CO_2 and CH_4 from ferroalloy production were calculated by multiplying annual ferroalloy production by material-specific emission factors. Emission factors taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) were applied to ferroalloy production. 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 CO_2/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 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.

Ferroalloy production data for 1990 through 2005 (see Table 4-34) were obtained from the USGS through personal

Table 4-34: 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
1995	184,000	128,000	163,000	99,500
2000	229,000	100,000	184,000	NA
2001	167,000	89,000	137,000	NA
2002	156,000	98,600	113,000	NA
2003	115,000	80,500	139,000	NA
2004	120,000	92,300	150,000	NA
2005	123,000	86,100	148,000	NA

NA (Not Available)

communications with the USGS Silicon Commodity Specialist (Corathers 2006) and through the *Minerals Yearbook: Silicon Annual Report* (USGS 1991 through 2005). 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 4-34). The composition data for petroleum coke was obtained from Onder and Bagdoyan (1993).

Uncertainty

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.[9] 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.

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 4-35. Ferroalloy production CO_2 emissions were estimated to be between 1.2 and 1.6 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below and 13 percent above the emission estimate of 1.4 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.

Recalculations Discussion

Estimates of CO_2 emissions from ferroalloy production were revised for the entire time series to reflect updated emission factors based on the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). This change resulted in a 9.5 percent (0.2 Tg CO_2 Eq.) increase in emissions on average throughout the timeseries.

Planned Improvements

Future improvements to the ferroalloy production source category include research into the data availability for ferroalloys other than ferrosilicon and silicon metal. If data are available, emissions will be estimated for those ferroalloys. 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.

Table 4-35: Tier 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Ferroalloy Production (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	1.4	1.2	1.6	-13%	+13%
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.

---

[9] Emissions and sinks of biogenic carbon are accounted for in the Land-Use, Land-Use Change, and Forestry chapter.

4.9. 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 ($CaSO_4 \bullet 2H_2O$), 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) (EF MA 1997). 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 2005 was 36.0 million metric tons. 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. In addition, 2.6 million metric tons of crude phosphate rock was imported for consumption in 2005. Marketable phosphate rock production, including domestic production and imports for consumption, decreased by approximately 1.0 percent between 2004 and 2005. However, over the 1990 to 2005 period, production decreased by 12 percent. The 35.3 million metric tons produced in 2001 was the lowest production level recorded since 1965 and was driven by a worldwide decrease in demand for phosphate fertilizers. Total CO_2 emissions from phosphoric acid production were 1.4 Tg CO_2 Eq. (1,383 Gg) in 2005 (see Table 4-36).

Table 4-36: CO_2 Emissions from Phosphoric Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.5	1,529
1995	1.5	1,513
2000	1.4	1,382
2001	1.3	1,264
2002	1.3	1,338
2003	1.4	1,382
2004	1.4	1,395
2005	1.4	1,383

Methodology

CO_2 emissions from production of phosphoric acid from phosphate rock is 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.

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 4-37). For the years 1990, 1991, 1992, and 2005, 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 1993 to 2004 data. Data for domestic production of phosphate rock, exports of phosphate rock, and imports of

Table 4-37: Phosphate Rock Domestic Production, Exports, and Imports (Gg)

Location	1990	1995	2000	2001	2002	2003	2004	2005
U.S. Production[a]	49,800	43,720	37,370	32,830	34,720	36,410	36,530	36,000
FL & NC	42,494	38,100	31,900	28,100	29,800	31,300	31,600	31,140
ID & UT	7,306	5,620	5,470	4,730	4,920	5,110	4,930	4,860
Exports—FL & NC	6,240	2,760	299	9	62	64	–	–
Imports—Morocco	451	1,800	1,930	2,500	2,700	2,400	2,500	2,630
Total U.S. Consumption	**44,011**	**42,760**	**39,001**	**35,321**	**37,358**	**38,746**	**39,030**	**38,630**

[a] USGS does not disaggregate production data regionally (FL & NC and ID & UT) for 1990 and 2005. Data for those years are estimated based on the remaining time series distribution.

– Assumed equal to zero.

phosphate rock for consumption for 1990 through 2005 were obtained from *USGS Minerals Yearbook: Phosphate Rock* (USGS 1994 through 2006). In 2004 and 2005, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2005, 2006).

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 4-38).

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. At last reporting, 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 2005). 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.

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.

Uncertainty

Phosphate rock production data used in the emission calculations are developed by the USGS through monthly and semiannual voluntary surveys of the active phosphate rock mines during 2005. For previous years in the timeseries, USGS provided the data disaggregated regionally; however, for 2005 only total U.S. phosphate rock production was reported. Regional production for 2005 was estimated based on regional-production data from the previous year and

Table 4-38: 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.

Table 4-39: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	1.4	1.1	1.6	-19%	+19%

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

multiplied by regionally-specific emission factors. There is uncertainty associated with the degree to which the estimated 2005 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 imports for consumption and exports of phosphate rock used in the emission calculation 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 10 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. This phosphate rock, consumed for other purposes, constitutes approximately 10 percent of total phosphate rock consumption.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-39. Phosphoric acid production CO_2 emissions were estimated to be between 1.1 and 1.6 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 19 percent above the emission estimate of 1.4 Tg CO_2 Eq.

4.10. 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). CO_2

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. CO_2 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 by-product from the energy and industrial production processes (e.g., ammonia production, fossil fuel combustion, ethanol production), and as a by-product 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 by-product 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. CO_2 captured from biogenic sources (e.g., ethanol production plants) is not included in the Inventory. CO_2 captured from crude oil and gas production is used in EOR applications and is therefore reported in the Energy Chapter. Any CO_2 captured from industrial or energy production processes (e.g., ammonia plants, fossil fuel combustion) and used in non-EOR applications is assumed to be emitted to the atmosphere. The CO_2 emissions from such capture and use are therefore accounted for under Ammonia Production, Fossil Fuel Combustion, or other appropriate source category.

CO_2 is produced as a by-product 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 "Box 3-3: 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.

Table 4-40: CO_2 Emissions from CO_2 Consumption (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.4	1,415
1995	1.4	1,423
2000	1.4	1,416
2001	0.8	825
2002	1.0	978
2003	1.3	1,310
2004	1.2	1,199
2005	1.3	1,324

There are currently two facilities, one in Mississippi and one 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). There are other naturally occurring CO_2 reservoirs, mostly located in the western United States Facilities are producing CO_2 from these natural reservoirs, but they are only producing CO_2 for EOR applications, not for other commercial applications (Allis et al. 2000). CO_2 production from these facilities is discussed in the Energy Chapter.

In 2005, the amount of CO_2 produced by the Mississippi and New Mexico facilities for commercial applications and subsequently emitted to the atmosphere was 1.3 Tg CO_2 Eq. (1,324 Gg) (see Table 4-40). This amount represents a increase of 10 percent from the previous year and a decrease of 6 percent from emissions in 1990. This decrease was due to a decrease in the percent of the Mississippi facility's total reported production that was used for commercial applications. During this period the Mississippi facility dedicated more of its total production to EOR.

Methodology

CO_2 emission estimates for 1990 through 2005 were based on production data for the two facilities currently producing CO_2 from naturally-occurring CO_2 reservoirs for use in non-EOR applications (see Table 4-41). 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 total production that was used

Table 4-41: CO_2 Production (Gg CO_2) and the Percent Used for Non-EOR Applications for Jackson Dome and Bravo Dome

Year	Jackson Dome CO_2 Production (Gg)	Jackson Dome % Used for Non-EOR	Bravo Dome CO_2 Production (Gg)	Bravo Dome % Used for Non-EOR
1990	1,353	100%	6,241	1%
1995	1,353	100%	7,003	1%
2000	1,353	100%	6,328	1%
2001	1,624	47%	6,196	1%
2002	2,010	46%	5,295	1%
2003	3,286	38%	6,090	1%
2004	4,214	27%	6,090	1%
2005	4,678	27%	6,090	1%

for EOR and in non-EOR applications were obtained from the Advanced Resources Institute (ARI 2006) for 1990 to 2000 and from the Annual Reports for Denbury Resources (Denbury Resources 2002, 2003, 2004, 2005, 2006) for 2001 to 2005. Denbury Resources reported the average CO_2 production in units of MMCF CO_2 per day for 2001 through 2005 and reported the percentage of the total average annual production that was used for EOR. CO_2 production data for the Bravo Dome, New Mexico facility were obtained from the New Mexico Bureau of Geology and Mineral Resources for the years 1990 through 2003 (Broadhead 2006). The New Mexico Bureau of Geology reported production in billion cubic feet per year. According to the New Mexico Bureau, the amount of CO_2 produced from Bravo Dome for use in non-EOR applications is less than one percent of total production (Broadhead 2003a). Production data for 2004 and 2005 were not available for Bravo Dome, so it is assumed that the production values for those years are equal to the 2003 value.

Uncertainty

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 4-42. CO_2 Consumption CO_2 emissions were estimated to be between 1.1 and 1.6 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 15 percent below to 21 percent above the emission estimate of 1.3 Tg CO_2 Eq.

Recalculations Discussion

Data for total Bravo Dome CO_2 production were updated for the entire time series based on new production data from the facility. Data for CO_2 production from Jackson Dome

Table 4-42: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from CO_2 Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	1.3	1.1	1.6	-15%	+21%

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

were provided for years 1990 through 2000 for the first time during the current inventory year. These changes resulted in an average emission increase of 70 percent for years 1990 through 2000 and an average emission increase of less than one percent for years 2001 to 2005.

4.11. Zinc Production (IPCC Source Category 2C5)

Zinc production in the United States consists of both primary and secondary processes. Primary production techniques used in the United States are the electro-thermic and electrolytic process while secondary techniques used in the United States include a range of 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, the electro-thermic process results in non-energy CO_2 emissions, as does the Waelz Kiln process—a technique used to produce secondary zinc from electric-arc furnace (EAF) dust (Viklund-White 2000).

During the electro-thermic zinc production process, roasted zinc concentrate and, when available, 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. This reduction process produces non-energy CO_2 emissions (Sjardin 2003). The electrolytic zinc production process does not produce non-energy CO_2 emissions.

In the 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 ton of zinc is produced for every ton of EAF dust treated (Viklund-White 2000).

Table 4-43: CO_2 Emissions from Zinc Production ($Tg\ CO_2$ Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	0.9	939
1995	1.0	1,003
2000	1.1	1,129
2001	1.0	976
2002	0.9	927
2003	0.5	502
2004	0.5	472
2005	0.5	460

In 2005, U.S. primary and secondary zinc production totaled 540,200 metric tons (Gabby 2006). The resulting emissions of CO_2 from zinc production in 2005 were estimated to be 0.5 Tg CO_2 Eq. (460 Gg) (see Table 4-43). All 2005 CO_2 emissions result from secondary zinc production.

After a gradual increase in total emissions from 1990 to 2000, largely due to an increase in secondary zinc production, 2005 emissions have decreased by nearly half that of 1990 (49 percent) due to the closing of an electro-thermic-process zinc plant in Monaca, PA (USGS 2004).

Methodology

Non-energy CO_2 emissions from zinc production result from those processes that use metallurgical coke or other C-based materials as reductants. Sjardin (2003) provides an emission factor of 0.43 metric tons CO_2/ton zinc produced for emissive zinc production processes; however, this emission factor is based on the Imperial Smelting Furnace production process. Because the Imperial Smelting Furnace production process is not used in the United States, emission factors specific to those emissive zinc production processes used in the United States, which consist of the electro-thermic and Waelz Kiln processes, were needed. Due to the limited amount of information available for these electro-thermic processes, only Waelz Kiln process-specific emission factors were developed. These emission factors were applied to both the Waelz Kiln process and the electro-thermic zinc production processes. A 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:

$$EF_{\text{Waelz Kiln}} = \frac{1.19\text{ metric tons coke}}{\text{metric tons zinc}} \times \frac{0.84\text{ metric tons C}}{\text{metric ton coke}} \times \frac{3.67\text{ metric tons CO}_2}{\text{metric ton C}} = \frac{3.66\text{ metric tons CO}_2}{\text{metric ton zinc}}$$

The USGS disaggregates total U.S. primary zinc production capacity into zinc produced using the electro-thermic process and zinc produced using the electrolytic process; however, the USGS does not report the amount of zinc produced using each process, only the total zinc production capacity of the zinc plants using each process. The total electro-thermic zinc production capacity is divided by total primary zinc production capacity to estimate the percent of primary zinc produced using the electro-thermic process. This percent is then multiplied by total primary zinc production to estimate the amount of zinc produced using the electro-thermic process, and the resulting value is multiplied by the Waelz Kiln process emission factor to obtain total CO_2 emissions for primary zinc production. According to the USGS, the only remaining plant producing primary zinc using the electro-thermic process closed in 2003 (USGS 2004). Therefore, CO_2 emissions for primary zinc production are reported only for years 1990 through 2002.

In the United States, secondary zinc is produced through either the electro-thermic or Waelz Kiln process. In 1997, the Horsehead Corporation plant, located in Monaca, PA, produced 47,174 metric tons of secondary zinc using the electro-thermic process (Queneau et al. 1998). This is the only plant in the United States that uses the electro-thermic process to produce secondary zinc, which, in 1997, accounted for 13 percent of total secondary zinc production. This percentage was applied to all years within the time series up until the Monaca plant's closure in 2003 (USGS 2004) to estimate the total amount of secondary zinc produced using the electro-thermic process. This value is then multiplied by the Waelz Kiln process emission factor to obtain total CO_2 emissions for secondary zinc produced using the electro-thermic process.

U.S. secondary zinc is also produced by processing recycled EAF dust in a Waelz Kiln furnace. Due to the complexities of recovering zinc from recycled EAF dust, an emission factor based on the amount of EAF dust consumed rather than the amount of secondary zinc produced is believed to represent actual CO_2 emissions from the process more accurately (Stuart 2005). An 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:

$$EF_{\text{EAF Dust}} = \frac{0.4\text{ metric tons coke}}{\text{metric tons EAF dust}} \times \frac{0.84\text{ metric tons C}}{\text{metric ton coke}} \times \frac{3.67\text{ metric tons CO}_2}{\text{metric ton C}} = \frac{1.23\text{ metric tons CO}_2}{\text{metric ton EAF dust}}$$

The Horsehead Corporation plant, located in Palmerton, PA, is the only large plant in the United States that produces secondary zinc by recycling EAF dust (Stuart 2005). In 2003, this plant consumed 408,240 metric tons of EAF dust, producing 137,169 metric tons of secondary zinc (Recycling Today 2005). This zinc production accounted for 36 percent of total secondary zinc produced in 2003. This percentage was applied to the USGS data for total secondary zinc production for all years within the time series to estimate the total amount of secondary zinc produced by consuming recycled EAF dust in a Waelz Kiln furnace. This value is multiplied by the Waelz Kiln process emission factor for EAF dust to obtain total CO_2 emissions.

The 1990 through 2004 activity data for primary and secondary zinc production (see Table 4-44) were obtained through the *USGS Mineral Yearbook: Zinc* (USGS 1994 through 2005). Activity data for 2005 were obtained from the USGS Commodity Specialist (Gabby 2006).

Table 4-44: Zinc Production (Metric Tons)

Year	Primary	Secondary
1990	262,704	341,400
1995	231,840	353,000
2000	227,800	440,000
2001	203,000	375,000
2002	181,800	366,000
2003	186,900	381,000
2004	188,200	358,000
2005	191,200	349,000

Uncertainty

The uncertainties contained in these estimates are two-fold, relating to activity data and emission factors used.

First, there are uncertainties associated with the percent of total zinc production, both primary and secondary, that is attributed to the electro-thermic and Waelz Kiln emissive zinc production processes. For primary zinc production, the amount of zinc produced annually using the electro-thermic process is estimated from the percent of primary-zinc production capacity that electro-thermic production capacity constitutes for each year of the time series. This assumes that each zinc plant is operating at the same percentage of total production capacity, which may not be the case and this calculation could either overestimate or underestimate the percentage of the total primary zinc production that is produced using the electro-thermic process. The amount of secondary zinc produced using the electro-thermic process is estimated from the percent of total secondary zinc production that this process accounted for during a single year, 2003. The amount of secondary zinc produced using the Waelz Kiln process is estimated from the percent of total secondary zinc production this process accounted for during a single year, 1997. This calculation could either overestimate or underestimate the percentage of the total secondary zinc production that is produced using the electro-thermic or Waelz Kiln processes. Therefore, there is uncertainty associated with the fact that percents of total production data estimated from production capacity, rather than actual production data, are used for emission estimates.

Second, there are uncertainties associated with the emission factors used to estimate CO_2 emissions from the primary and secondary production processes. Because the only published emission factors are based on the Imperial Smelting Furnace, which is not used in the United States, country-specific emission factors were developed for the Waelz Kiln zinc production process. Data limitations prevented the development of emission factors for the electro-thermic process. Therefore, emission factors for the Waelz Kiln process were applied to both electro-thermic and Waelz Kiln production processes. Furthermore, the Waelz Kiln emission factors are based on materials balances for metallurgical coke and EAF dust consumed during zinc production provided by Viklund-White (2000). Therefore, the accuracy of these emission factors depend upon the accuracy of these materials balances.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-45. Zinc production CO_2 emissions were estimated to be between 0.4 and 0.6 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 21 percent below and 25 percent above the emission estimate of 0.5 Tg CO_2 Eq.

Recalculations Discussion

The historical activity data used to calculate the emissions from zinc production were updated for the year 2004. The change resulted in a decrease of 0.03 Tg CO_2 Eq. (6 percent) in CO_2 emissions from zinc production for that year.

Table 4-45: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	0.5	0.4	0.6	-21%	+25%

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

4.12. Lead Production (IPCC Source Category 2C5)

Lead production in the United States consists of both primary and secondary processes. In the United States, primary lead production, in the form of direct smelting, mostly occurs at plants located in Alaska and Missouri, while secondary production largely involves the recycling of lead acid batteries at 14 separate smelters located in 11 states throughout the United States (USGS 2005). Secondary lead production has increased in the United States over the past decade while primary lead production has decreased. In 2005, secondary lead production accounted for approximately 89 percent of total lead production (Gabby 2006, USGS 1995). Both the primary lead and secondary lead production processes used in the United States emit CO_2 (Sjardin 2003).

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 decreased by 3 percent from 2004 to 2005 and has decreased by 63 percent since 1990 (Gabby 2006, USGS 1995).

In the United States, approximately 82 percent of secondary lead is produced by recycling lead acid batteries in either blast furnaces or reverberatory furnaces. The remaining 18 percent of secondary lead is produced from lead scrap. Similar to primary lead production, CO_2 emissions result when a reducing agent, usually metallurgical coke, is added to the smelter to aid in the reduction process (Sjardin 2003). U.S. secondary lead production increased by 3 percent from 2004 to 2005, and has increased by 24 percent since 1990.

The United States is the third largest mine producer of lead in the world, behind China and Australia, accounting for 14 percent of world production in 2005 (USGS 2005). In 2005, U.S. primary and secondary lead production totaled 1,288,000 metric tons (Gabby 2006). The resulting emissions of CO_2 from 2005 production were estimated to be 0.3 Tg CO_2 Eq. (265 Gg) (see Table 4-46). The majority of 2005 lead production is from secondary processes, which account for 86 percent of total 2005 CO_2 emissions.

After a gradual increase in total emissions from 1990 to 2000, total emissions have decreased by seven percent since 1990, largely due a decrease in primary production and a transition within the United States from primary lead production to secondary lead production, which is less emissive than primary production (USGS 2005).

Table 4-46: CO_2 Emissions from Lead Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	0.3	285
1995	0.3	298
2000	0.3	311
2001	0.3	293
2002	0.3	290
2003	0.3	289
2004	0.3	259
2005	0.3	265

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. For primary lead production using direct smelting, Sjardin (2003) provides an emission factor of 0.25 metric tons CO_2/ton lead. For secondary lead production, Sjardin (2003) provides an emission factor of 0.2 metric tons CO_2/ton lead produced. Both factors are multiplied by total U.S. primary and secondary lead production, respectively, to estimate CO_2 emissions.

The 1990 through 2004 activity data for primary and secondary lead production (see Table 4-47) were obtained through the USGS *Mineral Yearbook: Lead* (USGS 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005). Primary and secondary lead production data for 2005 were obtained from the USGS Lead Minerals Commodity Specialist (Gabby 2006).

Table 4-47: Lead Production (Metric Tons)

Year	Primary	Secondary
1990	404,000	922,000
1995	374,000	1,020,000
2000	341,000	1,130,000
2001	290,000	1,100,000
2002	262,000	1,120,000
2003	245,000	1,140,000
2004	148,000	1,110,000
2005	143,000	1,145,000

Table 4-48: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lead Production (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	0.3	0.2	0.3	-16%	+17%

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

Uncertainty

Uncertainty associated with lead production relates to the emission factors and activity data used. The direct smelting emission factor used in primary production is taken from Sjardin (2003) who averages the values provided by three other studies (Dutrizac et al. 2000, Morris et al. 1983, Ullman 1997). For secondary production, Sjardin (2003) reduces this factor by 50 percent and adds a CO_2 emissions 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 4-48. Lead production CO_2 emissions were estimated to be between 0.2 and 0.3 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 0.3 Tg CO_2 Eq.

4.13. 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. CH_4 emissions are presented here from the production of C black, ethylene, ethylene dichloride, and methanol, while CO_2 emissions are presented here for only C black production. The CO_2 emissions from petrochemical processes other than C 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 C 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.

C black is an intensely black powder generated by the incomplete combustion of an aromatic petroleum or coal-based feedstock. Most C 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 2005 were 2.9 Tg CO_2 Eq. (2,895 Gg) and 1.1 Tg CO_2 Eq. (52 Gg), respectively (see Table 4-49 and Table 4-50), totaling 4.0 Tg CO_2 Eq. Emissions of CO_2 from C black production in 2005 essentially equaled those from the previous year. There has been an overall increase in CO_2 emissions from C black production of 30 percent since 1990. CH_4 emissions from petrochemical production increased by six percent from the previous year and increased 26 percent since 1990.

Table 4-49: CO_2 and CH_4 Emissions from Petrochemical Production (Tg CO_2 Eq.)

Year	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
CO_2	2.2	2.8	3.0	2.8	2.9	2.8	2.9	2.9
CH_4	0.9	1.1	1.2	1.1	1.1	1.1	1.2	1.1
Total	**3.1**	**3.8**	**4.2**	**3.9**	**4.0**	**3.9**	**4.1**	**4.0**

Table 4-50: CO_2 and CH_4 Emissions from Petrochemical Production (Gg)

Year	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
CO_2	2,221	2,750	3,004	2,787	2,857	2,777	2,895	2,897
CH_4	41	52	58	51	52	51	55	51

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 C black, 1 kg CH_4/metric ton ethylene, 0.4 kg CH_4/metric ton ethylene dichloride,[10] and 2 kg CH_4/metric ton methanol. Although the production of other chemicals may also result in CH_4 emissions, there were not sufficient data available to estimate their emissions.

Emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Annual production data for 1990 (see Table 4-51) were obtained from the Chemical Manufacturer's Association *Statistical Handbook* (CMA 1999). Production data for 1991 through 2005 were obtained from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2002, 2003, 2005, 2006) and the International Carbon Black Association (Johnson 2003, 2005, 2006).

Almost all C 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 C black feedstock is combusted to provide energy to the process. C 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. C black plant produces C black using the thermal black process, and one U.S. C black plant produces C black using the acetylene black process (The Innovation Group 2004).

The furnace black process produces C black from "C black feedstock" (also referred to as "C 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 C black, the "primary feedstock" (i.e., C 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 C black feedstock are oxidized to provide heat to the production process and pyrolyze the remaining C black feedstock to C 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

Table 4-51: Production of Selected Petrochemicals (Thousand Metric Tons)

Chemical	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Carbon Black	1,307	1,619	1,769	1,641	1,682	1,635	1,705	1,651
Ethylene	16,542	21,215	24,971	22,521	23,623	22,957	25,660	23,955
Ethylene Dichloride	6,282	7,829	9,866	9,294	9,288	9,952	12,111	11,261
Methanol	3,785	4,992	4,876	3,402	3,289	3,166	2,937	2,336

---

[10] 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 ($C_2H_2Cl_2$).

the downstream C 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 C black production is subtracted from the total amount of C contained in primary and secondary C 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 C black feedstock consumed in the process (see Table 4-52) is estimated using a primary feedstock consumption factor and a secondary feedstock consumption factor estimated from U.S. Census Bureau (1999 and 2004) data. The average C black feedstock consumption factor for U.S. C black production is 1.43 metric tons of C black feedstock consumed per metric ton of C black produced. The average natural gas consumption factor for U.S. C black production is 341 normal cubic meters of natural gas consumed per metric ton of C 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).

For the purposes of emissions estimation, 100 percent of the primary C black feedstock is assumed to be derived from petroleum refining byproducts. C black feedstock derived from metallurgical (coal) coke production (e.g., creosote oil) is also used for C black production; however, no data are available concerning the annual consumption of coal-derived C black feedstock. C 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 C 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 C black because of the lack of data concerning the relatively small amount of C black produced using the acetylene black and thermal black processes. The C black produced from the furnace black process is assumed to be 97 percent elemental C (Othmer et al. 1992).

Uncertainty

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 C black production calculation are based on feedstock consumption, import and export data, and C black production data. The composition of C black feedstock varies depending upon the specific refinery production process, and therefore the assumption that C black feedstock is 89 percent C gives rise to uncertainty. Also, no data are available concerning the consumption of coal-derived C 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 C black production may be underreported by the U.S. Census Bureau. Finally, the amount of C 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 C black is produced using the furnace black process.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-53. Petrochemical production CO_2 emissions were estimated to be between 1.9 and 4.0 Tg CO_2 Eq. at the 95 percent confidence level . This indicates a range of approximately 35 percent below to 39 percent

Table 4-52: Carbon Black Feedstock (Primary Feedstock) and Natural Gas Feedstock (Secondary Feedstock) Consumption (Thousand Metric Tons)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Primary Feedstock	1,864	2,308	2,521	2,339	2,398	2,331	2,430	2,430
Secondary Feedstock	302	374	408	379	388	377	393	393

Table 4-53: Tier 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Petrochemical Production ($Tg\ CO_2$ Eq. and Percent)

Source	Gas	2005 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	2.9	1.9	4.0	-35%	+39%
Petrochemical Production	CH_4	1.1	1.0	1.2	-9%	+9%

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

above the emission estimate of 2.9 Tg CO_2 Eq. Petrochemical production CH_4 emissions were estimated to be between 1.0 and 1.2 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below to 9 percent above the emission estimate of 1.1 Tg CO_2 Eq.

Recalculations Discussion

Estimates of CH_4 emissions from petrochemical production have been revised for the entire time series to include the removal of styrene, which has been removed due to inconsistent information regarding its emissive use in the United States. On average, the removal of styrene resulted in a decrease of 0.4 Tg CO_2 Eq. (27 percent) from the previous estimate.

Planned Improvements

Future improvements to the petrochemicals source category include research into the use of acrylonitrile in the United States, revisions to the C black CH_4 and CO_2 emission factors, and research into process and feedstock data to obtain Tier 2 emission estimates from the production of methanol, ethylene, propylene, ethylene dichloride, and ethylene oxide.

4.14. Silicon Carbide Production (IPCC Source Category 2B4) and Consumption

CO_2 and CH_4 are emitted from the production 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.

CO_2 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 applications, primarily in iron and steel production (USGS 2005a).

CO_2 emissions from SiC production and consumption in 2005 were 219 Gg (0.2 Tg CO_2 Eq.). Approximately 42 percent of these emissions resulted from SiC production while the remainder result from SiC consumption. CH_4 emissions from SiC production in 2005 were 0.4 Gg CH_4 (0.01 Tg CO_2 Eq.) (see Table 4-54 and Table 4-55).

Table 4-54: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption ($Tg\ CO_2$ Eq.)

Year	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2
CH_4	+	+	+	+	+	+	+	+
Total	**0.4**	**0.3**	**0.3**	**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 4-55: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (Gg)

Year	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	375	329	248	199	183	202	224	219
CH_4	1	1	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 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 2005a). 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 2005 were obtained from the *Minerals Yearbook: Manufactured Abrasives* (USGS 1991a, 1992a, 1993a, 1994a, 1995a, 1996a, 1997a, 1998a, 1999a, 2000a, 2001a, 2002a, 2003a, 2004a, 2005a, 2006). Silicon carbide consumption by major end use was obtained from the Minerals Yearbook: Silicon (USGS 1991b, 1992b, 1993b, 1994b, 1995b, 1996b, 1997b, 1998b, 1999b, 2000b, 2001b, 2002b, 2003b, 2004b, 2005b) (see Table 4-56) for years 1990 through 2004 and from the USGS Minerals Commodity Specialist for 2005 (Corathers 2006). Net imports were obtained from the U.S. Census Bureau (2005, 2006).

Table 4-56: Production and Consumption of Silicon Carbide (Metric Tons)

Year	Production	Consumption
1990	105,000	172,464
1995	75,400	227,397
2000	45,000	225,280
2001	40,000	162,142
2002	30,000	180,956
2003	35,000	191,289
2004	35,000	229,692
2005	35,000	220,150

Uncertainty

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 4-57. Silicon carbide production and consumption CO_2 emissions were estimated

Table 4-57: Tier 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Silicon Carbide Production and Consumption (Tg CO_2 Eq. and Percent)

		2005 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
Source	Gas	(Tg CO_2 Eq.)	(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	-10%	+10%
Silicon Carbide Production and Consumption	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.

to be between 10 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.

Recalculations Discussion

Emissions of CO_2 from SiC production were included for the first time during this inventory year. Overall emissions from CO_2 production and consumption increased throughout the time series by an average of 56 percent as a result of this change.

Planned Improvements

Future improvements to the carbide production source category include performing research to determine if calcium carbide production and consumption data are available for the United States. If these data are available, calcium carbide emission estimates will be included in this source category.

4.15. 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 by-product 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 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 20 percent of nitric acid plants use NSCR (Choe et al. 1993). The remaining 80 percent use SCR or extended absorption, neither of which is known to reduce N_2O emissions.

Table 4-58: N_2O Emissions from Nitric Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	17.8	58
1995	19.9	64
2000	19.6	63
2001	15.9	51
2002	17.2	56
2003	16.7	54
2004	16.0	52
2005	15.7	51

N_2O emissions from this source were estimated to be 15.7 Tg CO_2 Eq. (51 Gg) in 2005 (see Table 4-58). Emissions from nitric acid production have decreased by 12.1 percent since 1990, with the trend in the time series closely tracking the changes in production.

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 2 kg N_2O / metric ton HNO_3 for plants using non-selective catalytic reduction (NSCR) systems and 9.5 kg N_2O/metric ton HNO_3 for plants not equipped with NSCR (Choe et al. 1993). 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. An estimated 20 percent of HNO_3 plants in the United States are equipped with NSCR (Choe et al. 1993). Hence, the emission factor is equal to $(9.5 \times 0.80) + (2 \times 0.20) = 8$ kg N_2O per metric ton HNO_3.

Nitric acid production data for 1990 (see Table 4-59) was obtained from *Chemical and Engineering News*, “Facts and Figures” (C&EN 2001). Nitric acid production data for 1991 through 1992 (see Table 4-59) were obtained from *Chemical and Engineering News*, “Facts and Figures” (C&EN 2002). Nitric acid production data for 1993 was obtained from *Chemical and Engineering News*, “Facts and Figures” (C&EN 2004). Nitric acid production data for 1994 was obtained from *Chemical and Engineering News*, “Facts and Figures” (C&EN 2005). Nitric acid production data for 1995 through 2005 were obtained from *Chemical and*

Table 4-59: Nitric Acid Production (Gg)

Year	Gg
1990	7,196
1995	8,018
2000	7,898
2001	6,416
2002	6,940
2003	6,747
2004	6,466
2005	6,328

Engineering News, "Facts and Figures" (C&EN 2006). The emission factor range was taken from Choe et al. (1993).

Uncertainty

The overall uncertainty associated with the 2005 N_2O emissions estimate from nitric acid production was calculated using the IPCC *Good Practice Guidance* 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, and the emission factors applied to each abatement technology type.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-60. N_2O emissions from nitric acid production were estimated to be between 13.2 and 18.5 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below to 18 percent above the 2005 emissions estimate of 15.7 Tg CO_2 Eq.

Recalculations Discussion

The nitric acid production values for 1998, 2002, and 2004 have been updated relative to the previous Inventory based on revised production data presented in C&EN (2006). The updated production data for 1998 and 2002 resulted in an increases of less than 0.01Tg CO_2 Eq. (0.01 percent), respectively, in N_2O emissions from nitric acid production for these years relative to the previous Inventory. The updated production data for 2004 resulted in a decrease of 0.6 Tg CO_2 Eq. (3.5 percent) in N_2O emissions relative to the previous Inventory.

Planned Improvements

Planned improvements are focused on assessing the plant-by-plant implementation of NO_x abatement technologies to more accurately match plant production capacities to appropriate emission factors, instead of using a national profiling of abatement implementation.

4.16. 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 is the major producer, with three companies in four locations accounting for approximately one-third of world production (CW 2005). Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, coatings, plastics, urethane foams, elastomers, and synthetic lubricants. Commercially, it is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Approximately 90 percent of all adipic acid produced in the United States is used in the production of nylon 6,6 (CMR 2001). Food-grade adipic acid is also 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 by-product

Table 4-60: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions From Nitric Acid Production ($Tg CO_2$ Eq. and Percent)

Source	Gas	2005 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	15.7	13.2	18.5	-16%	+18%

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

Table 4-61: N_2O Emissions from Adipic Acid Production ($Tg\ CO_2$ Eq. and Gg)

Year	$Tg\ CO_2$ Eq.	Gg
1990	15.2	49
1995	17.2	56
2000	6.0	19
2001	4.9	16
2002	5.9	19
2003	6.2	20
2004	5.7	19
2005	6.0	19

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.[11] Only one small plant, representing approximately two percent of production, does not control for N_2O (Reimer 1999).

N_2O emissions from adipic acid production were estimated to be 6.0 Tg CO_2 Eq. (19 Gg) in 2005 (see Table 4-61). National adipic acid production has increased by approximately 42 percent over the period of 1990 through 2005, to approximately one million metric tons. At the same time, emissions have been reduced by 61 percent due to the widespread installation of pollution control measures.

Methodology

For two production plants, 1990 to 2002 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 (Childs 2002, 2003). These estimates were based on continuous emissions monitoring equipment installed at the two facilities. Reported estimates for 2003, 2004, and 2005 were unavailable and thus were calculated by applying 4.4, 4.2 and 4.2 percent production growth rates, respectively. The production for 2003 was obtained through linear interpolation between 2002 and 2004 reported national production data. Subsequently, the growth rate for 2004 and 2005 was based on the change between the estimated 2003 production data and the reported 2004 production data (see discussion below on sources of production data). For the other two plants, 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 (Thiemens and Trogler 1991). Emissions are estimated using the following equation:

$$\begin{gathered}\text{N}_2\text{O emissions} = (\text{production of adipic acid} \\ [\text{metric tons \{MT\} of adipic acid}]) \times \\ (0.3\ \text{MT N}_2\text{O / MT adipic acid}) \times \\ (1\text{-}[\text{N}_2\text{O destruction factor} \times \text{abatement system utility factor}])\end{gathered}$$

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, one plant employs thermal destruction, and the smallest plant uses no N_2O abatement equipment. The N_2O abatement system destruction factor is assumed to be 95 percent for catalytic abatement and 98 percent for thermal abatement (Reimer et al. 1999, Reimer 1999). For the one plant that uses thermal destruction and for which no reported plant-specific emissions are available, the abatement system utility factor is assumed to be 98 percent.

For 1990 to 2003 and 2005, plant-specific production data was estimated where direct emission measurements were not available. In order to calculate plant-specific production for the two plants, national adipic acid production was allocated to the plant level using the ratio of their known plant capacities to total national capacity for all U.S. plants. The estimated plant production for the two plants was then used for calculating emissions as described above. For 2004, actual plant production data were obtained for these two plants and used for emission calculations.

National adipic acid production data (see Table 4-62) for 1990 through 2002 were obtained from the American

---

[11] During 1997, the N_2O emission controls installed by the third plant operated for approximately a quarter of the year.

Table 4-62: Adipic Acid Production (Gg)

Year	Gg
1990	735
1995	830
2000	925
2001	835
2002	921
2003	961
2004	1,002
2005	1,044

Chemistry Council (ACC 2003). Production for 2003 was estimated based on linear interpolation of 2002 and 2004 reported production. Production for 2004 was obtained from *Chemical Week*, Product Focus: Adipic Acid (CW 2005). Production for 2005 was calculated by applying a 4.2 percent production growth rate to reported 2004 production. This growth rate was based on the change between the estimated 2003 production and the reported 2004 production. The 4.2 percent production growth rate applied in this case is in line with the expected growth in global adipic acid demand of 3.2 percent per year from 2005 to 2010 (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, 1993, 1994, 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 2005, the plant capacities for these three plants were kept the same as the year 2000 capacities. Plant capacity for 1999 to 2005 for the one remaining plant was kept the same as 1998.

Uncertainty

The overall uncertainty associated with the 2005 N_2O emission estimate from adipic acid production was calculated using the IPCC *Good Practice Guidance* Tier 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions included that of company specific production data, industry wide estimated production growth rates, emission factors for abated and unabated emissions, and company-specific historical emissions estimates.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-63. N_2O emissions from adipic acid production were estimated to be between 3.2 and 8.8 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 46 percent below to 47 percent above the 2005 emission estimate of 6.0 Tg CO_2 Eq.

Planned Improvements

Improvement efforts will be focused on obtaining direct measurement data from facilities. If they become available, cross verification with top-down approaches will provide a useful Tier-2-level QC check. Also, additional information on the actual performance of the latest catalytic and thermal abatement equipment at plants with continuous emission monitoring may support the re-evaluation of current default abatement values.

4.17. Substitution of Ozone Depleting Substances (IPCC Source Category 2F)

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used as alternatives to several classes of ozone-depleting

Table 4-63: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	6.0	3.2	8.8	-46%	+47%

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

substances (ODSs) that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990.[12] 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 4-64 and Table 4-65.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—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.[13] In 1993, the use of HFCs in foam production and as an aerosol propellant began, and in 1994 these compounds also found applications as solvents and sterilants. In 1995, ODS substitutes for halons entered widespread use in the United States as halon production was phased-out.

The use and subsequent emissions of HFCs and PFCs as ODS substitutes has been increasing from small amounts in 1990 to 123.3 Tg CO_2 Eq. in 2005. This increase was in large part the result of efforts to phase out CFCs and other ODSs in the United States. In the short term, this trend is expected to continue, and will likely accelerate 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

Table 4-64: Emissions of HFCs and PFCs from ODS Substitutes (Tg CO_2 Eq.)

Gas	1990	1995	2000	2001	2002	2003	2004	2005
HFC-23	+	+	+	+	+	+	+	+
HFC-32	+	+	0.3	0.3	0.4	0.4	0.5	0.6
HFC-125	+	3.5	11.2	12.4	13.7	15.4	17.3	19.8
HFC-134a	+	26.0	56.3	60.7	64.7	68.3	71.8	74.0
HFC-143a	+	0.9	8.3	10.3	12.7	15.4	18.4	22.1
HFC-236fa	+	0.2	0.7	0.8	0.8	0.9	1.0	1.0
CF_4	+	+	+	+	+	+	+	+
Others*	0.3	1.6	4.2	4.0	4.5	5.1	5.4	5.7
Total	**0.3**	**32.2**	**80.9**	**88.6**	**96.9**	**105.5**	**114.5**	**123.3**

+ Does not exceed 0.05 Tg CO_2 Eq.
* Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-4310mee, 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 4-65: Emissions of HFCs and PFCs from ODS Substitution (Mg)

Gas	1990	1995	2000	2001	2002	2003	2004	2005
HFC-23	+	+	1	2	2	2	3	3
HFC-32	+	+	465	498	558	645	762	963
HFC-125	+	1,267	3,983	4,423	4,901	5,484	6,177	7,065
HFC-134a	+	19,999	43,274	46,677	49,774	52,521	55,265	56,943
HFC-143a	+	228	2,193	2,723	3,338	4,045	4,847	5,822
HFC-236fa	+	36	110	123	135	145	155	163
CF_4	+	+	1	1	1	1	1	2
Others*	M	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.

---

[12] [42 U.S.C § 7671, CAA § 601]

[13] R-404A contains HFC-125, HFC-143a, and HFC-134a.

of these gases and the introduction of alternative gases and technologies, however, may help to offset this anticipated increase in emissions.

The end-use sectors that contribute the most toward emissions of HFCs and PFCs as ODS substitutes include refrigeration and air-conditioning (107.8 Tg CO_2 Eq., or approximately 87 percent), aerosols (11.3 Tg CO_2 Eq., or approximately 9 percent), and solvents (1.6 Tg CO_2 Eq., or approximately 1 percent). Within the refrigeration and air-conditioning end-use sector, motor vehicle air-conditioning was the highest emitting end-use (53.1 Tg CO_2 Eq.), followed by retail food and refrigerated transport. In the aerosols end-use sector, non-metered-dose inhaler (MDI) emissions make up a majority of the end-use sector emissions.

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 the model tracks the use and emissions of various compounds for the annual "vintages" of new equipment that enter service in each end-use. This 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 more than 50 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

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/UNEP/OECD/IEA (1997). 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 over 50 end-uses. The uncertainty analysis, however, quantifies the level of uncertainty associated with the aggregate emissions resulting from the top 16 end-uses and 5 others. 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. This year, one new end-use was included in the uncertainty estimate—fire extinguishing streaming agents. 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 mobile air-conditioning and retail food refrigeration, as well as the stock (MT) of retail food refrigerant.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-66. Substitution of Ozone Depleting Substances HFC and PFC emissions were estimated to be between 112.7 and 148.6 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 9 percent below to 20 percent above the emission estimate of 123.3 Tg CO_2 Eq.

Table 4-66: Tier 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes ($Tg\ CO_2$ Eq. and Percent)

		2005 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
Source	Gases	($Tg\ CO_2$ Eq.)	($Tg\ CO_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	123.3	112.7	148.6	-9%	+20%

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

Recalculations Discussion

An extensive review of the chemical substitution trends, market sizes, growth rates, and charge sizes, together with input from industry representatives, resulted in updated assumptions for the Vintaging Model. These changes resulted in an average annual net increase of 7.6 Tg CO_2 Eq. (21 percent) in HFC and PFC emissions from the substitution of ozone depleting substances for the period 1990 through 2004.

4.18. HCFC-22 Production (IPCC Source Category 2E1)

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. Since 2000, U.S. production has fluctuated. 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.[14] 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 is generally vented to the atmosphere as an unwanted by-product, but it is sometimes captured for use in a limited number of applications.

Emissions of HFC-23 in 2005 were estimated to be 16.5 Tg CO_2 Eq. (1.3 Gg) (Table 4-67). This quantity represents a 6 percent increase from 2004 emissions and a 53 percent decline from 1990 emissions. The increase in 2005 emissions is due primarily to a slight increases in the HFC-23 emission rate (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured), while the decline from 1990 emissions is primarily due to the large decline in the HFC-23 emission rate between 1990 and 2005. Three HCFC-22 production plants operated in the United States in 2005, two of which used thermal oxidation to significantly lower their HFC-23 emissions.

Table 4-67: HFC-23 Emissions from HCFC-22 Production ($Tg\ CO_2$ Eq. and Gg)

Year	$Tg\ CO_2$ Eq.	Gg
1990	35.0	3
1995	27.0	2
2000	29.8	3
2001	19.8	2
2002	19.8	2
2003	12.3	1
2004	15.6	1
2005	16.5	1

---

[14] 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]

Methodology

The methodology employed for estimating emissions is based upon measurements at individual HCFC-22 production plants. 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. The other plants periodically measure HFC-23 concentrations in the output stream using gas chromatography. This information is combined with information on quantities of critical feed components (e.g., HF) and/or products (HCFC-22) to estimate HFC-23 emissions using a material balance approach. HFC-23 concentrations are determined at the point the gas leaves the chemical reactor; therefore, estimates also include fugitive emissions.

Production data and emission estimates were prepared in cooperation with the U.S. manufacturers of HCFC-22 (ARAP 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006; RTI 1997). Annual estimates of U.S. HCFC-22 production are presented in Table 4-68.

Table 4-68: HCFC-22 Production (Gg)

Year	Gg
1990	139
1995	155
2000	187
2001	152
2002	144
2003	138
2004	155
2005	156

Uncertainty

A high level of confidence has been attributed to the HFC-23 concentration data employed because measurements were conducted frequently and accounted for day-to-day and process variability. The results of the Tier 1 quantitative uncertainly analysis are summarized in Table 4-69. HFC-23 emissions from HCFC-22 production were estimated to be between 14.9 and 18.2 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 10 percent above and 10 percent below the 2005 emission estimate of 16.5 Tg CO_2 Eq.

4.19. 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 switch gear through seals, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and

Table 4-69: Tier 1 Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	16.5	14.9	18.2	-10%	+10%

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

Table 4-70: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufactures (Tg CO_2 Eq.)

Year	Electric Power Systems	Electrical Equipment Manufacturers	Total
1990	26.8	0.3	27.1
1995	21.3	0.5	21.8
2000	14.5	0.7	15.2
2001	14.4	0.7	15.1
2002	13.7	0.7	14.3
2003	13.2	0.7	13.8
2004	12.9	0.7	13.6
2005	12.5	0.7	13.2

Table 4-71: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufactures (Gg)

Year	Emissions
1990	1.1
1995	0.9
2000	0.6
2001	0.6
2002	0.6
2003	0.6
2004	0.6
2005	0.6

disposal. Emissions of SF_6 from equipment manufacturing and from electrical transmission and distribution systems were estimated to be 13.2 Tg CO_2 Eq. (0.6 Gg) in 2005. This quantity represents a 51 percent decrease from the estimate for 1990 (see Table 4-70 and Table 4-71). This decrease is believed to be a response to increases in the price of SF_6 during the 1990s and to growing awareness of the environmental impact of SF_6 emissions, through programs such as the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems.

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 to 2005 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2005 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) utilities' transmission miles as reported in the 2001 and 2004 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004). (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV.) Over the period from 1999 to 2005, participating utilities represented between 31 percent and 39 percent of total U.S. transmission miles. For each year, the emissions reported by participating utilities were added to the emissions estimated for utilities that do not participate in the Partnership (i.e., non-partners).

Emissions from partner utilities were estimated using a combination of reported data and, where reported data were unavailable, interpolated or extrapolated data. If a partner utility did not provide data for a historical year, emissions were interpolated between years for which data were available. For 2005, if no data was provided, estimates were calculated based on historical trends or partner-specific emission reduction targets (i.e., emissions were assumed to decline linearly toward a partners' future stated goal). In 2005, non-reporting partners account for approximately 2 percent of the total emissions attributable to utilities involved in the SF_6 Emission Reduction Partnership.

Emissions from non-partners in every year since 1999 were estimated using the results of a regression analysis that showed that the emissions of 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 at or above 34.5 kV. The equations were developed based on the 1999 SF_6 emissions reported by 49 partner utilities (representing approximately 31 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 less 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 (less than 10,000 transmission miles, in kilograms):

$$\text{Emissions (kg)} = 0.874 \times \text{Transmission Miles}$$

Non-partner large utilities (more than 10,000 transmission miles, in kilograms):

$$\text{Emissions (kg)} = 0.558 \times \text{Transmission Miles}$$

Data on transmission miles for each non-partner utility for the years 2000 and 2003 were obtained from the 2001 and 2004 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004). Given that the U.S. transmission system grew by over 14,000 miles between 2000 and 2003, and that this increase probably occurred gradually, transmission mileage was assumed to increase exponentially at an annual rate of 0.7 percent between 2000 and 2003. This growth rate is assumed to have continued through 2005.

As a final step, total emissions were determined for each year by summing the partner emissions (reported to the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems), and the non-partner emissions (determined using the 1999 regression equation).

1990 to 1998 Emissions from Electric Power Systems

Because most participating utilities reported emissions only for 1999 through 2005, it was necessary to model SF_6 emissions from electric power systems for the years 1990 through 1998. To do so, it was assumed that U.S. emissions followed the same trajectory as global emissions from this source during the 1990 to 1998 period. To estimate global emissions, the RAND survey of global SF_6 sales were used, together with the following equation, 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). (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.)

$$\text{Emissions (kilograms)} = SF_6 \text{ purchased to refill existing equipment (kilograms)} + \text{nameplate capacity of retiring equipment (kilograms)}$$

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.

Sulfur hexafluoride purchased to refill existing equipment in a given year was assumed to be approximately equal to the SF_6 purchased by utilities in that year. 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 1998.

U.S. emissions between 1990 and 1998 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 15.3 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, but may have been significant during the 1990 through 1999 period. This factor was not accounted for; however, atmospheric studies confirmed that the downward trend in the estimated global emissions between 1995 and 1998 was real (see the Uncertainty discussion below).

1990 to 2005 Emissions from Manufacture of Electrical Equipment

The 1990 to 2005 emissions estimates for original equipment manufacturers (OEMs) were derived by assuming that manufacturing emissions equal 10 percent of the quantity of SF_6 charged into new equipment. The quantity of SF_6 charged into 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 charged into new equipment for 2001 to 2005 were assumed to equal that charged into equipment in 2000. 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 variables 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 4.9 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 2005 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 61 percent of U.S. transmission miles) 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 the quantity of SF_6 charged into equipment by equipment manufacturers, which is projected from 2000 data from NEMA, and the manufacturers' SF_6 emissions rate.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-72. Electrical Transmission and Distribution SF_6 emissions were estimated to be between 12.4 and 14.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 6 percent below and 7 percent above the emission estimate of 13.2 Tg CO_2 Eq.

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

Table 4-72: Tier 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Electrical Transmission and Distribution (Tg CO_2 Eq. and Percent)

Source	Gas	2005 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to 2005 Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Transmission and Distribution	SF_6	13.2	12.4	14.1	-6%	+7%

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

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. However, U.S. emission patterns may differ from global emission patterns.

Recalculations Discussion

Relative to the previous Inventory report, SF_6 emission estimates for the period 1990 through 2004 were updated based on (1) new data from EPA's SF_6 Emission Reduction Partnership, and (2) revisions to the assumptions used in estimating global emissions between 1990 and 1999. For the period 1999 through 2004, estimates have been revised to incorporate additional data from new partners. For the period 1990 through 1998, estimates have been revised by updating the estimated lifetime of electrical equipment and the estimated historical emission rate during equipment manufacturing. Previously, it was assumed that the equipment lifetime was 30 years, and that during manufacture 22.5 percent of the SF_6 purchased by equipment manufacturers was emitted. These variables have been revised to 40 years and 18.8 percent, respectively, to reflect new data presented in IPCC *Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Based on these revisions, SF_6 emissions from electric transmission and distribution have decreased by approximately 1 percent for each year during the 1999 to 2004 period. Between 1990 and 1998, estimates have changed between -16 percent (decrease) to +5 percent (increase) depending on the specific year, relative to the previous report.

4.20. Semiconductor Manufacture (IPCC Source Category 2F6)

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 2005, total weighted emissions of all fluorinated greenhouse gases by the U.S. semiconductor industry were estimated to be 4.3 Tg CO_2 Eq. Combined emissions of all fluorinated greenhouse gases are presented in Table 4-73 and Table 4-74. The rapid growth of this industry and the increasing complexity (growing number of layers) of semiconductor products led to an increase in emissions of 147 percent between 1990 and 1999. The emissions growth rate began to slow after 1997, and emissions declined by 41 percent between 1999 and 2005. The initial implementation of PFC emission reduction methods such as process optimization and abatement technologies is responsible for this decline. Together, these two trends resulted in a net increase in emissions of 47 percent between 1990 and 2005.

Table 4-73: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq.)

Gas	1990	1995	2000	2001	2002	2003	2004	2005
CF_4	0.7	1.3	1.8	1.3	1.1	1.0	1.2	1.1
C_2F_6	1.5	2.5	3.0	2.1	2.2	2.1	2.2	1.9
C_3F_8	0.0	+	0.1	0.1	0.1	0.1	0.0	0.0
C_4F_8	0.0	+	0.0	0.0	0.0	0.1	0.1	0.1
HFC-23	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.2
SF_6	0.5	0.9	1.1	0.8	0.7	0.8	0.9	1.0
NF_3*	0.0	0.1	0.1	0.1	0.3	0.2	0.3	0.2
Total	**2.9**	**5.0**	**6.3**	**4.5**	**4.4**	**4.3**	**4.7**	**4.3**

Note: Totals may not sum due to independent rounding.
* NF_3 emissions are presented for informational purposes, using a GWP of 8,000, and are not included in totals.
\+ Does not exceed 0.05 Tg CO_2 Eq.

Table 4-74: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Mg)

Gas	1990	1995	2000	2001	2002	2003	2004	2005
CF_4	115	192	281	202	175	161	185	163
C_2F_6	160	272	324	231	244	228	245	211
C_3F_8	0	0	17	14	9	13	6	4
C_4F_8	0	0	0	0	5	8	9	13
HFC-23	15	26	23	16	15	17	20	18
SF_6	22	38	46	31	28	35	38	40
NF_3	3	6	11	12	32	30	31	27

Methodology

Emissions from semiconductor manufacturing were estimated using three distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, and 2000 and beyond. For 1990 through 1994, emissions were estimated using the most recent version of EPA's PFC Emissions Vintage Model (PEVM) (Burton and Beizaie 2001).[15] PFC emissions per square centimeter of silicon increase as the number of layers in semiconductor devices increases. Thus, PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest feature size, which leads to an increasing number of layers),[16] and (2) product type (memory vs. logic).[17] PEVM derives historical consumption of silicon (i.e., square centimeters) by linewidth technology from published data on annual wafer starts and average wafer size (Burton and Beizaie 2001). 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) specific to product type (Burton and Beizaie 2001, ITRS 2005). The distribution of memory/logic devices ranges over the period covered from 52 percent logic devices in 1995 to 59 percent logic devices in 2000. These figures were used to determine emission factors that express emissions per average layer per unit of area of silicon consumed during product manufacture. The per-layer emission factor was based on the total annual emissions reported by participants in EPA's PFC Reduction/Climate Partnership for the Semiconductor Industry in 1995 and later years.

For 1995 through 1999, total U.S. emissions were extrapolated from the total annual emissions reported by the Partnership participants (2005 Aggregate PFC Emissions

---

[15] The most recent version of this model is v.3.2.0506.0507, completed in September 2005.

[16] 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 requires 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, 2005).

[17] Memory devices manufactured with the same feature sizes as microprocessors (a logic device) require approximately one-half the number of interconnect layers (ITRS, 2005).

provided to EPA by Latham & Watkins). The emissions reported by the participants were divided by the ratio of the total layer-weighted capacity of the plants operated by the participants and the total layer-weighted capacity of all of the semiconductor plants in the United States; this ratio represents the share of layer-weighted capacity attributable to partnership participants. The layer-weighted capacity of a plant (or group of plants) consists of the silicon capacity of that plant multiplied by the estimated number of layers used to fabricate products at that plant. This method assumes that participants and non-participants have similar capacity utilizations and per-layer emission factors. Plant capacity, linewidth technology, products manufactured information is contained in the World Fab Watch (WFW) database, which is updated quarterly (see for example, Semiconductor Equipment and Materials Industry 2006).

The U.S. estimate for the years 2000 through 2005—the period during which partners began the consequential application of PFC-reduction measures—was based on a different estimation method. The emissions reported by Partnership participants 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), however, were estimated using PEVM and the method described above. (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. figure by the non-partner share of total layer-weighted silicon capacity for each year (as described above). Annual updates to PEVM reflect published figures for actual silicon consumption from VLSI Research, Inc. as well as revisions and additions to the world population of semiconductor manufacturing plants (see Semiconductor Equipment and Materials Industry 2006).[18,19]

Two different approaches were also used to estimate the distribution of emissions of specific PFCs. Before 1999, when there was no consequential adoption of PFC-reducing measures, a fixed distribution was assumed to apply to the entire U.S. industry. This distribution was based upon the average PFC purchases 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 2005 period, the 1990 through 1999 distribution was assumed to apply to the non-Partners. Partners, however, began to report gas-specific emissions during this period. Thus, gas specific emissions for 2000 through 2005 were estimated by adding the emissions reported by the Partners to those estimated for the non-Partners.[20]

Partners estimate their emissions using a range of methods. For 2005, we assume that most partners used a method as least as accurate as the IPCC's Tier 2c Methodology, recommended in the IPCC (2000), since that has been their approach for the past several years. However, this is expected to change with publication of the updated IPCC (2006). The partners with relatively high emissions typically use the more accurate IPCC 2b or 2a methods, multiplying estimates of their PFC consumption by process-specific emission factors that they have either measured or obtained from tool suppliers.

Data used to develop emission estimates were prepared in cooperation with the Partnership. Estimates of operating plant capacities and characteristics for participants and non-participants were derived from the Semiconductor Equipment and Materials Industry (SEMI) *World Fab Watch* (formerly *International Fabs on Disk*) database (1996 to 2006). Estimates of silicon consumed by line-width from 1990 through 2005 were derived from information from VLSI Research (2005), and the number of layers per line-

---

[18] Special attention was given to the manufacturing capacity of plants that use wafers with 300 mm diameters because the actual capacity of these plants in 2004 is below design capacity, the figure provided in WFW. 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 percentage points. 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 but approximately 70 percent of the design capacity. For 2005, actual installed capacities was estimated using an entry in the World Fab Watch database (April 2006 Edition) called "wafers/month, 8-inch equivalent, which denotes the actual installed capacity instead of the fully-ramped capacity.

[19] In 2005, the trend in co-owernship of manufacturing facilities in the industry continued. Several manufacturers, who are partners, now operate fabs with other manufacturers, who in some cases are also partners and in other cases not partners. Special attention was given to this occurrence when estimating the partner and non-partner shares of U.S. layer-weighted manufacturing capacity.

[20] In recent years, the Partnership started reporting gas-specific emissions using GWP values from the Third Assessment Report (TAR), while in previous years the values were taken from the Second Assessment Report (SAR). The emissions reported here are restated using GWPs from the SAR.

width was obtained from International Technology Roadmap for Semiconductors: 1998–2004 (Burton and Beizaie 2001, ITRS 2005).

Uncertainty

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:

U.S. emissions = PEVM estimate - (Partnership share × PEVM estimate) + Partnership submittal

The Monte Carlo analysis results presented below relied on estimates of uncertainty attributed to the three variables on the right side of the equation. Estimates of uncertainty for the three variables were in turn developed using the estimated uncertainties associated with the individual inputs to each variable, error propagation analysis, and expert judgment. For the relative uncertainty associated with the PEVM estimate in 2005, an uncertainty of ±20 percent was estimated, using the calculus of error propagation and considering the aggregate average emission factor, world silicon consumption, and the U.S. share of layer-weighted silicon capacity. For the share of U.S. layer-weighted silicon capacity accounted for by Partners, a relative uncertainty of ±10 percent was estimated based on information from the firm that compiled the World Fab Watch database (SMA 2003). For the aggregate PFC emissions data supplied to the partnership, a relative uncertainty of approximately ±10 percent was estimated (representing a 95 percent confidence interval).

Consideration was also given to the nature and magnitude of the potential bias that PEVM 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 PEVM overstates the average number of layers across all product categories and all manufacturing technologies for 2004 by 0.12 layers or 2.9 percent. This bias is represented in the uncertainty analysis by deducting the absolute bias value from the PEVM emission estimate when it is incorporated into the Monte Carlo analysis.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-75. The emissions estimate for total U.S. PFC emissions from semiconductor manufacturing were estimated to be between 3.6 and 5.4 Tg CO_2 Eq. at a 95 percent confidence level. This range represents 21 percent below to 20 percent above the 2005 emission estimate of 4.3 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.

Planned Improvements

The method to estimate non-partner-related emissions (i.e., PEVM) is not expected to change (with the exception of possible future updates to emission factors and added technology nodes). 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). 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.)

Table 4-75: Tier 2 Quantitative Uncertainty Estimates for HFC, PFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq. and Percent)

Source	Gases	2005 Emission Estimate[a] (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[b] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Semiconductor Manufacture	HFC, PFC, and SF_6	4.3	3.6	5.4	-21%	+20%

[a] Because the uncertainty analysis covered all emissions (including NF_3), the emission estimate presented here does not match that shown in Table 4-73.

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

4.21. 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. In 2005, the United States was the fourth largest producer of primary aluminum, with approximately eight percent of the world total (USGS 2006). 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 C lining that serves as the cathode. C is also contained in the anode, which can be a C mass of paste, coke briquettes, or prebaked C blocks from petroleum coke. During reduction, most of this C is oxidized and released to the atmosphere as CO_2.

Process emissions of CO_2 from aluminum production were estimated to be 4.2 Tg CO_2 Eq. (4,208 Gg) in 2005 (see Table 4-76). The C anodes consumed during aluminum production consist of petroleum coke and, to a minor extent, coal tar pitch. The petroleum coke portion of the total CO_2 process emissions from aluminum production is considered to be a non-energy use of petroleum coke, and is accounted for here and not under the CO_2 from Fossil Fuel Combustion source category of the Energy sector. Similarly, the coal tar pitch portion of these CO_2 process emissions is accounted for here rather than in the Iron and Steel source category of the Industrial Processes sector.

In addition to CO_2 emissions, the aluminum production industry is also a source of PFC emissions. During the smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, which are termed "anode effects." These anode effects cause C from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF_4 and C_2F_6. In general, the magnitude of emissions for a given 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 both declined by 84 percent to 2.5 Tg CO_2 Eq. of CF_4 (0.4 Gg) and 0.4 Tg CO_2 Eq. of C_2F_6 (0.05 Gg) in 2005, as shown in Table 4-77 and Table 4-78. This decline is due both to reductions in domestic aluminum production and to actions taken by

Table 4-76: CO_2 Emissions from Aluminum Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	6.8	6,831
1995	5.7	5,659
2000	6.1	6,086
2001	4.4	4,381
2002	4.5	4,490
2003	4.5	4,503
2004	4.2	4,231
2005	4.2	4,208

Table 4-77: PFC Emissions from Aluminum Production (Tg CO_2 Eq.)

Year	CF_4	C_2F_6	Total
1990	15.9	2.7	18.5
1995	10.2	1.7	11.8
2000	7.8	0.8	8.6
2001	3.0	0.4	3.5
2002	4.6	0.7	5.2
2003	3.3	0.5	3.8
2004	2.4	0.4	2.8
2005	2.5	0.4	3.0

Note: Totals may not sum due to independent rounding.

Table 4-78: PFC Emissions from Aluminum Production (Gg)

Year	CF_4	C_2F_6
1990	2.4	0.3
1995	1.6	0.2
2000	1.2	0.1
2001	0.5	+
2002	0.7	0.1
2003	0.5	0.1
2004	0.4	+
2005	0.4	+

+ Does not exceed 0.05 Gg

aluminum smelting companies to reduce the frequency and duration of anode effects. Since 1990, aluminum production has declined by 39 percent, while the average CF_4 and C_2F_6 emission rates (per metric ton of aluminum produced) have each been reduced by 74 percent.

In 2005, U.S. primary aluminum production totaled approximately 2.5 million metric tons, similar to 2004 production levels. Due to high electric power costs in various regions of the country, aluminum production has been curtailed at several U.S. smelters, which resulted in 2005 production levels that were approximately 34 percent lower than the levels in 1999, the year with the highest production over the prior decade, 1995 through 2005. The transportation industry remained the largest domestic consumer of primary aluminum, accounting for about 39 percent of U.S. consumption (USGS 2006).

Methodology

CO_2 emissions released during aluminum production were estimated using the combined application of process-specific emissions estimates modeling with individual partner reported data. These estimates are achieved through 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 C anode, as described by the following reaction.

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

For prebake smelter technologies, CO_2 is also emitted during the anode baking process. These emissions can account for approximately 10 percent of total process CO_2 emissions from prebake smelters. The CO_2 emission factor employed was estimated from the production of primary aluminum metal and the C consumed by the process. Emissions vary depending on the specific technology used by each plant (e.g., prebake or Søderberg). CO_2 process emissions were estimated using the methodology recommended by IPCC (2006).

The prebake process specific formula recommended by IPCC (2006) accounts for various parameters, including net C consumption, and the sulfur, ash, and impurity content of the baked anode. For anode baking emissions, process formulas account 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. The Søderberg process formula accounts for the weight of paste consumed per metric ton of aluminum produced, and pitch properties, including sulfur, hydrogen, and ash content.

Through the VAIP, process data have been reported for 1990, 2000, 2003, 2004, and 2005. 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, and by 14 out of 15 operating smelters in 2005. For years where CO_2 process data were not reported by these companies, estimates were developed through linear interpolation, and/or assuming industry default values.

In the absence of any smelter-specific process data (i.e., 1 out of 15 smelters in 2005, and 5 out of 23 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 all operating smelters were reported under the VAIP in 2005. Between 1990 and 2004, 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 2006), with allocation to specific smelters based on reported production capacities (USGS 2002).

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 = Slope coefficient (kg PFC/metric ton Al/(Anode Effect minutes/cell day))

Anode Effect Minutes/Cell-Day = Anode Effect Frequency/Cell-Day × (Anode Effect Duration (minutes)

Smelter-specific slope coefficients that are based on field measurements yield the most accurate results. To estimate emissions between 1990 and 2004, smelter-specific coefficients were available and were used for 12 out of the 23 U.S. smelters that operated during at least part of that period. To estimate 2005 emissions, smelter-specific coefficients were available and were used for 5 out of the 15 operating U.S. smelters, representing approximately 33 percent of operating 2005 U.S. production capacity. For the remaining 10 operating smelters, technology-specific slope coefficients from IPCC (2001) were applied. 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. In 2005, smelter-specific anode effect data were available for all operating smelters. Where smelter-specific anode effect data were not available (i.e., 2 out of 23 smelters between 1990 and 2004), industry averages were used. For all smelters, emission factors were multiplied by annual production to estimate annual emissions at the smelter level. In 2005, smelter-specific production data were available for all operating smelters. Between 1990 and 2004, production data has been provided by 21 of the 23 U.S. smelters. Emissions were then aggregated across smelters to estimate national emissions. The methodology used to estimate emissions is consistent with the methodologies recommended by IPCC (2006).

National primary aluminum production data for 1990 through 2001 (see Table 4-79) were obtained from USGS, *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1995, 1998, 2000, 2001, 2002). For 2002 through 2005, national aluminum production data were obtained from the United States Aluminum Association's *Primary Aluminum Statistics* (USAA 2004, 2005, 2006).

Table 4-79: Production of Primary Aluminum (Gg)

Year	Gg
1990	4,048
1995	3,375
2000	3,668
2001	2,637
2002	2,705
2003	2,705
2004	2,517
2005	2,478

Uncertainty

The overall uncertainties associated with the 2005 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 reported production data was assumed to be 2 percent (IPCC 2006). For additional variables, such as net C 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 or company and for the U.S. aluminum industry as a whole.

The results of this quantitative uncertainty analysis are summarized in Table 4-80. Aluminum production-related CO_2 emissions were estimated to be between 4.0 and 4.4 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the emission estimate of 4.2 Tg CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 2.3 and 2.7 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below to 8 percent above the emission estimate of 2.5 Tg CO_2 Eq. Finally, aluminum production-related C_2F_6 emissions were estimated to be between 0.4 and 0.5 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 15 percent below to 16 percent above the emission estimate of 0.4 Tg CO_2 Eq.

Note that the 2005 emission estimate was developed using IPCC (2001) slope coefficients for the 10 operating smelters without site-specific PFC measurements. If these slope coefficients were revised to incorporate recent IPCC (2006) slope data, overall PFC emission estimates for 2005 would be on the order of 10 percent lower than current

Table 4-80: Tier 2 Quantitative Uncertainty Estimates for CO_2 and PFC Emissions from Aluminum Production (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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
Aluminum Production	CO_2	4.2	4.0	4.4	-5%	+5%
Aluminum Production	CF_4	2.5	2.3	2.7	-8%	+8%
Aluminum Production	C_2F_6	0.4	0.4	0.5	-15%	+16%

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

estimates. Additionally, since these smelters are owned by one company, data have been reported on a company-wide basis as totals or weighted averages. Consequently, uncertainties in anode effect minutes per cell day, slope coefficients, and aluminum production have been applied to the company as a whole, and not on a smelter-specific basis. 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 uncertainties calculated above for the total U.S. 2005 emission estimates for CF_4 and C_2F_6 are also high.

This Inventory may slightly underestimate greenhouse gas emissions from aluminum production and casting because it does not account for the possible use of SF_6 as a cover gas or a fluxing and degassing agent in experimental and specialized casting operations. The extent of such use in the United States is not known. Historically, SF_6 emissions from aluminum activities have been omitted from estimates of global SF_6 emissions, with the explanation that any emissions would be insignificant (Ko et al. 1993, Victor and MacDonald 1998). The concentration of SF_6 in the mixtures is small and a portion of the SF_6 is decomposed in the process (MacNeal et al. 1990, Gariepy and Dube 1992, Ko et al. 1993, Ten Eyck and Lukens 1996, Zurecki 1996).

Recalculations Discussion

Relative to the previous Inventory report, CO_2 emission estimates for the period 1990 through 2004 were updated based on revisions to default parameters used in the estimation methodology. Previous CO_2 emission estimates were based on default emission factors defined by IPCC/UNEP/OED/IEA (1997) and *Aluminum Sector Greenhouse Gas Protocol* (IAI 2003). Current estimates utilize default parameters defined in IPCC (2006). Based on this revision, CO_2 emissions from aluminum production have decreased by approximately 3 percent for each year during the 1990 to 2004 period relative to the previous report.

The default slope coefficients used to estimate PFC emissions from two smelters that have not developed Tier 3b site-specific estimates were revised to reflect data presented in IPCC (2006). This change has resulted in an increase in PFC emissions of approximately 1 percent in 1990, an average decrease of 0.1 percent between 1991 and 1996 and 2002 through 2004, and an average decrease of 6 percent from 1997 through 2001, relative to the estimates developed for the 1990 to 2004 Inventory.

4.22. Magnesium Production and Processing (IPCC Source Category 2C4)

The magnesium metal production and casting industry uses sulfur hexafluoride (SF_6) as a cover gas to prevent the rapid oxidation of molten magnesium in the presence of air. 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 assumed to be negligible and thus all SF_6 used is assumed to be emitted into the atmosphere. Sulfur hexafluoride has been used in this application around the world for the last twenty years.

The magnesium industry emitted 2.7 Tg CO_2 Eq. (0.1 Gg) of SF_6 in 2005, representing an increase of approximately 2 percent from 2004 emissions (see Table 4-81). A planned expansion of primary magnesium production in the United States has been delayed due to unfavorable market conditions. Antidumping duties imposed on Chinese

Table 4-81: 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
1995	5.6	0.2
2000	3.0	0.1
2001	2.4	0.1
2002	2.4	0.1
2003	2.9	0.1
2004	2.6	0.1
2005	2.7	0.1

imports by the U.S. International Trade Commission have shifted the majority of U.S. demand for primary magnesium to imports from Canada, Israel, and Russia (USGS 2006). Die casting operations in the United States have remained stable and are expected to increase as demand for die cast parts for the automotive sector increases due to fuel efficiency design objectives.

Methodology

1999 to 2005 Emissions

Emission estimates for the magnesium industry from 1999 through 2005 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 (i.e., die, sand, permanent mold, wrought, and anode casting). Absolute emissions for 1999 through 2005 from primary production, secondary production (i.e., recycling), and die casting were reported by Partnership participants. Emission factors for 2002 to 2005 for sand casting activities were also acquired through the Partnership. The 1999 through 2005 emissions from casting operations (other than die) were estimated by multiplying emission factors (kg SF_6 per metric ton of Mg produced or processed) by the amount of metal produced or consumed. U.S. magnesium metal production (primary and secondary) and consumption (casting) data from 1990 through 2005 were available from the USGS (USGS 2002, 2003, 2005a, 2005b, 2006). The emission factors for casting activities are provided below in Table 4-82. 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 1995 value of 1.1 kg SF_6 per metric ton, and the emission factor for secondary production is slightly lower than the industry-reported historic value of 1 kg SF_6 per metric ton.

Die casting emissions for 1999 through 2005, which accounted for 33 to 52 percent of all SF_6 emissions from the U.S. magnesium industry during this period, were estimated based on information supplied by industry Partners. From 2000 to 2005, Partners accounted for all U.S. die casting that was tracked by USGS. If Partners did not report emissions data for a certain year, SF_6 emissions data were estimated using available information on emission factors and production reported in prior years. Each non-reporting Partner's production was assumed to have remained constant since the last report, while each non-reporting Partner's emission factor was assumed to have followed the same trend as the emission factors for reporting die casting partners. Emissions from non-reporting Partners are estimated to have accounted for less than 15 percent of die-casting emissions in all years since 1999.

In 1999, Partners did not account for all die casting tracked by USGS, and, therefore, it was necessary to estimate the emissions of die casters who were not Partners. Die casters who were not Partners were assumed to be similar to Partners who cast small parts. Due to process requirements, these casters consume larger quantities of SF_6 per metric ton of processed magnesium than casters that process large parts. Consequently, emission estimates from this group of die casters were developed using an average emission factor of 5.2 kg SF_6 per metric ton of magnesium. The emission factors for the other industry sectors (i.e., permanent mold,

Table 4-82: 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	0.73	2	1	1
2001	0.77	2	1	1
2002	0.70	2	1	1
2003	0.84	2	1	1
2004	0.78	2	1	1
2005	0.75	2	1	1

[a] Weighted average that includes an estimated emission factor of 5.2 kg SF_6 per metric ton of magnesium for die casters that do not participate in the Partnership.

wrought, and anode casting) were based on discussions with industry representatives.

1990 to 1998 Emissions

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 1996. These factors were based on information reported 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, based on an international survey (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). The emission factor for sand casting between 1990 and 2001 was assumed to have been the same as the 2002 emission factor provided by Partners for this process. The emission factor for secondary production from 1990 through 1998 was similarly assumed to be constant at 1 kg per metric ton. 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 4-82.

Uncertainty

To estimate the uncertainty of the estimated 2005 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 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. In general, where precise quantitative information was not available on the uncertainty of a parameter, an upper-bound value was used.

Additional uncertainties exist in these estimates, 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 at hot-chambered die casting machines on the order of 10 percent (Bartos et al. 2003). As is the case for other sources of SF_6 emissions, total SF_6 consumption data for magnesium production and processing in the United States were not available. Sulfur hexafluoride may also be used as a cover gas for the casting of molten aluminum with high magnesium content; however, to what extent this technique is used in the United States is unknown.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-83. SF_6 emissions associated with magnesium production and processing were estimated to be between 2.6 and 2.8 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below to 4 percent above the 2005 emissions estimate of 2.7 Tg CO_2 Eq.

Recalculations Discussion

The methodology for estimating secondary magnesium production (recycling) emissions from 1999 to 2005 was adjusted to rely solely on Partner-reported information, because this was believed to yield a more accurate estimate than adding Partner-reported emissions to the product of USGS secondary magnesium production and a default industry SF_6 emission factor. In previous years, the "remelt"

Table 4-83: Tier 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Magnesium Production and Processing (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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 and Processing	SF_6	2.7	2.6	2.8	-4%	+4%

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

activity reported by Partners was small compared to the secondary production reported by USGS, and it was uncertain whether this remelt activity was included in USGS totals. Thus, emissions were estimated both for Partner-reported remelt and for USGS-reported secondary production. With the addition of new Partners, however, it appears that Partner-reported remelt is actually a more complete estimate of U.S. secondary production than the USGS value. Thus, to avoid double-counting, only the emissions reported by the Partners are included in the totals for the time series. The change resulted in a decrease of 0.2 Tg CO_2 Eq. (approximately 7 percent) in SF_6 emissions from magnesium production and processing for 1999 to 2002, and a decrease in SF_6 emissions of 0.1 Tg CO_2 Eq. (approximately 4 percent) for 2003 to 2004 relative to the previous report.

Planned Improvements

As more work assessing the degree of cover gas degradation and associated byproducts is undertaken and published, results could potentially be used to refine the emission estimates, which currently assume (per IPCC *Good Practice Guidance*, IPCC 2000) that all SF_6 utilized is emitted to the atmosphere. EPA-funded measurements of SF_6 in hot chamber die casting have indicated that the latter assumption may be incorrect, with observed SF_6 degradation on the order of 10 percent (Bartos et al. 2003). More recent EPA-funded measurement studies have confirmed this observation for cold chamber die casting (EPA 2004). 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 decompose during their exposure to the molten metal. Additionally, as more companies join the Partnership, in particular those from sectors not currently represented such as permanent mold and anode casting, emission factors will be refined to incorporate these additional data.

4.23. Industrial Sources of Indirect Greenhouse Gases

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 2005 are reported in Table 4-84.

Table 4-84: NO_x, CO, and NMVOC Emissions from Industrial Processes (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
NO_x	**591**	**607**	**626**	**656**	**532**	**533**	**534**	**535**
Other Industrial Processes	343	362	434	457	389	390	390	391
Chemical & Allied Product Manufacturing	152	143	95	97	63	63	63	63
Metals Processing	88	89	81	86	63	63	63	63
Storage and Transport	3	5	14	15	17	17	17	17
Miscellaneous*	5	8	2	1	1	1	1	1
CO	**4,125**	**3,959**	**2,217**	**2,339**	**1,710**	**1,730**	**1,751**	**1,772**
Metals Processing	2,395	2,159	1,175	1,252	895	906	917	928
Other Industrial Processes	487	566	538	558	445	450	456	461
Chemical & Allied Product Manufacturing	1,073	1,110	327	338	258	261	264	267
Storage and Transport	69	23	154	162	107	108	109	111
Miscellaneous*	101	102	23	30	5	5	5	4
NMVOCs	**2,422**	**2,642**	**1,773**	**1,769**	**1,811**	**1,813**	**1, 815**	**1,818**
Storage and Transport	1,352	1,499	1,067	1,082	1,140	1,142	1,143	1,144
Other Industrial Processes	364	408	412	381	400	401	401	402
Chemical & Allied Product Manufacturing	575	599	230	238	227	227	227	227
Metals Processing	111	113	61	65	42	42	42	42
Miscellaneous*	20	23	3	4	2	2	2	2

* 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 2006), 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

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.

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 Usage, 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 carbon equivalent basis in 2005 (see Table 5-1). Indirect greenhouse gas emissions also result from solvent and other product use, and are presented in Table 5-2 in teragrams of carbon dioxide equivalent (Tg CO_2 Eq.) and gigagrams (Gg).

5.1. Nitrous Oxide Product Usage (IPCC Source Category 3D)

N_2O is a clear, colorless, oxidizing liquefied gas, with a slightly sweet odor. N_2O is produced by thermally decomposing ammonium nitrate (NH_4NO_3), a chemical commonly used in fertilizers and explosives. The decomposition creates steam (H_2O) and N_2O through a low-pressure, low-temperature (500 °F) reaction. Once the steam is removed through condensation, the remaining N_2O is purified, compressed, dried, and liquefied for storage and distribution. Two companies operate a total of five N_2O production facilities in the United States (CGA 2003).

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;

Table 5-1: N_2O Emissions from Solvent and Other Product Use (Tg CO_2 Eq. and Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
N_2O Product Usage								
Tg CO_2 Eq.	4.3	4.5	4.8	4.8	4.3	4.3	4.3	4.3
Gg	14	14	15	15	14	14	14	14

Table 5-2: Indirect Greenhouse Gas Emissions from Solvent and Other Product Use (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
NMVOCs	5,216	5,609	4,384	4,547	3,911	3,916	3,921	3,926
CO	5	5	46	45	1	1	1	1
NO_x	1	3	3	3	5	5	5	5

Table 5-3: N_2O Emissions from N_2O Product Usage (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	4.3	14
1995	4.5	14
2000	4.8	15
2001	4.8	15
2002	4.3	14
2003	4.3	14
2004	4.3	14
2005	4.3	14

- 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 2005 was approximately 15 Gg. N_2O emissions were 4.3 Tg CO_2 Eq. (14 Gg) in 2005 (see 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).

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 emissions 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:

$$\begin{gathered}\text{N}_2\text{O Product Usage Emissions} = \\ \sum_i [\text{Total U.S. Production of N}_2\text{O}] \times \\ [\text{Share of Total Quantity of N}_2\text{O Usage by Sector i}] \times \\ [\text{Emissions Rate for Sector i}],\end{gathered}$$

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 2005, 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 decade of 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. The N_2O was allocated across these subcategories; 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, approximately 97.5 percent of the N_2O is not metabolized during anesthesia and quickly leaves the body in exhaled breath. Therefore, an emission factor of 97.5 percent was used for this subcategory (Tupman 2002). 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 emissions factor of 100 percent for this subcategory (Heydorn 1997). For the remaining subcategories, all of the N_2O is consumed/reacted during the process, and therefore the emissions rate was considered to be zero percent (Tupman 2002).

The 1990 through 1992 and 1996 N_2O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997). These data were provided as a range. For example, in 1996, Heydorn (1997) estimates N_2O production to range between 13.6 and 18.1 thousand metric tons. Tupman (2003) provided a narrower range for 1996 that falls within the production bounds described by Heydorn (1997). These data are considered more industry-specific and current. The midpoint of the narrower production range (15.9 to 18.1 thousand metric tons) 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 for 2004 and 2005 were held at the value provided for 2003. N_2O production data for 1990 through 2005 are presented in Table 5-4.

Table 5-4: N_2O Production (Gg)

Year	Gg
1990	16
1995	17
2000	17
2001	17
2002	15
2003	15
2004	15
2005	15

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 2001 share of total quantity of N_2O usage by sector was obtained from communication with a N_2O industry expert (Tupman 2002). The 2002 and 2003 share of total quantity of N_2O usage by sector was obtained from CGA (2002, 2003). Due to unavailable data, the share of total quantity of N_2O usage data for 2004 and 2005 was assumed to equal that of 2003. 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 substantiated by the *Encyclopedia of Chemical Technology* (Othmer 1990).

Uncertainty

The overall uncertainty associated with the 2005 N_2O emission estimate from N_2O product usage was calculated using the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance Tier 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions included that of 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 5-5. N_2O emissions from N_2O product usage were estimated to be between 4.1 and 4.5 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 4 percent below to 4 percent above the 2005 emissions estimate of 4.3 Tg CO_2 Eq.

Table 5-5: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions From N_2O Product Usage ($Tg CO_2$ Eq. and Percent)

Source	Gas	2005 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	4.3	4.1	4.5	-4%	+4%

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

Recalculations Discussion

The N_2O production values for 2002, 2003, and 2004 have been updated relative to the previous Inventory based on revised production data presented in CGA (2003). The updated production data resulted in a decrease of 0.5 Tg CO_2 Eq. (10 percent), respectively, in N_2O emissions from N_2O product usage for these years relative to the previous Inventory.

Planned Improvements

Planned improvements include a continued evaluation of alternative production statistics for cross-verification and a reassessment of subcategory usage to accurately represent the latest trends in the product usage.

5.2. Indirect Greenhouse Gas Emissions from Solvent Use

The use of solvents and other chemical products can result in emissions of various ozone precursors (i.e., indirect greenhouse gases).[1] Non-methane 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 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 2005 are reported in Table 5-6.

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 2006), 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

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.

---

[1] 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.

Table 5-6: Emissions of NO_x, CO, and NMVOC from Solvent Use (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
NO_x	**1**	**3**	**3**	**3**	**5**	**5**	**5**	**5**
Surface Coating	1	2	3	3	5	5	5	5
Degreasing	+	+	+	+	+	+	+	+
Graphic Arts	+	1	+	+	+	+	+	+
Dry Cleaning	+	+	+	+	+	+	+	+
Other Industrial Processes[a]	+	+	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+	+	+
Other	NA	+	+	+	+	+	+	+
CO	**5**	**5**	**46**	**45**	**1**	**1**	**1**	**1**
Surface Coating	+	1	46	45	1	1	1	1
Degreasing	+	+	+	+	+	+	+	+
Graphic Arts	+	+	+	+	+	+	+	+
Dry Cleaning	+	1	+	+	+	+	+	+
Other Industrial Processes[a]	4	3	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+	+	+
Other	NA	NA	+	+	+	+	+	+
NMVOCs	**5,216**	**5,609**	**4,384**	**4,547**	**3,911**	**3,916**	**3,921**	**3,926**
Surface Coating	2,289	2,432	1,767	1,863	1,602	1,604	1,606	1,608
Non-Industrial Processes[b]	1,724	1,858	1,676	1,707	1,468	1,470	1,472	1,474
Degreasing	675	716	316	331	285	285	286	286
Dry Cleaning	195	209	265	272	234	234	234	235
Graphic Arts	249	307	222	229	197	197	197	197
Other Industrial Processes[a]	85	87	98	103	89	89	89	89
Other	+	+	40	42	36	36	36	37

[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.

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 conversion of grassland to cultivated land, are presented in the Land Use, Land-Use Change, and Forestry chapter. CO_2 emissions from on-farm energy use are accounted for in the Energy chapter.

In 2005, the agricultural sector was responsible for emissions of 536.3 teragrams of CO_2 equivalent (Tg CO_2 Eq.), or 7 percent of total U.S. greenhouse gas emissions. Methane (CH_4) and nitrous oxide (N_2O) were the primary greenhouse gases emitted by agricultural activities. CH_4 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 78 percent. Manure management

Figure 6-1

2005 Agriculture Chapter Greenhouse Gas Sources

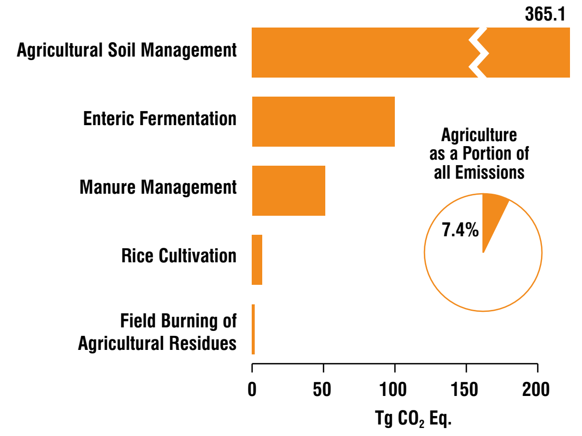


Table 6-1: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**154.4**	**164.0**	**160.5**	**161.0**	**161.2**	**161.1**	**158.7**	**161.2**
Enteric Fermentation	115.7	120.6	113.5	112.5	112.6	113.0	110.5	112.1
Manure Management	30.9	35.1	38.7	40.1	41.1	40.5	39.7	41.3
Rice Cultivation	7.1	7.6	7.5	7.6	6.8	6.9	7.6	6.9
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.8	0.7	0.8	0.9	0.9
N_2O	**375.9**	**362.7**	**386.9**	**399.2**	**376.2**	**359.9**	**348.7**	**375.1**
Agricultural Soil Management	366.9	353.4	376.8	389.0	366.1	350.2	338.8	365.1
Manure Management	8.6	9.0	9.6	9.8	9.7	9.3	9.4	9.5
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.4	0.4	0.5	0.5
Total	**530.3**	**526.8**	**547.4**	**560.3**	**537.4**	**521.1**	**507.4**	**536.3**

Note: Totals may not sum due to independent rounding.

Table 6-2: Emissions from Agriculture (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**7,353**	**7,811**	**7,643**	**7,668**	**7,678**	**7,673**	**7,556**	**7,674**
Enteric Fermentation	5,510	5,744	5,404	5,356	5,361	5,379	5,262	5,340
Manure Management	1,471	1,673	1,844	1,911	1,959	1,928	1,892	1,966
Rice Cultivation	339	363	357	364	325	328	360	328
Field Burning of Agricultural Residues	33	32	38	37	34	38	42	41
N_2O	**1,213**	**1,170**	**1,248**	**1,288**	**1,213**	**1,161**	**1,125**	**1,210**
Agricultural Soil Management	1,184	1,140	1,215	1,255	1,181	1,130	1,093	1,178
Manure Management	28	29	31	32	31	30	30	31
Field Burning of Agricultural Residues	1	1	1	1	1	1	2	2
CO	**691**	**663**	**792**	**774**	**709**	**800**	**879**	**858**
NO_x	**28**	**29**	**35**	**35**	**33**	**34**	**39**	**39**

Note: Totals may not sum due to independent rounding.

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 2005, CH_4 emissions from agricultural activities increased by 4 percent, while N_2O emissions fluctuated from year to year, but overall decreased by less than 1 percent. In addition to CH_4 and N_2O, field burning of agricultural residues was also a minor source of the indirect greenhouse gases carbon monoxide (CO) and nitrogen oxides (NO_x).

6.1. Enteric Fermentation (IPCC Source Category 4A)

CH_4 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 by-product, which can be exhaled or eructated by the animal. The amount of CH_4 produced and excreted 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 "forestomach," 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 domesticated 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 affects CH_4 emissions. In general, lower feed quality or higher feed intake lead to higher CH_4 emissions. Feed intake is positively related 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.

CH_4 emission estimates from enteric fermentation are provided in Table 6-3 and Table 6-4. Total livestock CH_4 emissions in 2005 were 112.1 Tg CO_2 Eq. (5,340 gigagrams [Gg]), increasing slightly since 2004 due to minor increases in most animal populations and dairy cow milk production in all regions. Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71 percent in 2005. Emissions from dairy cattle in 2005 accounted for 25 percent, and the remaining emissions were from horses, sheep, swine, and goats.

From 1990 to 2005, emissions from enteric fermentation have decreased by 3 percent. Generally, emissions have been decreasing since 1995, mainly due to decreasing populations of both beef and dairy cattle and improved feed quality for

Table 6-3: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	1990	1995	2000	2001	2002	2003	2004	2005
Beef Cattle	81.0	87.4	81.3	80.3	80.2	80.5	78.3	79.2
Dairy Cattle	28.9	27.7	27.0	26.9	27.1	27.3	27.0	27.7
Horses	1.9	1.9	2.0	2.0	2.0	2.0	2.0	2.0
Sheep	1.9	1.5	1.2	1.2	1.1	1.1	1.0	1.0
Swine	1.7	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Goats	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Total	**115.7**	**120.6**	**113.5**	**112.5**	**112.6**	**113.0**	**110.5**	**112.1**

Note: Totals may not sum due to independent rounding.

Table 6-4: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	1990	1995	2000	2001	2002	2003	2004	2005
Beef Cattle	3,859	4,160	3,869	3,825	3,821	3,832	3,730	3,772
Dairy Cattle	1,375	1,320	1,283	1,280	1,288	1,299	1,285	1,319
Horses	91	92	94	95	95	95	95	95
Sheep	91	72	56	55	53	51	49	49
Swine	81	88	88	88	90	90	91	91
Goats	13	12	12	12	13	13	13	13
Total	**5,510**	**5,744**	**5,404**	**5,356**	**5,361**	**5,379**	**5,262**	**5,340**

Note: Totals may not sum due to independent rounding.

feedlot cattle. During this timeframe, populations of sheep have decreased by an average annual rate of about 4 percent per year while horse, goat, and swine populations have remained relatively constant.

Methodology

Livestock emission estimates 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., Intergovernmental Panel on Climate Change [IPCC] Tier 2) was therefore applied to estimate emissions for all cattle except for bulls. Emission estimates for other domesticated animals (horses, sheep, swine, goats, and bulls) 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 describes the quantity of CH_4 produced by individual ruminant animals, particularly cattle. A detailed model that incorporates this information and other analyses of livestock population, feeding practices and production characteristics was used to estimate emissions from cattle populations.

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 model cohorts of individual animal types and their specific emissions 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 National Agricultural Statistics

Service (1995a,b; 1999a,c,d,f,g; 2000a,c,d,e; 2001a,c,d,f; 2002a,c,d,f; 2003a,c,d,f; 2004a,c,d,f, 2005a-d, 2006a-d).

Diet characteristics were estimated by region for U.S. dairy, beef, and feedlot cattle. These estimates were used to calculate Digestible Energy (DE) values and CH_4 conversion rates (Y_m) for each population category. The IPCC recommends Y_m values of 3.5 to 4.5 percent for feedlot cattle and 5.5 to 6.5 percent for other well-fed cattle consuming temperate-climate feed types. 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, rather than using the recommended IPCC values. 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, expert opinion, and modeling of animal physiology. The diet characteristics for dairy cattle were from Donovan (1999), while those for beef cattle were derived from NRC (2000). DE and Y_m for dairy cows were calculated from diet characteristics using a model simulating ruminant digestion in growing and/or lactating cattle (Donovan and Baldwin 1999). For feedlot animals, DE and Y_m values recommended by Johnson (1999) were used. Values from EPA (1993) were used for dairy replacement heifers. For grazing beef cattle, DE values were based on diet information in NRC (2000) and Y_m values were based on Johnson (2002). Weight data were estimated from Feedstuffs (1998), Western Dairyman (1998), and expert opinion. See Annex 3.9 for more details on the method used to characterize cattle diets in the United States.

To estimate CH_4 emissions from cattle, the population was divided into region, age, sub-type (e.g., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, and heifer and steer in feedlots), and production (e.g., pregnant, lactating) groupings to more fully capture differences in CH_4 emissions from these animal types. Cattle diet characteristics were used to develop regional emission factors for each sub-category. Tier 2 equations from IPCC (2000) were used 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, and heifer feedlot animals. To estimate emissions from cattle, population data were multiplied by the 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. CH_4 emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2005. 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 these other livestock types, except horses and goats, as well as feedlot placement information were obtained for all years from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1995a,c, 1998a-b, 1999a,b,e,f, 2000a,b,e,f, 2001 a,b,e,f, 2002 a,b,e,f, 2003 a,b,e,f, 2004a,b,e-h, 2005a,d-h, 2006a,d-h). Horse population data were obtained from the FAOSTAT database (FAO 2006), because USDA does not estimate U.S. horse populations annually. Goat population data for 1992, 1997, and 2002 were obtained from the Census of Agriculture (USDA 2005i); these data were interpolated and extrapolated to derive estimates for the other years. Information regarding poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service personnel (Lange 2000). Additional population data for different farm size categories for dairy and swine were obtained from the *1992 and 1997 Census of Agriculture* (USDA 2005i). CH_4 emissions from sheep, goats, swine, and horses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC/UNEP/OECD/IEA 1997). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. The methodology is the same as that recommended by IPCC (IPCC/UNEP/OECD/IEA 1997, IPCC 2000).

See Annex 3.9 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation.

Uncertainty

Quantitative uncertainty of this source category was performed through the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique as described in ICF (2003). These estimates were developed for the 2001 inventory estimates. No significant changes occurred in the method of data collection, data estimation methodology, or other factors that influence the uncertainty ranges around the 2005 activity data and emission factor input variables. Consequently, these uncertainty estimates were directly applied to the 2005 emission estimates.

A total of 185 primary input variables (177 for cattle and 8 for non-cattle) were identified as key input variables for uncertainty analysis. The 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). For some key input variables, the uncertainty ranges around their estimates (used for inventory estimation) were collected from published documents and other public sources. 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 as educated estimates.

The uncertainty ranges associated with the activity-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 (Table 6-5) indicate that, on average, the emission estimate range of this source is approximately 99.8 to 132.3 Tg CO_2 Eq., within the range of approximately 11 percent below and 18 percent above the actual 2005 emission estimate of 112.1 Tg CO_2 Eq. Among the individual 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. Consequently, the cattle sub-source categories together contribute to the largest degree of uncertainty in the inventory estimates of CH_4 emissions from livestock enteric fermentation. Among non-cattle, horses account for the largest degree of uncertainty in the inventory emission estimates.

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. Particular emphasis was placed this year on cattle population and growth data, and on evaluating the effects of data updates as described in the recalculations discussion below.

Recalculations Discussion

While there were no changes in the methodologies used for estimating CH_4 emissions from enteric fermentation, emissions were revised slightly due to changes in data. USDA published revised population estimates which affected historical emissions estimated for swine, sheep, goats, and poultry. Recent historical emission estimates also changed for certain beef and dairy populations as a result USDA inputs and the calving rate described below.

The emission factor for bulls has also changed according to IPCC (2006). Previously, the emission factor for bulls was 100 kg CH_4/head/yr, which in the 2006 IPCC Guidelines was changed to 53 kg CH_4/head/yr. This change in the emission factor resulted in an annual 47 percent decrease in emissions from bulls.

Several changes to previously reported emissions occurred due to revisions to population data and a change to the emissions factor for bulls. Year 2002 total (dairy and beef) cattle CH_4 emissions decreased by 2 percent. For 2004, beef cattle CH_4 emissions decreased 2.6 percent while dairy cattle emissions remained relatively constant. The majority of the change in emissions from beef cattle is a result of the change in emission factor for bulls. The decreased emission factor in bull emissions from 1990 through 2005 resulted in a decrease in CH_4 emissions for each of those years. In 2004,

Table 6-5: Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq. and Percent)

Source	Gas	2005 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a, b] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Enteric Fermentation	CH_4	112.1	99.8	132.3	-11%	+18%

[a] Range of emission 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 and applied to 2005 estimates.

this change lowered emissions by 100 Gg (2.0 percent of total enteric fermentation emissions from all animals). Recent historical emission estimates for swine changed (by less than one half of one percent of respective 2004 emissions) as a result of the USDA revisions described above.

Planned Improvements

Continued research and regular updates are necessary to maintain a current model of cattle diet characterization, feedlot placement data, rates of weight gain and calving, among other data inputs. While EPA has no plans for methodological changes in the modeling framework, the opportunity exists to continue to refine the model's results through identifying and improving individual data inputs. Research is currently underway to differentiate emissions from "dry" and lactating cows within the model. This improvement to the model would improve inventory estimates by taking into account the milk production for lactating cows. Other research is currently underway to identify updates of this nature.

6.2. Manure Management (IPCC Source Category 4B)

The management of livestock manure can produce anthropogenic CH_4 and N_2O emissions. CH_4 is produced by the anaerobic decomposition of manure. N_2O is produced as part of the nitrogen cycle through the nitrification and denitrification of the organic nitrogen in livestock manure and urine.[1]

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 N_2O 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 N_2O emissions to occur, the manure must first be handled aerobically where ammonia or organic nitrogen is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to nitrogen gas (N_2), with intermediate production of N_2O and nitric oxide (NO) (denitrification) (Groffman et al. 2000). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. A very small portion of the total nitrogen excreted is expected to convert to N_2O in the waste management system.

Estimates of CH_4 emissions in 2005 were 41.3 Tg CO_2 Eq. (1,966 Gg), 34 percent higher than in 1990. Emissions increased on average by 0.7 Tg CO_2 Eq. (2 percent) annually over this period. The majority of this increase was from swine and dairy cow manure, where emissions increased 37 and 50 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

---

[1] Emissions from livestock manure and urine deposited on pasture, range, or paddock lands, indirect emissions from volatile nitrogen losses that occur primarily in the forms of ammonia and NO_x, and emissions from manure and urine spread onto fields either directly as "daily spread" or after it is removed from manure management systems (e.g., lagoon, pit, etc.) are accounted for and discussed in the Agricultural Soil Management source category within the Agriculture chapter.

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-specific weighted CH_4 conversion factor (MCF) values in combination with the 1992, 1997, and 2002 farm-size distribution data reported in the *Census of Agriculture* (USDA 2005e). From 2004 to 2005, there was a 4 percent increase in CH_4 emissions, due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

In 2005, total N_2O emissions were estimated to be 9.5 Tg CO_2 Eq. (31 Gg); in 1990, emissions were 8.6 Tg CO_2 Eq. (28 Gg). Emissions increased on average by 0.06 Tg CO_2 Eq. (0.7 percent) annually over this period, driven by beef cattle. The 10 percent increase in N_2O emissions from 1990 to 2005 can be partially attributed to a shift in the poultry industry away from the use of liquid manure management systems in favor of litter-based systems and high-rise houses. In addition, there was an overall increase in the population of poultry and swine from 1990 to 2005, although swine populations periodically declined slightly throughout the time series. N_2O emissions showed a 0.9 percent increase from 2004 through 2005, due to minor shifts in animal populations.

The population of beef cattle in feedlots increased over the period of 1990 to 2005, resulting in increased N_2O emissions from this sub-category of cattle. N_2O emissions from dairy cattle increased slightly over the period 1990 through 2005, a net result of different emission trends for dairy cows and dairy heifers. Although dairy cow populations decreased overall for the period 1990 through 2005, the population of dairy cows increased at dairies that manage and store manure on-site (as opposed to using pasture, range, or paddock or daily spread systems). The shift at dairies to more liquid manure management systems at large operations resulted in lower N_2O emissions for dairy cows. This trend differed from the increasing dairy heifer N_2O emissions from dairy heifers, whose populations were increasingly managed in drylot systems.

Table 6-6 and Table 6-7 provide estimates of CH_4 and N_2O emissions from manure management by animal category.

Methodology

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal

Table 6-6: CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq.)

Gas/Animal Type	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**30.9**	**35.1**	**38.7**	**40.1**	**41.1**	**40.5**	**39.7**	**41.3**
Dairy Cattle	11.9	13.3	15.7	16.6	17.2	17.6	17.1	17.9
Beef Cattle	2.5	2.6	2.4	2.5	2.4	2.4	2.3	2.3
Swine	13.1	16.0	17.4	17.8	18.3	17.2	17.1	17.9
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+	+
Poultry	2.7	2.7	2.6	2.7	2.7	2.7	2.6	2.6
Horses	0.5	0.4	0.5	0.5	0.5	0.5	0.5	0.5
N_2O	**8.6**	**9.0**	**9.6**	**9.8**	**9.7**	**9.3**	**9.4**	**9.5**
Dairy Cattle	2.4	2.4	2.5	2.5	2.5	2.5	2.5	2.5
Beef Cattle	4.9	5.3	5.9	6.1	6.0	5.6	5.7	5.8
Swine	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+	+
Poultry	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Horses	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**39.5**	**44.1**	**48.3**	**50.0**	**50.8**	**49.8**	**49.2**	**50.8**

\+ Does not exceed 0.05 Tg CO_2 Eq.

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	1995	2000	2001	2002	2003	2004	2005
CH_4	**1,471**	**1,673**	**1,844**	**1,911**	**1,959**	**1,928**	**1,892**	**1,966**
Dairy Cattle	568	634	748	789	818	839	814	851
Beef Cattle	120	122	114	117	114	113	110	111
Swine	623	762	830	849	873	821	815	852
Sheep	7	5	4	4	4	4	4	4
Goats	1	1	1	1	1	1	1	1
Poultry	131	128	125	129	127	127	126	125
Horses	22	21	22	22	22	22	22	22
N_2O	**28**	**29**	**31**	**32**	**31**	**30**	**30**	**31**
Dairy Cattle	8	8	8	8	8	8	8	8
Beef Cattle	16	17	19	20	19	18	19	19
Swine	2	2	2	1	2	2	2	2
Sheep	0	0	0	0	0	0	0	0
Goats	0	0	0	0	0	0	0	0
Poultry	1	1	1	1	1	1	1	1
Horses	1	1	1	1	1	1	1	1

+ Does not exceed 0.5 Gg.

Note: Totals may not sum due to independent rounding.

type. The calculation of emissions requires the following information:

- Animal population data (by animal type and state);
- Amount of nitrogen produced (excretion rate by animal type times animal population);
- Amount of volatile solids produced (excretion rate by animal type times animal population);
- CH_4 producing potential of the volatile solids (by animal type);
- Extent to which the CH_4 producing potential is realized for each type of manure management system (by state and manure management system, including the impacts of any biogas collection efforts);
- Portion of manure managed in each manure management system (by state and animal type); and
- Portion of manure deposited on pasture, range, or paddock or used in daily spread systems.

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.

Both CH_4 and N_2O emissions were estimated by first determining activity data, including animal population, waste characteristics, and manure management system usage. For swine and dairy cattle, manure management system usage was determined for different farm size categories using data from USDA (USDA 1996b, 1998c, 2000b) 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 2000c, UEP 1999). For other animal types, manure management system usage was based on previous estimates (EPA 1992).

MCFs and N_2O emission factors were determined for all manure management systems. MCFs for dry systems were set equal to default IPCC factors based on each state's 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. The MCF calculations model the average monthly ambient temperature, a minimum system temperature, the carryover of volatile solids in the system from month to month due to long storage times exhibited by anaerobic lagoon systems, and a factor to account for management and design practices that result in the loss of volatile solids from lagoon systems. N_2O emission factors for all systems were set equal to default IPCC factors (IPCC 2006).

CH_4 emissions were estimated using the volatile solids (VS) production for all livestock. For most cattle groups, regional animal-specific VS production rates that are related to the diet of the animal for each year of the inventory were used (Pederson and Pape 2006). For all other animal groups, VS production was calculated using a national average VS production rate from the *Agricultural Waste Management Field Handbook* (USDA 1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. The resulting VS for each animal group were then multiplied by the maximum CH_4 producing capacity of the waste (B_o) and the state-specific MCFs.

The maximum CH_4 producing capacity of the VS, or B_o, was determined based on data collected in a literature review (ERG 2000b). B_o data were collected for each animal type for which emissions were estimated.

Anaerobic digester reductions are estimated based on data from the EPA AgSTAR program, including information presented in the *AgSTAR Digest* (EPA 2000, 2003b, 2006). A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions from digesters. The value for efficiency was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in EPA's "AP-42 Compilation of Air Pollutant Emission Factors, Chapter 2.4," efficiencies used to establish new source performance standards (NSPS) for landfills, and in recommendations for closed flares used in LMOP.

Nitrogen excretion rate data from the USDA *Agricultural Waste Management Field Handbook* (USDA 1996a) were used for all livestock except sheep, goats, and horses. Data from the American Society of Agricultural Engineers (ASAE 1999) were used for these animal types. VS excretion rate data from USDA (1996a) were used for swine, poultry, bulls, and calves not on feed.

N_2O emissions were estimated by determining total Kjeldahl nitrogen (TKN)[2] production for all livestock wastes using a national average nitrogen excretion rate for each animal group from USDA (1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. State-specific weighted N_2O emission factors specific to the type of manure management system were then applied to total nitrogen production to estimate N_2O emissions.

Uncertainty

An analysis was conducted for the manure management emission estimates presented in EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2001* (EPA 2003a, ERG 2003) to determine the uncertainty associated with estimating CH_4 and N_2O emissions from livestock manure management. Because no substantial modifications were made to the inventory methodology since the development of these estimates, it is expected that this analysis is applicable to the uncertainty associated with the current manure management emission estimates.

The quantitative uncertainty analysis for this source category was performed 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.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-8. Manure management CH_4 emissions in 2005 were estimated to be between 33.8 and 49.5 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2005 emission estimate of 41.3 Tg CO_2 Eq. At the 95

Table 6-8: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	41.3	33.8	49.5	-18%	+20%
Manure Management	N_2O	9.5	8.0	11.8	-16%	+24%

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

---

[2] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

percent confidence level, N_2O emissions were estimated to be between 8.0 and 11.8 Tg CO_2 Eq. (or approximately 16 percent below and 24 percent above the actual 2005 emission estimate of 9.5 Tg CO_2 Eq.).

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 2004 and 2005 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 nitrogen 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 waste management system type for the full time series, between national level estimates for nitrogen excreted and the sum of county estimates for the full time series.

Recalculations Discussion

A few changes have been incorporated into the overall methodology for the manure management emission estimates. State temperatures are now calculated using data from every county in the state. The previous methodology linked the temperature data to a list of counties/climate divisions that were determined using a weather station list from the National Climatic Data Center (NCDC). The list of weather stations, however, did not include a match of county to climate division for all U.S. counties. The new methodology for utilizing the temperature data for the contiguous United States is to link the temperature data by climate division to a complete list of U.S. counties/climate divisions (NOAA 2005). Although this change in methodology provides a more accurate calculation of state temperatures, it has little effect on the final temperature calculations, MCFs, or emissions estimates.

Another major change in methodology was using climate-specific MCFs for dry manure management systems. In previous inventories, a "temperate" climate zone was assumed for all U.S. states and years of the Inventory, and the temperate MCFs for all dry manure management systems were used in CH_4 emission calculations. A climate classification (cool, temperate, or warm) was assigned to each state and year using the average state temperatures. New climate-specific MCFs were incorporated into the current Inventory for the following manure management systems: pasture/range/paddock, daily spread, solid storage, dry lot, burned for fuel, cattle deep bedding (<1 month and >1 month), composting—intensive windrow, and composting—passive windrow. The change in status for some states from temperate to cool climates and MCFs caused the most significant changes in CH_4 emissions for animal groups that most rely on pasture/range/paddock waste management systems (i.e., beef cattle, sheep, horses, and goats), which showed decreased CH_4 emissions for all years in the current Inventory compared to the previous Inventory.

The percentage of dairy cattle, swine, and sheep on each type of manure management system was also updated for the 2005 Inventory, based on farm size data from the 2002 USDA Census of Agriculture. Liquid-based systems are in increasing use for swine and dairy manure, due to the increasing farm size for these animals. Sheep continue to be managed using dry manure management systems. These manure management system updates decreased N_2O estimates and increased CH_4 estimates for dairy cattle and increased N_2O and CH_4 estimates for swine in the current Inventory.

Changes were also made to the current calculations involving animal population data. Animal population data were updated to reflect the final estimates reports from USDA NASS, and 2002 USDA Census of Agriculture data (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a, 2004a-e, 2005a-d, 2006a-e). The population data in the most recent final estimates reflect some adjustments due to USDA NASS review. For horses, state-level populations were estimated using the national FAO population data (FAO 2006) and the state distributions from the 1992, 1997, and 2002 Census of Agriculture (USDA 2005e).

For the current Inventory, new VS production and nitrogen excretion rates were calculated for poultry hens and pullets, based on 1990 to 2004 population and VS data and nitrogen excretion data. This change was incorporated because USDA now reports a combined hen and pullet population, therefore weighted average rates for the combined population were developed.

With these recalculations, CH_4 emission estimates from manure management systems are slightly higher than reported in the previous Inventory for the years 1999 through 2004 and slightly lower for 1990 through 1998. On average, annual emissions estimates are less than those of the previous Inventory by less than one percent.

N_2O emission estimates from manure management systems have decreased for all years of the current Inventory compared to the previous Inventory, by 47 percent on average, due to the use of updated emission factors published by IPCC (2006).

Planned Improvements

Although an effort was made to introduce the variability in VS production due to differences in diet for beef and dairy cows, heifers, and steer, further research is needed to confirm and track diet changes over time. A methodology to assess variability in swine VS production would be useful in future inventory estimates.

Research will be initiated into the estimation and validation of the maximum CH_4-producing capacity of animal manure (B_o), for the purpose of obtaining more accurate data to develop emission estimates.

The American Society of Agricultural Engineers proposed new standards for manure production characteristics in 2004 and finalized them in 2005. These data will be investigated and evaluated for incorporation into future estimates.

The methodology to calculate MCFs for liquid systems will be examined to determine how to account for a maximum temperature in the liquid systems. It will also be evaluated whether the lower bound estimate of temperature established for lagoons and other liquid systems should be revised for use with this methodology. Additionally, available research will be investigated to develop a relationship between ambient air temperature and temperature in liquid waste management systems in order to improve that relationship in the MCF methodology.

The development of the National Ammonia Emissions Inventory for the United States (EPA 2004) used similar data sources to the current estimates of emissions from manure management, and through the course of development of the ammonia inventory, updated waste management distribution data were identified. Future inventory estimates will incorporate these updated data.

The estimation of indirect N_2O emissions associated with manure management (e.g., ammonia NO_x) is currently included in the Agricultural Soil Management source category. Based on IPCC (2006), a methodology to estimate these indirect N_2O emissions separately and include them in the Manure Management source category will be evaluated for future inventories.

The IPCC provides a suggested MCF for poultry waste management operations of 1.5 percent. Additional study is needed in this area to determine if poultry high-rise houses promote sufficient aerobic conditions to warrant a lower MCF.

A minor error was identified in the MCF calculations, which used a value of 303.17 K instead of 303.15 K when calculating the f factor. This error will be corrected in future inventory estimates. This error has little impact overall on the CH_4 emission estimates. The calculated MCFs are expected to increase up to 0.1 percent, and the overall CH_4 emissions are expected to increase by up to 0.05 percent.

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,[3] 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.[4] 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 Arkansas, southwest Louisiana, Texas, and Florida allow for a second, or ratoon, rice crop. CH_4 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

Table 6-9: CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq.)

State	1990	1995	2000	2001	2002	2003	2004	2005
Primary	**5.1**	**5.6**	**5.5**	**5.9**	**5.7**	**5.4**	**6.0**	**6.0**
Arkansas	2.1	2.4	2.5	2.9	2.7	2.6	2.8	2.9
California	0.7	0.8	1.0	0.8	0.9	0.9	1.1	0.9
Florida	+	0.0	+	+	+	+	+	+
Louisiana	1.0	1.0	0.9	1.0	1.0	0.8	1.0	0.9
Mississippi	0.4	0.5	0.4	0.5	0.5	0.4	0.4	0.5
Missouri	0.1	0.2	0.3	0.4	0.3	0.3	0.3	0.4
Oklahoma	+	0.0	+	+	+	+	+	+
Texas	0.6	0.6	0.4	0.4	0.4	0.3	0.4	0.4
Ratoon	**2.1**	**2.1**	**2.0**	**1.7**	**1.1**	**1.5**	**1.6**	**0.9**
Arkansas	+	0.0	+	+	+	+	+	+
Florida	+	0.1	0.1	+	+	+	+	+
Louisiana	1.1	1.1	1.3	1.1	0.5	1.0	1.1	0.5
Texas	0.9	0.8	0.7	0.6	0.5	0.5	0.5	0.4
Total	**7.1**	**7.6**	**7.5**	**7.6**	**6.8**	**6.9**	**7.6**	**6.9**

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

---

[3] 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.

[4] Additionally, 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 emissions estimates.

Table 6-10: CH_4 Emissions from Rice Cultivation (Gg)

State	1990	1995	2000	2001	2002	2003	2004	2005
Primary	**241**	**265**	**260**	**283**	**274**	**255**	**283**	**287**
Arkansas	102	114	120	138	128	124	132	139
California	34	40	47	40	45	43	50	45
Florida	1	2	2	1	1	+	1	1
Louisiana	46	48	41	46	45	38	45	45
Mississippi	21	24	19	22	22	20	20	22
Missouri	7	10	14	18	15	15	17	18
Oklahoma	+	+	+	+	+	+	+	+
Texas	30	27	18	18	18	15	19	17
Ratoon	**98**	**98**	**97**	**81**	**52**	**73**	**77**	**41**
Arkansas	+	+	+	+	+	+	+	1
Florida	2	4	2	2	2	2	2	2
Louisiana	52	54	61	52	25	50	50	22
Texas	45	40	34	27	24	22	24	17
Total	**339**	**363**	**357**	**364**	**325**	**328**	**360**	**328**

+ Less than 0.5 Gg

Note: Totals may not sum due to independent rounding.

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 2005, CH_4 emissions from rice cultivation were 6.9 Tg CO_2 Eq. (328 Gg). Although annual emissions fluctuated unevenly between the years 1990 and 2005, ranging from an annual decrease of 11 percent to an annual increase of 17 percent, there was an overall decrease of 3 percent over the fifteen-year period, due to an overall decrease in primary crop area.[5] 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.

Methodology

The IPCC/UNEP/OECD/IEA (1997) recommends using harvested rice areas and area-based seasonally integrated emission factors (i.e., amount of CH_4 emitted over a growing season per unit harvested area) to estimate annual CH_4 emissions from rice cultivation. This Inventory uses the recommended methodology and employs U.S.-specific emission factors derived from rice field measurements. 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 *Good Practice Guidance* (IPCC 2000).

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 6-11. Primary crop areas for 1990 through 2005 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, 2006). Harvested rice areas in Florida, which are not reported by USDA, were obtained from: Tom Schueneman (1999b, 1999c, 2000, 2001a) and Arthur Kirstein (2003, 2006), Florida agricultural extension agents; Dr. Chris Deren (2002) of the Everglades Research and Education Centre at the University of Florida; and Gaston Cantens (2004, 2005), Vice President of Corporate Relations of the Florida Crystals Company. Harvested rice area in Florida for 2005 was unavailable and set equal to the 2004 figure (Kirstein 2006, Cantens 2005). Harvested rice areas for Oklahoma, which also are not reported by USDA, were obtained from Danny Lee of the Oklahoma Farm Services Agency (2003, 2004, 2005, 2006). Acreages for the ratoon crops were derived from conversations with the agricultural extension agents in each state. In Arkansas, ratooning occurred only in 1998, 1999,

---

[5] The 11 percent decrease occurred between 1992 and 1993 and 2001 and 2002; the 17 percent increase happened between 1993 and 1994.

Table 6-11: Rice Areas Harvested (Hectares)

State/Crop	1990	1995	2000	2001	2002	2003	2004	2005
Arkansas								
Primary	485,633	542,291	570,619	656,010	608,256	588,830	629,300	661,675
Ratoon*	0	0	0	0	0	0	0	662
California	159,854	188,183	221,773	190,611	213,679	205,180	238,770	212,869
Florida								
Primary	4,978	9,713	7,801	4,562	5,077	2,369	3,755	3,755
Ratoon	2,489	4,856	3,193	2,752	2,734	2,369	2,899	2,899
Louisiana								
Primary	220,558	230,676	194,253	220,963	216,512	182,113	215,702	212,465
Ratoon	66,168	69,203	77,701	66,289	32,477	63,739	64,711	27,620
Mississippi	101,174	116,552	88,223	102,388	102,388	94,699	94,699	106,435
Missouri	32,376	45,326	68,393	83,772	73,654	69,203	78,915	86,605
Oklahoma	617	364	283	265	274	53	158	271
Texas								
Primary	142,857	128,693	86,605	87,414	83,367	72,845	88,223	81,344
Ratoon	57,143	51,477	43,302	34,966	30,846	27,681	30,878	21,963
Total Primary	**1,148,047**	**1,261,796**	**1,237,951**	**1,345,984**	**1,303,206**	**1,215,291**	**1,349,523**	**1,365,418**
Total Ratoon	**125,799**	**125,536**	**124,197**	**104,006**	**66,056**	**93,790**	**98,488**	**53,144**
Total	**1,273,847**	**1,387,333**	**1,362,148**	**1,449,991**	**1,369,262**	**1,309,081**	**1,448,011**	**1,418,562**

*Arkansas ratooning occurred only in 1998, 1999, and 2005.
Note: Totals may not sum due to independent rounding.

and 2005, when the ratooned area was less than 1 percent of the primary area (Slaton 1999, 2000, 2001a; Wilson 2002, 2003, 2004, 2005, 2006). In Florida, the ratooned area was 50 percent of the primary area from 1990 to 1998 (Schueneman 1999a), about 65 percent of the primary area in 1999 (Schueneman 2000), around 41 percent of the primary area in 2000 (Schueneman 2001a), about 60 percent of the primary area in 2001 (Deren 2002), about 54 percent of the primary area in 2002 (Kirstein 2003), about 100 percent of the primary area in 2003 (Kirstein 2004), and about 77 percent of the primary area in 2004 (Cantens 2005). Ratooned area for 2005 was set equal to 2004, since no new data were available. In Louisiana, the percentage of the primary area that was ratooned was constant at 30 percent over the 1990 to 1999 period, increased to approximately 40 percent in 2000, returned to 30 percent in 2001, dropped to 15 percent in 2002, rose to 35 percent in 2003, returned to 30 percent in 2004, and dropped to 13 percent in 2005 (Linscombe 1999, 2001a, 2002, 2003, 2004, 2005, 2006; Bollich 2000). In Texas, the percentage of the primary area that was ratooned was constant at 40 percent over the 1990 to 1999 period, increased to 50 percent in 2000 due to an early primary crop, and then decreased to 40 percent in 2001, 37 percent in 2002, 38 percent in 2003, 35 percent in 2004, and 27 percent in 2005 (Klosterboer 1999, 2000, 2001a, 2002, 2003; Stansel 2004, 2005; Texas Agricultural Experiment Station 2006). California, Mississippi, Missouri, and Oklahoma have not ratooned rice over the period 1990–2005 (Guethle 1999, 2000, 2001a, 2002, 2003, 2004, 2005, 2006; Lee 2003, 2004, 2005, 2006; Mutters 2002, 2003, 2004, 2005; Street 1999, 2000, 2001a, 2002, 2003; Walker 2005).

To determine what seasonal 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 which 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[6] 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).

---

[6] 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 2.041 $g/m^2/day$ 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 in Europe and Asia (IPCC/UNEP/OECD/IEA 1997).

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

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, in particular, fertilizer type, amount, and mode of application; differences in cultivar type; and differences in soil and climatic conditions. A portion of this variability is accounted for by separating primary from ratooned areas. However, even within a cropping season or a given management regime, measured emissions may vary significantly. Of the experiments used to derive the emission factors applied here, primary emissions ranged from 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 uncertainties 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 6-12. Rice cultivation CH_4 emissions in 2005 were estimated to be between 2.1 and 18.6 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 70 percent below to 170 percent above the actual 2005 emission estimate of 6.9 Tg CO_2 Eq.

QA/QC and Verification

A source-specific QA/QC plan for rice cultivation was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing trends across years, states, and cropping seasons to attempt to identify any outliers or inconsistencies. No problems were found.

Recalculations Discussion

An error in the spreadsheets used to calculate emissions estimates was found during the development of the current Inventory and corrected, resulting in a 0.06 percent decrease in the 2004 emission estimates.

Table 6-12: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	6.9	2.1	18.6	-70%	+170%

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

6.4. Agricultural Soil Management (IPCC Source Category 4D)

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and denitrification.[7] A number of agricultural activities increase mineral nitrogen (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 in 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 cultivation of organic soils (i.e., soils with a high organic matter content, otherwise known as histosols).[8] 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.[9] Indirect emissions of N_2O occur through two pathways: (1) volatilization and subsequent atmospheric deposition of applied N,[10] and (2) surface runoff and leaching of applied N into groundwater and surface water. Direct emissions from agricultural lands (i.e., croplands and grasslands) 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. In contrast, indirect N_2O emissions from all sources (agriculture, forest lands, settlements, and managed manure) are reported in this chapter.

Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions from this source in 2005 were 365.1 Tg CO_2 Eq. (1,178 Gg N_2O) (see Table 6-13 and Table 6-14). Annual agricultural soil management N_2O emissions fluctuated between 1990 and 2005, although overall emissions were 0.5 percent lower in 2005 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 75 percent of total direct emissions, while grassland accounted for approximately 25 percent.

Estimated direct and indirect N_2O emissions by sub-source category are provided in Table 6-15 and Table 6-16.

Figure 6-3 through Figure 6-6 show regional patterns in N_2O emissions for direct sources and regional patterns of N losses leading to indirect N_2O emissions, respectively, for major crops and grasslands across the United States. Direct N_2O emissions tend to be high in the Corn Belt (Illinois, Iowa, Southern Minnesota and Wisconsin, and Eastern Nebraska). A large portion of the land in many of these counties is covered with high input corn and N-fixing soybean cropping, resulting in high emissions on a per county basis. Emissions are also high in some counties in the Dakotas, Kansas, Eastern Colorado, Oklahoma, and Texas. High input irrigated cropping and moderate input dryland wheat cropping are major contributors to emissions in these counties. Emissions are high along the lower Mississippi Valley because this area is intensively cropped and fine-textured soils along the river facilitate denitrification and high N_2O emissions. Emissions are also high in some counties in California where intensive, irrigated cropping is a dominant land use. Emissions are low in the eastern United States because a small portion of land in most of these counties is cropped, and also low in many counties in the West where rainfall and access to irrigation water are limited. Counties with less than a minimum number of cropped acres were not simulated by DAYCENT (white areas). Emissions from

---

[7] 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 nitrogen gas (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).

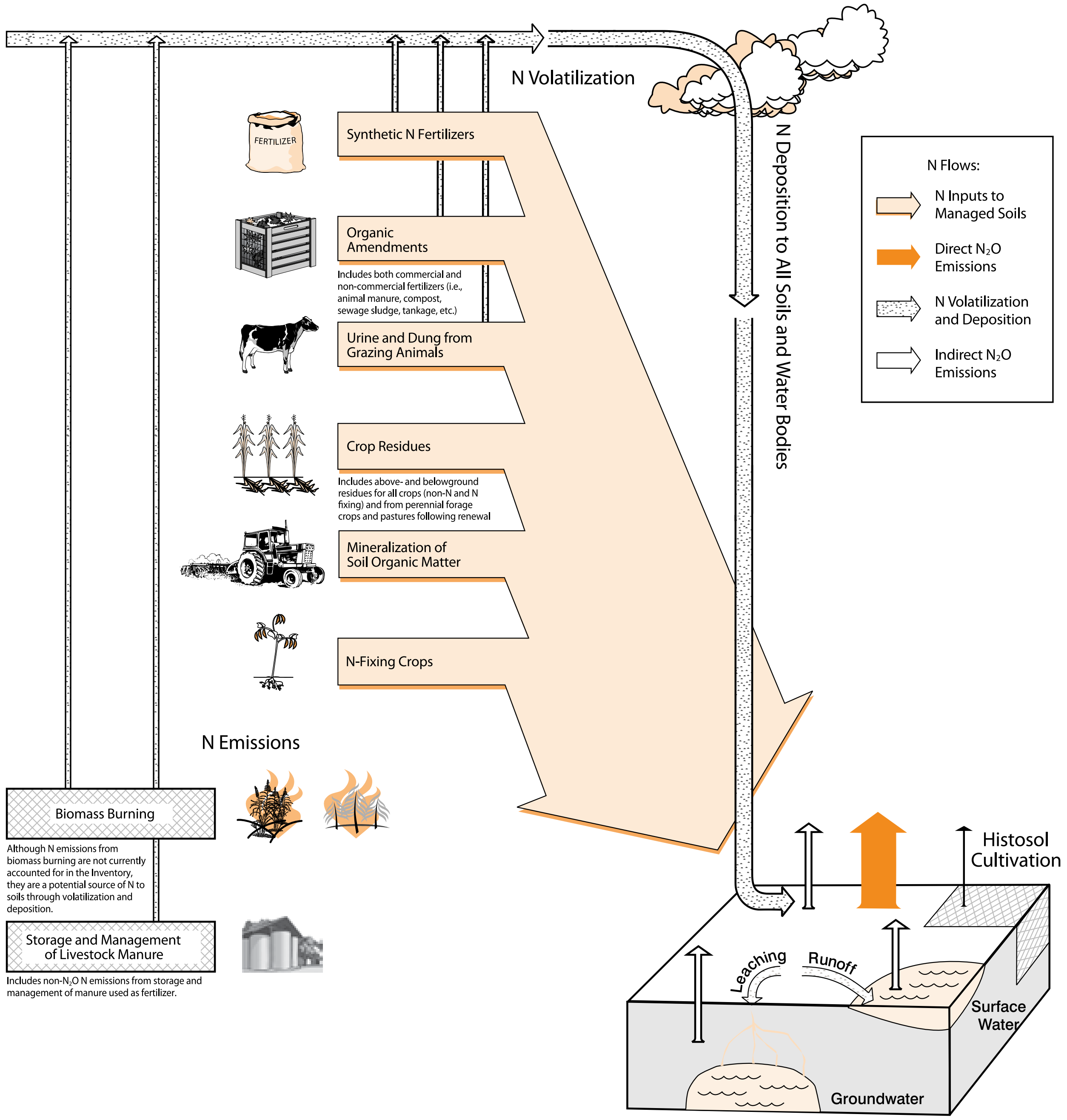
[8] Drainage and cultivation of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby enhancing N_2O emissions from these soils.

[9] Asymbiotic N fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[10] These processes entail volatilization of applied N as ammonia (NH_3) and oxides of N (NO_x), transformation of these gases within the atmosphere (or upon deposition), and deposition of the N primarily in the form of particulate ammonium (NH_4), nitric acid (HNO_3), and NO_x.

Figure 6-2

Agricultural Sources and Pathways of N that Result in N_2O Emissions



Includes both commercial and non-commercial fertilizers (i.e., animal manure, compost, sewage sludge, tankage, etc.)

Includes above- and belowground residues for all crops (non-N and N fixing) and from perennial forage crops and pastures following renewal

Although N emissions from biomass burning are not currently accounted for in the Inventory, they are a potential source of N to soils through volatilization and deposition.

Includes non-N_2O N emissions from storage and management of manure used as fertilizer.

This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from soils in the United States. Sources of nitrogen applied to, or deposited on, soils are represented with arrows on the left-hand side of the graphic. Emission pathways are also 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.

Table 6-13: N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Direct	**310.1**	**292.0**	**324.4**	**327.4**	**314.1**	**297.4**	**292.1**	**310.5**
Cropland	222.1	214.2	250.5	252.6	234.0	226.4	220.9	234.2
Grassland	88.0	77.8	73.9	74.8	80.1	71.0	71.3	76.4
Indirect (All Land-Use Types)	**56.8**	**61.4**	**52.4**	**61.6**	**52.0**	**52.8**	**46.6**	**54.6**
Cropland	27.2	27.2	25.0	26.1	22.5	25.7	20.1	26.2
Grassland	20.4	24.3	17.1	25.1	18.9	16.5	16.0	17.8
Managed Manure[a]	7.5	8.0	8.4	8.5	8.7	8.5	8.5	8.5
Forest Land	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements	1.7	1.8	1.8	1.8	1.9	1.9	2.0	1.9
Total	**366.9**	**353.4**	**376.8**	**389.0**	**366.1**	**350.2**	**338.8**	**365.1**

+ Less than 0.05 Tg CO_2 Eq.

[a] Accounts for loss of manure N prior to soil application during transport, treatment, and storage, including both volatilization and leaching/runoff.

Table 6-14: N_2O Emissions from Agricultural Soils (Gg N_2O)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Direct	**1,000**	**942**	**1,046**	**1,056**	**1,013**	**959**	**942**	**1,002**
Cropland	716	691	808	815	755	730	712	755
Grassland	284	251	238	241	259	229	230	246
Indirect (All Land-Use Types)	**183**	**198**	**169**	**199**	**168**	**170**	**150**	**176**
Cropland	88	88	81	84	72	83	65	84
Grassland	66	78	55	81	61	53	52	57
Managed Manure[a]	24	26	27	27	28	28	27	28
Forest Land	+	+	+	+	+	+	+	+
Settlements	5	6	6	6	6	6	6	6
Total	**1,184**	**1,140**	**1,215**	**1,255**	**1,181**	**1,130**	**1,093**	**1,178**

+ Less than 0.5 Gg N_2O.

[a] Accounts for loss of manure N prior to soil application during transport, treatment, and storage, including both volatilization and leaching/runoff.

Table 6-15: Direct N_2O Emissions from Agricultural Soils by Land Use and N Input (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Cropland	**222.1**	**214.2**	**250.5**	**252.6**	**234.0**	**226.4**	**220.9**	**234.2**
Mineral Soils	**219.3**	**211.4**	**247.6**	**249.7**	**231.1**	**223.5**	**217.9**	**231.2**
Synthetic Fertilizer	83.6	85.1	91.9	94.2	90.2	84.6	88.5	86.9
Organic Amendment[a]	10.3	10.9	12.1	12.9	12.0	11.2	11.6	11.7
Residue N[b]	15.0	15.8	18.5	16.6	15.1	18.3	14.7	16.0
Other[c]	110.3	99.6	125.1	126.0	113.8	109.4	103.1	116.6
Organic Soils	**2.8**	**2.8**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**
Grassland	**88.0**	**77.8**	**73.9**	**74.8**	**80.1**	**71.0**	**71.3**	**76.4**
Synthetic Fertilizer	2.0	1.7	1.6	1.7	1.8	1.6	1.7	1.7
PRP Manure	16.4	15.8	16.8	15.3	20.6	15.5	17.2	14.3
Managed Manure[d]	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.4
Sewage Sludge	0.2	0.4	0.5	0.5	0.5	0.5	0.5	0.5
Residue N[b]	34.4	29.9	28.1	29.9	28.0	27.9	26.4	29.8
Other[c]	34.5	29.6	26.5	27.0	28.8	25.2	25.0	29.7
Total	**310.1**	**292.0**	**324.4**	**327.4**	**314.1**	**297.4**	**292.1**	**310.5**

[a] Organic amendment inputs include managed manure amendments and other commercial organic fertilizer (i.e., dried blood, dried manure, tankage, compost, and other).

[b] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

[c] Other N inputs include mineralization from decomposition of soil organic matter as well as asymbiotic fixation of N from the atmosphere.

[d] Accounts for managed manure that is applied to grassland soils.

Table 6-16: Indirect N_2O Emissions from all Land-Use Types and Managed Manure Systems (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Cropland	**27.2**	**27.2**	**25.0**	**26.1**	**22.5**	**25.7**	**20.1**	**26.2**
Volatilization and Atm. Deposition	4.6	4.9	5.3	4.9	5.0	5.4	5.3	5.4
Surface Leaching & Run-Off	22.6	22.3	19.7	21.2	17.5	20.3	14.8	20.7
Grassland	**20.4**	**24.3**	**17.1**	**25.1**	**18.9**	**16.5**	**16.0**	**17.8**
Volatilization and Atm. Deposition	10.7	10.3	9.3	9.4	9.3	9.4	9.1	9.9
Surface Leaching & Run-Off	9.6	14.0	7.8	15.7	9.5	7.1	6.9	7.9
Managed Manure Systems	**7.5**	**8.0**	**8.4**	**8.5**	**8.7**	**8.5**	**8.5**	**8.5**
Volatilization and Atm. Deposition[a]	7.5	8.0	8.4	8.5	8.7	8.5	8.5	8.5
Forest Land	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Volatilization and Atm. Deposition	+	+	+	+	+	+	+	+
Surface Leaching & Run-Off	+	+	0.1	0.1	0.1	0.1	0.1	0.1
Settlements	**1.7**	**1.8**	**1.8**	**1.8**	**1.9**	**1.9**	**2.0**	**1.9**
Volatilization and Atm. Deposition	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Surface Leaching & Run-Off	1.2	1.2	1.3	1.2	1.3	1.3	1.3	1.3
Total	**56.8**	**61.4**	**52.4**	**61.6**	**52.0**	**52.8**	**46.6**	**54.6**

+ Less than 0.05 Tg CO_2 Eq.

[a] Accounts for loss of manure N prior to soil application during transport, treatment, and storage.

these counties were calculated at the national scale using Tier 1 methodology.

Direct emissions (Tg CO_2 Eq./county/year) from grasslands are highest in the western United States (Figure 6-4) where counties tend to be large and a high proportion of the land in many of these counties is used for cattle grazing. Some counties in the Great Lake states, the Northeast, and Florida have moderate county level emissions even though emissions from these areas tend to be high on a per unit area basis, because the total amount of grazed land in these counties is much less than many counties in the West.

Indirect emissions for crops and grasslands (Figure 6-5 and Figure 6-6) show patterns similar to direct emissions, because the factors that control direct emissions (N inputs, weather, soil type) also influence indirect emissions. However, there are some exceptions, because the processes that contribute to indirect emissions (NO_3 leaching, N volatilization) do not respond in exactly the same manner to these controls as the processes that control direct emissions (nitrification and denitrification). For example, coarse-textured soils facilitate nitrification and moderate direct emissions in Florida grasslands, but indirect emissions are relatively high in Florida grasslands due to high rates of N volatilization and NO_3 leaching in coarse-textured soils. Indirect emissions from crops in some counties in the Carolinas are also relatively high compared to direct emissions because these soils tend to be coarse-textured.

Methodology

The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) divide the Agricultural Soil Management source category into three components: (1) direct emissions from agricultural soils due to N additions to cropland and grassland mineral soils, planting of legumes on cropland and grassland soils, and drainage and cultivation of organic cropland soils; (2) direct emissions from soils due to the deposition of manure by livestock on PRP grasslands; and (3) indirect emissions from soils and water due to N additions and manure deposition to soils that leads to volatilization, leaching, or runoff of N and subsequent conversion to N_2O. Moreover, the *2006 IPCC Guidelines* (IPCC 2006) recommend reporting total emissions from managed lands, and, therefore, this chapter includes estimates for direct emissions due to decomposition of soil organic matter and litter, and asymbiotic fixation of N from the atmosphere.[11]

The methodology used to estimate 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. The Tier 3 approach is more refined for estimating 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

---

[11] 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 Inventory.

Figure 6-3

Major Crops, Average Annual Direct N_2O Emissions, 1990–2005 (Tg CO_2 Eq./county/year)

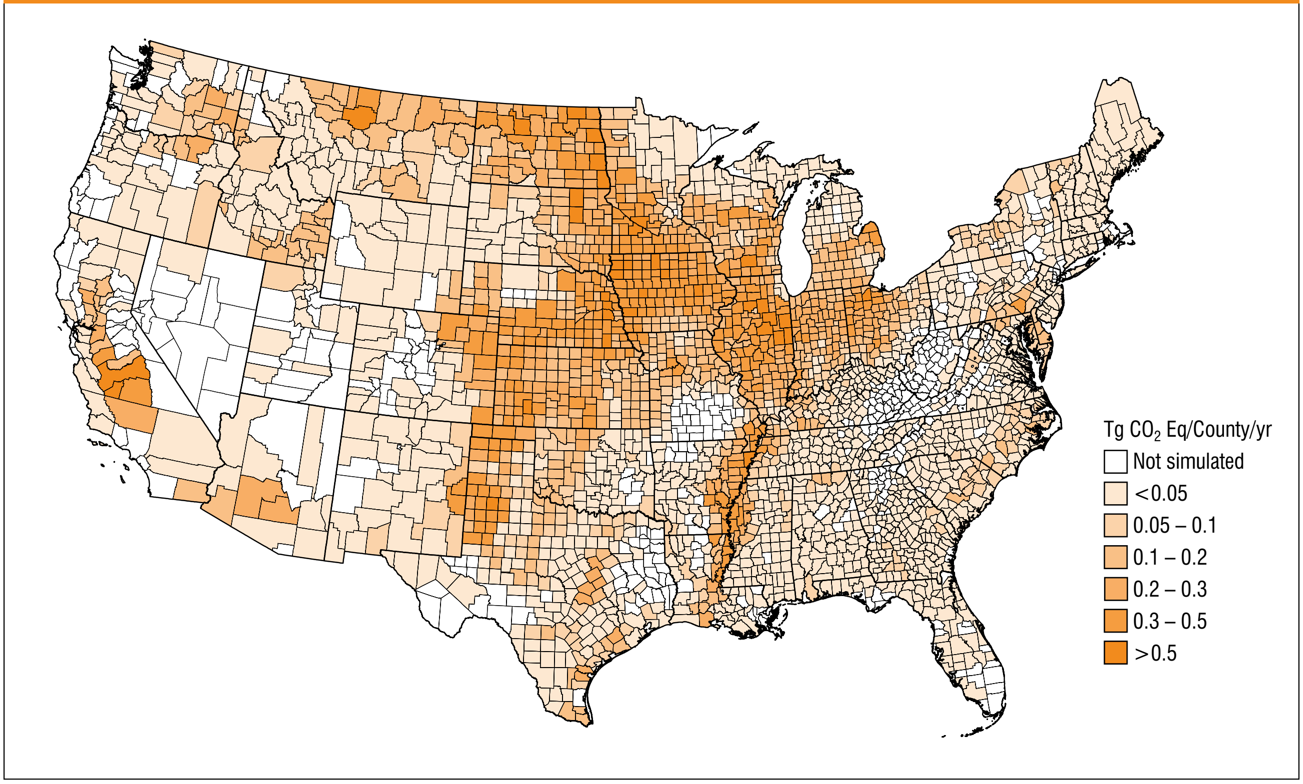


Figure 6-4

Grasslands, Average Annual Direct N_2O Emissions, 1990–2005 (Tg CO_2 Eq./county/year)

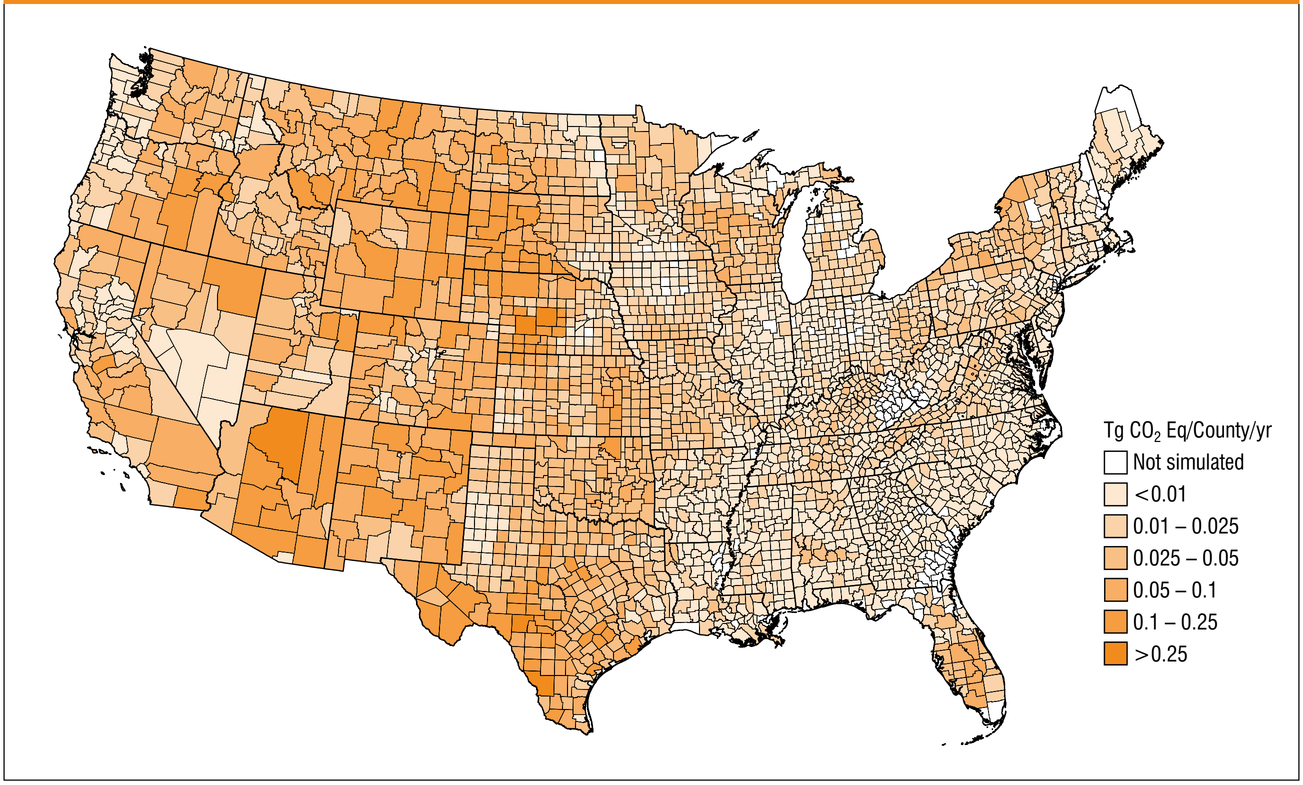


Figure 6-5

Major Crops, Average Annual N Losses Leading to Indirect N_2O Emissions, 1990–2005 (Tg CO_2 Eq./county/year)

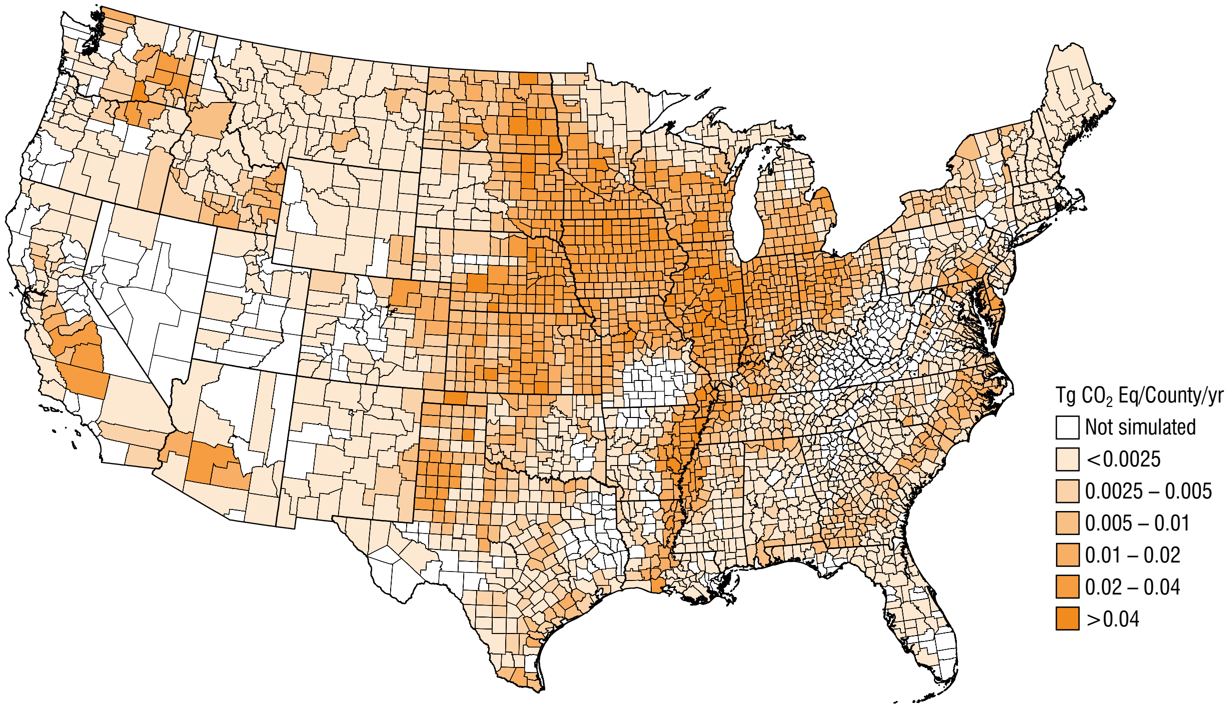
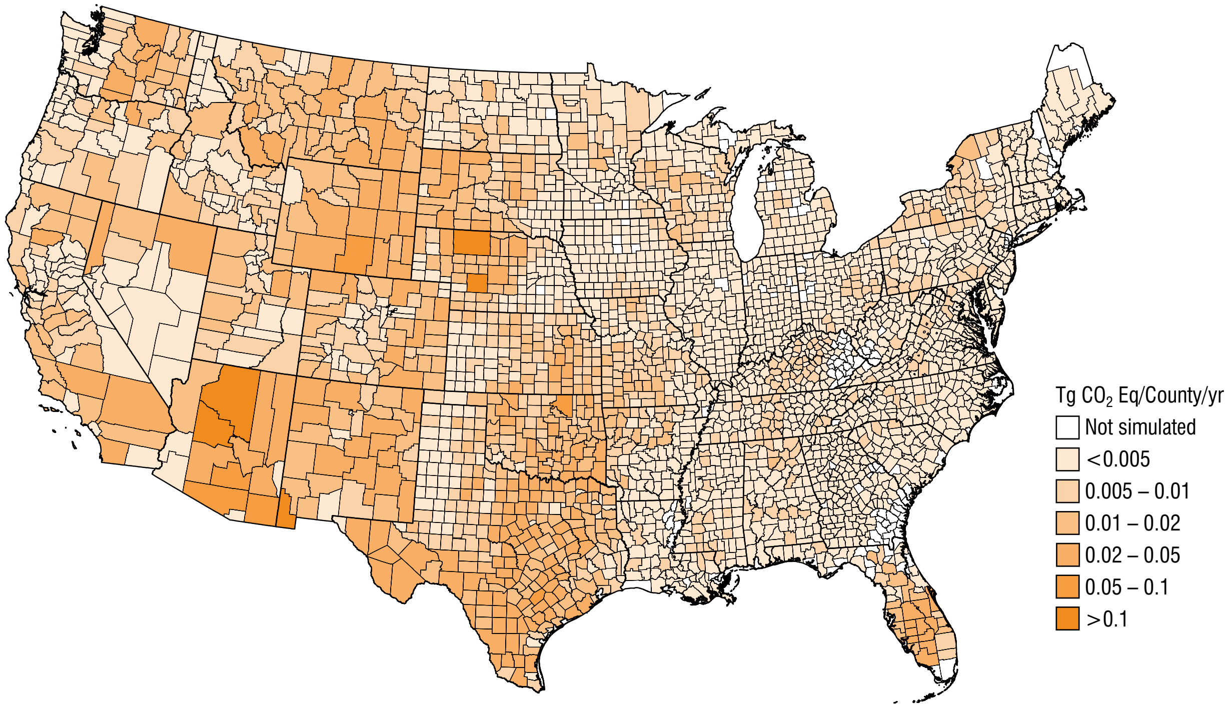


Figure 6-6

Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions, 1990–2005 (Tg CO_2 Eq./county/year)



Box 6-1: Tier 1 vs. Tier 3 Approach for Estimating N_2O Emissions

The Tier 1 approach (IPCC 2006) is based on multiplying activity data on different N sources (e.g., synthetic fertilizer, manure, N fixation, etc.) by the appropriate default IPCC emission factors to estimate N_2O emissions on a source-by-source basis. The Tier 3 approach developed for this Inventory employs a process-based model (i.e., DAYCENT) and is based on the interaction of N inputs and the environmental conditions at a specific location. Consequently, it is necessary not only to know the amount of N inputs but also the conditions under which the anthropogenic activity is increasing mineral N in a soil profile. 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. The Tier 3 approach is thought to produce more accurate estimates; it accounts for land-use and management impacts and their interaction with environmental factors (i.e., weather patterns and soil characteristics), which may enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more refined activity data (e.g., crop-specific N amendment rates, daily weather, soil types, etc.) and considerable computational resources and programming expertise. The Tier 3 methodology is less transparent. 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; e.g., N added as fertilizer or through fixation contributes to N_2O emissions for that year, but cannot be stored in soils and contribute to N_2O emissions in subsequent years. In contrast, the process-based model used in the Tier 3 approach includes such legacy effects when N is mineralized from soil organic matter and emitted as N_2O during subsequent years.

further elaboration). The Tier 1 IPCC methodology was used to estimate direct emissions from non-major crops on mineral soils, the portion of the grassland direct emissions that were not estimated with the Tier 3 DAYCENT model, and direct emissions from drainage and cultivation of organic cropland soils. The Tier 1 approach was based on the *2006 IPCC Guidelines* (IPCC 2006), which was originally developed in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) and IPCC Good Practice Guidance Reports (IPCC 2000, 2003). A combination of DAYCENT and the IPCC Tier 1 method was used to estimate indirect emissions from soils.

The Agricultural Soil Management sector has adopted several recommendations from IPCC (2006) that are considered improvements over previous IPCC methods, including: (1) estimating the contribution of N from crop residues to indirect soil N_2O emissions, (2) adopting the revised emission factor for direct N_2O emissions, (3) removing double counting of emissions due to estimating N-fixing crops in both the symbiotic and crop residue N input categories, (4) using revised crop residue statistics to compute N inputs to soil based on harvest yield data, and (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 (i.e., computing total emissions from managed land). 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 from Cropland Soils

Major Crop Types on Mineral Cropland Soils

The DAYCENT ecosystem model (Del Grosso et al. 2001, Parton et al. 1998) was used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of major crops, specifically corn, soybean, wheat, alfalfa hay, other hay, sorghum, and cotton, representing approximately 90 percent of total croplands in the United States. DAYCENT simulated crop growth, soil organic matter decomposition, greenhouse gas fluxes, and key biogeochemical processes affecting N_2O emissions, and the simulations were driven by model input data generated from daily weather records (Thornton et al. 1997, 2000; Thornton and Running 1999), land management surveys (see citations below), and soil physical properties determined from national soil surveys (Soil Survey Staff 2005).

DAYCENT simulations were conducted for each major crop at the county scale in the United States. The county scale was selected, because soil and weather data were available for every county with more than 100 acres of agricultural land. However, land management data (e.g., timing of planting, harvesting, intensity of cultivation) were only available at the agricultural region level as defined by the Agricultural Sector Model (McCarl et al. 1993). There are 63 agricultural regions in the contiguous United States, and most states correspond to one region, except for those states with greater heterogeneity in agricultural practices, where there are further subdivisions. While several cropping systems were simulated for each county in an agricultural region with county-level weather and soils data, the model parameters that determined the influence of management activities on soil N_2O emissions (e.g., when crops were planted/harvested) did not differ among the counties in an agricultural region. Consequently, the results will best represent emissions at the regional and national levels due to the scale of management data.

Nitrous oxide emission estimates from DAYCENT include the influence of N additions, crop type, irrigation, and other factors in aggregate, and, therefore, it is not possible to partition N_2O emissions by anthropogenic activity directly from model outputs (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). Nitrous oxide emissions from managed agricultural lands are the result of interactions between the combined anthropogenic interventions that are implemented (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). According to IPCC/UNEP/OECD/IEA (1997), soil N_2O inventories are expected to report emissions from mineral soils associated with mineral N fertilization, organic amendments, crop residue N added to soils, and symbiotic N-fixation. In addition, IPCC (2006) recommends reporting total N_2O emissions from managed lands, which would also include "other N Inputs" from mineralization due to decomposition of soil organic matter and litter, as well as asymbiotic fixation of N from the atmosphere. To approximate emissions by activity, the amount of mineral N added to the soil for each of these practices 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 N_2O emissions in order to approximate the portion attributed to key practices. This approach is not precise 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. Since it is not possible to track N flows from different sources using the DAYCENT model, this approach allows for further disaggregation by source of N, which is valuable for reporting purposes.

Consequently, DAYCENT was used to estimate direct N_2O emissions due to mineral N available from: (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), and (4) mineralization of soil organic matter and litter, in addition to asymbiotic fixation. This last source is generated internally by the DAYCENT model. For each of the first 3 practices, annual increases in soil mineral N due to anthropogenic activity were obtained or derived from the following sources:

- Crop-specific N-fertilization rates: Data sources for fertilization rates include Alexander and Smith (1990), Anonymous (1924), Battaglin and Goolsby (1994), Engle and Makela (1947), ERS (1994, 2003), Fraps and Asbury (1931), Ibach and Adams (1967), Ibach et al. (1964), NFA (1946), NRIAI (2003), Ross and Mehring (1938), Skinner (1931), Smalley et al. (1939), Taylor (1994), USDA (1966, 1957, 1954, 1946). 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 (ERS 1997) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004).
- Managed manure production and application to croplands and grasslands: Manure N amendments applied to croplands and grasslands (not including PRP manure) were determined using USDA Manure N Management Databases for 1997 (Kellogg et al. 2000; Edmonds et al. 2003). These values were scaled to estimate values for other years based on estimates of annual production of managed manure. The amount of managed manure for each livestock type was calculated by determining the population of animals that were on feedlots or otherwise housed in order to collect and manage the manure. Annual animal population data for all livestock types, except horses and goats, were obtained for all years from the U.S. Department of Agriculture-National Agricultural Statistics Service (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a, 2004a-e, 2005a-d, 2006a). Horse population data were

obtained from the FAOSTAT database (FAO 2006). Goat population data for 1992, 1997, and 2002 were obtained from the Census of Agriculture (USDA 2005g); these data were interpolated and extrapolated to derive estimates for the other years. Information regarding the poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service personnel (Lange 2000). Additional population data for different farm size categories for dairy and swine were obtained from the 1992 and 1997 Census of Agriculture (USDA 2005g). These values may be slightly high because about 5 percent of poultry manure is used for feed (Carpenter 1992). However, poultry manure production is relatively small compared to other livestock categories, particularly cattle. Only a portion of the managed manure N is applied to crop and grassland soils according to Edmonds et al. (2003). The difference between manure N applied to soils and remaining N in the managed manure was assumed to be lost through volatilization and leaching/runoff of N species during treatment, storage, and transportation. Instead of assuming that 20 percent of organic N applied to soils is volatilized and 30 percent of applied N was lost through leaching/runoff, as approximated with IPCC (2006) methodology, volatilization and N leaching/runoff from manure that was amended to soils was calculated by the DAYCENT process-based model. Frequency and rates of manure application to cropland during the Inventory period were estimated from data compiled by the USDA Natural Resources Conservation Service for 1997 (Edmonds et al. 2003), with adjustments based on managed manure N excretion in other years of the Inventory.

- Nitrogen-fixing crops and forages, retention of crop residue, N mineralization from soil organic matter, and asymbiotic N fixation from the atmosphere: The IPCC approach considers this information as separate activity data. However, they are not considered separate activity data for the DAYCENT simulations because residue production, N fixation, mineralization of N from soil organic matter, and asymbiotic fixation are internally generated by the model. In other words, DAYCENT accounts for the influence of N fixation, mineralization of N from soil organic matter, and retention of crop residue on N_2O emissions, but these are not model inputs. The total input of N from these sources is determined during the model simulations.
- Historical and modern crop rotation and management information (e.g., timing and type of cultivation, timing of planting/harvest, etc.): These activity data were derived from Hurd (1930, 1929), Latta (1938), Iowa State College Staff Members (1946), Bogue (1963), Hurt (1994), USDA (2004f), USDA (2000b) as extracted by Eve (2001) and revised by Ogle (2002), CTIC (1998), Piper et al. (1924), Hardies and Hume (1927), Holmes (1902, 1929), Spillman (1902, 1905, 1907, 1908), Chilcott (1910), Smith (1911), Kezer (ca. 1917), Hargreaves (1993), ERS (2002), Warren (1911), Langston et al. (1922), Russell et al. (1922), Elliott and Tapp (1928), Elliott (1933), Ellsworth (1929), Garey (1929), Hodges et al. (1930), Bonnen and Elliott (1931), Brenner et al. (2002, 2001), and Smith et al. (2002).

DAYCENT-generated per-area estimates of N_2O emissions (g N_2O-N m^{-2}) from major crops were multiplied by the cropland area data to obtain county-scale emission estimates. Cropland area data were from NASS (USDA 2005g). The emission estimates by reported crop areas in the county were scaled to the regions, and the national estimate was calculated by summing results across all regions. DAYCENT is sensitive to actual interannual variability in weather patterns and other controlling variables, and so emissions associated with individual activities vary through time even if the management practices remain the same (e.g., if N fertilization remains the same for two years). In contrast, Tier 1 methods do not capture this variability and rather have a linear, monotonic response that depends solely on management practices. DAYCENT's ability to capture these interactions between management and environmental conditions enables it to produce more accurate estimates of N_2O emissions.

Non-Major Crop Types on Mineral Cropland Soils

The Tier 1 methodology (IPCC/UNEP/OECD/IEA 1997, IPCC 2006) was used to estimate direct N_2O emissions for mineral cropland soils that are managed for production of non-major crop types. 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 non-manure other commercial organic fertilizers;[12] and (3) the retention of above- and below-ground crop residues. No manure amendments were considered here because most of this material was applied to crops simulated by DAYCENT. DAYCENT simulations included the 5 major cropping systems (corn, hay, sorghum, soybean, wheat), which are the land management systems receiving the vast majority (approximately 95 percent) of manure applications to cropped land in the United States (Kellogg et al. 2000, Edmonds et al. 2003). Non-manure organic amendments were not included in the DAYCENT simulations, because county-level data for this source were not available and this source is a very small portion of total organic amendments. Consequently, non-manure organic amendments were included in the Tier 1 analysis.

1. A process-of-elimination approach was used to estimate N fertilizer additions for these crops, because little information exists on fertilizer application rates for non-major crop types. N fertilizer additions to major crops, grassland, forest land, and settlements were summed, this sum was subtracted from total annual fertilizer sales, and the difference was assumed to be applied to non-major crop types. Non-major crop types include: (a) fruits, nuts, and vegetables, and (b) other annual crops not simulated by DAYCENT (barley, oats, tobacco, sugarcane, sugar beets, sunflowers, millet, peanuts, etc.).
2. Annual non-manure organic fertilizer additions were based on organic fertilizer consumption statistics, which were converted to units of N using average organic fertilizer N content statistics (TVA 1991, 1992a, 1993, 1994; AAPFCO 1995, 1996, 1997, 1998, 1999, 2000a, 2000b, 2002, 2003, 2004, 2005, 2006).
3. Crop residue N was derived by combining amounts of above- and below-ground biomass, which were determined based on crop production yield statistics (1994a, 1998b, 2003, 2005i, 2006b), dry matter fractions (IPCC 2006), linear equations to estimate above-ground biomass given dry matter crop yields (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and N contents of the residues (IPCC 2006).

The total increase in soil mineral N from applied fertilizers and crop residues was multiplied by the IPCC (2006) default emission factor (Bouwman et al. 2002a, 2002b, Novoa and Tejeda 2006, Stehfest and Bouwman 2006) to derive an estimate of cropland direct N_2O emissions from non-major crop types.

Drainage and Cultivation of Organic Cropland Soils

Tier 1 methods were used to estimate direct N_2O emissions from the drainage and cultivation of organic cropland soils. Estimates of the total U.S. acreage of drained organic soils cultivated annually for temperate and sub-tropical climate regions were obtained for 1982, 1992, and 1997 from the Natural Resources Inventory (USDA 2000b, as extracted by Eve 2001 and amended by Ogle 2002), using temperature and precipitation data from Daly et al. (1994, 1998). These areas were linearly interpolated and extrapolated to estimate areas for the missing years. 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).

Direct N_2O Emissions from Grassland Soils

As with N_2O from croplands, the Tier 3 process-based DAYCENT model and Tier 1 methods described in the IPCC (2006) guidelines 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, that may or may not be improved with practices such as irrigation and interseeding legumes.

DAYCENT was used to simulate N_2O emissions from grasslands at the county scale resulting from manure deposited by livestock directly onto the pasture (i.e., PRP manure, which is simulated internally within the model), N fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure), and synthetic fertilizer application. The simulations used the same weather and soils 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)

---

[12] Other commercial organic fertilizers include dried blood, dried manure, tankage, compost, other, but excludes manure and sewage sludge, which are used as commercial fertilizers.

and adjusted for annual variation using managed manure N production data according to methods described in Annex 3.11. "other N inputs" were simulated within the DAYCENT framework, including N input from mineralization due to decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere and atmospheric N deposition.

DAYCENT-generated per-area estimates of N_2O emissions (g N_2O-N m^{-2}) from pasture and rangelands were multiplied by the reported pasture and rangeland areas in the county. Grassland area data were obtained from the National Resources Inventory (NRI) (USDA 2000b). The 1997 NRI area data for pastures and rangeland were aggregated to the county level to estimate the grassland areas for 1995 to 2005, and the 1992 NRI pasture and rangeland data were aggregated to the county level to estimate areas from 1990 to 1994. The county estimates were scaled to the regions, and the national estimate was calculated by summing results across all regions.

Manure N deposition from grazing animals is modeled internally within DAYCENT. Comparisons with estimates of total manure deposited on PRP (see Annex 3.11) showed that DAYCENT accounted for approximately 70 percent of total PRP manure. It is reasonable that DAYCENT did not account for all PRP manure, because the NRI data do not include some grassland areas such as federal grasslands. N_2O emissions from the portion of PRP manure N not accounted for by DAYCENT were estimated using the Tier 1 method with IPCC default emission factors (de Klein 2004, IPCC 2006). Sewage sludge was assumed to be applied on grasslands (but not included in the DAYCENT simulations) 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, 1997, 1999, 2003), Bastian (2002, 2003, 2005), and Metcalf and Eddy (1991). Sewage sludge data on soil amendments in 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. Consequently, emissions from sewage sludge were also estimated using the Tier 1 method with IPCC default emission factors (Bouwman et al. 2002a, 2002b, Novoa and Tejeda 2006, Stehfest and Bouwman 2006, IPCC 2006). Emission estimates from DAYCENT and the IPCC method were summed to provide total national emissions for grasslands in the United States.

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 total direct N_2O emissions from agricultural soil management (see Table 6-13 and Table 6-14).

Indirect N_2O Emissions from Managed Soils of all Land-Use Types and Managed Manure Systems

This section describes methods for estimating indirect soil N_2O emissions from all land-use types (i.e., cropland, grassland, forest land, and settlements) and managed manure systems based on losses of N through volatilization, leaching, and runoff. The sources of indirect N from volatilization, leaching, and runoff are estimated in the same manner as direct N_2O emissions from soils (i.e., using DAYCENT and the Tier 1 method as described for direct emissions). The indirect emissions from these N sources are estimated using the Tier 1 method (IPCC 2006). 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 or organic amendments (e.g., manure, sewage sludge); deposition of PRP manure; or during storage, treatment, and transport of managed manure. N made available from mineralization of soil organic matter and asymbiotic fixation also contributes to volatilized N emissions. Through atmospheric deposition, volatilized N can be returned to soils, and a portion is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil N (primarily in the form of nitrate [NO_3^-]) that was made available through anthropogenic activity on managed lands, mineralization of soil organic matter, asymbiotic fixation, and atmospheric deposition. The nitrate is subject to denitrification in water bodies, which leads to additional 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 N Volatilized by Managed Soils and Managed Manure Systems

Similar to the direct emissions calculation, several approaches were combined to estimate the amount of applied N that was exported from application sites through volatilization. DAYCENT was used to simulate the amount of N transported from land areas whose direct emissions were simulated with DAYCENT (i.e., major croplands and most grasslands), while the IPCC method was used for land areas that were not simulated with DAYCENT (i.e., non-major croplands and a small portion of grasslands) (IPCC 2006). Manure N from managed systems assumed to be volatilized during storage, treatment, and transport was also estimated and included as a source of N for indirect emissions.

The N volatilized from managed agricultural, forest land, and settlement soils, in addition to volatilization during storage, treatment, and transport of managed manure was summed to obtain total volatilization. N lost from storage, treatment, and transport of managed manure is counted as volatilized even though some of this N is likely to be leached/runoff. This is a conservative approach because the IPCC emission factor for volatilization is slightly higher than for leaching/runoff (IPCC 2006). The IPCC default emission factor (Brumme et al. 1999, Butterbach-Bahl et al. 1997, Corre et al. 1999, Denier van der Gon and Bleeker 2005, IPCC/UNEP/OECD/IEA 1997, IPCC 2006) was applied to the total amount of N volatilized to estimate indirect N_2O emissions from volatilization due to the use and management of U.S. croplands, grasslands, forest lands, settlements and managed manure (Table 6-16).

Indirect N_2O from Leaching/Runoff

Similar to the indirect emissions calculation from volatilized N, several approaches were combined to estimate the amount of applied N that was transported from application sites through leaching and surface runoff into waterbodies. DAYCENT was used to simulate the amount of N transported from major cropland types and most grasslands, while N transport from non-major croplands and grasslands not addressed in the DAYCENT model simulations (i.e., from land areas that were not simulated with DAYCENT), settlements, and forestland were obtained by applying the IPCC default fractions for leaching and runoff (IPCC/UNEP/OECD/IEA 1997, IPCC 2006) to total N made available from fertilizer applied, manure applied or deposited, above- and below-ground crop residue retention, soil organic matter decomposition, and asymbiotic fixation.

The N leached/runoff from managed soils, forests, and settlements was summed to obtain total N leaching or surface runoff. The IPCC default emission factor was applied to the total amount of N leached/runoff to estimate total indirect N_2O emissions due to the use and management of croplands, grasslands, forest lands, and settlements (Table 6-16) (IPCC 2006).

Uncertainty

Uncertainty was estimated differently for each of the following three components of N_2O emissions from agricultural soil management: (1) direct emissions calculated by DAYCENT, (2) direct emissions not calculated by DAYCENT, and (3) indirect emissions.

For direct emissions calculated using DAYCENT, uncertainty in the results was attributed to model inputs and the structure of the model (i.e., underlying model equations and parameterization). A Monte Carlo analysis was implemented to address these uncertainties and propagate errors through the modeling process (Del Grosso et al., in prep). A Monte Carlo analysis was conducted using probability distribution functions (PDFs) for weather, soil characteristics, and N inputs to simulate direct N_2O emissions for each crop- or grassland type in a county. A joint PDF was used to address the structural uncertainty for direct N_2O emissions from crops, which was derived using an empirically-based method (Ogle et al. 2007).

County-scale PDFs for weather were based on the variation in temperature and precipitation as represented in DAYMET weather data grid cells (1x1 km) occurring in croplands and grasslands in a county. The National Land Cover Dataset (Vogelman et al. 2001) provided the data on distribution of croplands and grasslands. Similarly, county-scale PDFs for soil characteristics were based on STATSGO Soil Map Units (Soil Survey Staff 2005), that occurred in croplands and grasslands. PDFs for fertilizer were derived from survey data for major U.S. crops, both irrigated and rainfed (ERS 1997; NASS 2004, 1999, 1992; Grant and Krenz 1985). State-level PDFs were developed for each crop if a minimum of 15 data points existed for each of the two categories (irrigated and rainfed). Where data were insufficient at the state-level, PDFs were developed for multi-state Farm Production Regions. Uncertainty in manure applications for specific crops was incorporated into the analysis based on total manure available for application in each county, a weighted average application rate, and the crop-specific land area amended with manure for 1997 (compiled from USDA data on animal numbers, manure production, storage practices, application rates and associated land areas receiving manure amendments; see Edmonds et al. 2003). Together with the total area for each crop within a county, the result yielded a probability that a given crop in a specific county would either receive manure or not in the Monte Carlo analysis. A ratio of manure N production in each year of the Inventory relative to 1997 was used to adjust the amount of area amended with manure, under the assumption that greater or less manure N production would lead to a proportional change in amended area (see the section on Major Crop Types on Mineral Soils for data sources on manure N production). If soils were amended with manure, a reduction factor was applied to the N fertilization rate accounting for the interaction between fertilization and manure N amendments (i.e., producers often reduce mineral fertilization rates if applying manure). Reduction factors were randomly selected from probability distribution factors based on relationships between manure N application and fertilizer rates (ERS 1997).

An empirically-based uncertainty estimator was developed using a method described by Ogle et al. (2007) to assess uncertainty in model structure associated with the algorithms and parameterization. The estimator was based on a linear mixed-effect modeling analysis comparing N_2O emission estimates from eight agricultural experiments with 50 treatments. Although the dataset was relatively small, modeled emissions were significantly related to measurements with a p-value of less than 0.01. Random effects were included to capture the dependence in time series and data collected from the same experimental site, which were needed to estimate appropriate standard deviations for parameter coefficients. The structural uncertainty estimator accounted for bias and prediction error in the DAYCENT model results, as well as random error associated with fine-scale emission predictions in counties over a time series from 1990 to 2005. Note that the current application only addresses structural uncertainty in cropland estimates; further development will be needed to address these uncertainties in model estimates for grasslands, which is a planned improvement as more soil N_2O measurement data become available for grassland sites. In general, DAYCENT tended to underestimate emissions if the rates were above 6 g N_2O m^{-2} (Del Grosso et al., in prep).

A simple error propagation method (IPCC 2006) was used to estimate uncertainties for direct emissions from mineral N inputs estimated with Tier 1 methods, including management on croplands that were used to produce minor crops and N inputs on grasslands that were not addressed in the DAYCENT simulations. Similarly, indirect emissions from agricultural soil management, which were calculated according to the IPCC methodology, were estimated using the simple error propagation method (IPCC 2006).

Uncertainties from Tier 3 and Tier 1 approaches were combined using simple error propagation (IPCC 2006). The results of the uncertainty analysis are summarized in Table 6-17. Agricultural direct soil N_2O emissions in 2005 were estimated to be between 247.5 and 380.0 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 20 percent below and 22 percent above the actual 2005 emission estimate of 310.5 Tg CO_2 Eq. The indirect soil N_2O emissions in 2005 were estimated to range from 31.9 to 128.4 Tg CO_2 Eq. at a 95 percent confidence level, indicating an uncertainty of 42 percent below and 135 percent above the actual 2005 emission estimate of 54.6 Tg CO_2 Eq.

Table 6-17: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2005 (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	310.5	247.5	380.0	-20%	+22%
Indirect Soil N_2O Emissions	N_2O	54.6	31.9	128.4	-42%	+135%

Note: Due to lack of data, uncertainties in 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; every attempt will be made to include these sources of uncertainty in future Inventories.

QA/QC and Verification

For quality control, DAYCENT results for N_2O emissions and NO_3 leaching were compared with field data representing various cropped/grazed systems, soils types, and climate patterns (Del Grosso et al. 2005). N_2O measurement data were available for seven sites in the United States and one in Canada, representing 25 different combinations of fertilizer treatments and cultivation practices. NO_3 leaching data were available for three sites in the United States representing nine different combinations of fertilizer amendments. Linear regressions of simulated vs. observed emission and leaching data yielded correlation coefficients of 0.74 and 0.96 for annual N_2O emissions and NO_3 leaching, respectively.

Spreadsheets containing input data and PDFs required for DAYCENT simulations of major croplands and grasslands and unit conversion factors were checked, as well as the program scripts that were used to run the Monte Carlo Analysis. There is a pending problem with timing of management activities (e.g., planting dates, harvest) as scheduled in the DAYCENT simulations for sorghum production in some counties, and this issue has been prioritized for correction. Spreadsheets containing input data and emission factors required for the Tier 1 approach used for non-major crops and grasslands not simulated by DAYCENT were checked and no errors were found. Total emissions and emissions from the different categories were compared with inventories from previous years and differences were reasonable given the methodological differences (see Recalculations section for further discussion).

Recalculations Discussion

Major revisions in the Agricultural Soil Management sector this year included (1) modifying N inputs to be consistent with the agricultural soil C sector, (2) modeling within-county variation in soil characteristics and weather, (3) developing a Monte Carlo Analysis to address uncertainties in the DAYCENT results, (4) implementing a separate uncertainty analysis for direct emissions calculated with the IPCC default methodology, and (5) incorporating revised methods and emission factors from IPCC (2006).

In terms of N inputs, several changes were needed in order to achieve consistency between the agricultural soil N_2O and soil C inventories. First, the method for simulating mineral N fertilization was changed, so that application rates for major crops were assumed to be stable over the Inventory time period. Changes in the amount of fertilizer applied to soils were assumed to be a result of changing land area for application rather than the rate of application. Second, manure amendment data were altered, so that the area of application varied from year to year based on a county-scale ratio of manure production in an Inventory year relative to 1997. Therefore, the amount of area amended with manure varies through time as a function of the amount of manure. Third, N_2O emissions from soil application of sewage sludge were estimated using the Tier 1 methodology (IPCC 2006) instead of the DAYCENT model. DAYCENT simulates N_2O emissions at the county scale, but sewage sludge application data were only available at the national scale. This created a mismatch in the scale of the DAYCENT model analysis compared to input data availability. The Tier 1 method was assumed to better represent these emissions, since it was not possible with the current dataset to associate sewage sludge application with specific soil and weather conditions at the county scale. Fourth, non-manure commercial organic amendments to soils were assumed to be applied on fields used to produce minor crops, and N_2O emissions were estimated with the IPCC default methodology. Commercial organic fertilizers are more expensive than manure and mineral fertilizers, and, therefore, assumed to be used on cash crops (e.g., vegetables). Cash crops are considered non-major crops for purposes of the Inventory calculations, and, thus, estimated using the Tier 1 methods. Fifth, N inputs from forage legumes not accounted for by the DAYCENT simulations are no longer included in the emissions calculations. In the previous Inventory, the difference between the total N inputs from forage legumes, estimated using an alternative approach, and the DAYCENT estimate was included in the N_2O emissions estimate. However, it was determined that DAYCENT is likely providing a reasonable estimate of total N inputs from forage legumes so the additional production from the alternative approach is no longer included.

In last year's Inventory, weather and soils data were based on the conditions at the centroid location of a county. However, conditions do vary across a county, so the analysis was modified to include sub-county scale heterogeneity in these data. The National Land Cover Dataset (Vogelman et al. 2001) was used to determine the overlap between cropland and DAYMET weather records, which are produced on a 1 × 1 km grid, as well as the soil map units from the STATSGO database that overlap with cropland. The same procedure was also used to determine heterogeneity in weather and soil characteristics for grasslands. PDFs were formed for each of these data inputs and used in a Monte Carlo uncertainty analysis.

The methods for Agricultural Soil Management have been revised in IPCC (2006), and key changes have been incorporated into this year's Inventory. First, the default emission factor for direct soil N_2O emissions was lowered from 1.25 to 1.0 percent of N inputs. Second, previously a portion of the N inputs were removed from the calculation of direct N_2O emissions because it was assumed to be lost through volatilization before direct emissions occurred. However, the direct emission factor was developed based on total N inputs, and therefore the new method has been revised to estimate direct N_2O emissions based on total N input. Third, unlike IPCC/UNEP/OECD/IEA (1997) that counted N fixed by legumes and transported to aboveground biomass as N inputs, as well as N in crop residues, the IPCC (2006) does not double-count symbiotic N fixation separately from the crop residue N inputs. However, the new method does incorporate crop N inputs from not only the aboveground residues, as in IPCC/UNEP/OECD/IEA (1997), but also the root N input to the soil as well. Fourth, regarding indirect emissions, only N inputs from synthetic and organic fertilizer additions were assumed to contribute to NO_3 runoff and leaching in IPCC/UNEP/OECD/IEA (1997). IPCC (2006) assumes that N from crop residues, which includes unharvested N that was symbiotically fixed, is also available for runoff and leaching. Sixth, the amount of N leached out of the soil profile or run off the soil surface that is assumed to be denitrified to N_2O in aquatic systems was lowered from 2.5 to 0.75 percent. Lastly, IPCC (2006) recommends reporting total emissions from managed lands because of the subjectivity with attempting to separate anthropogenic influences from "natural" emissions in a managed environment (i.e., all processes leading to N mineralization in a managed environment and resulting emissions are influenced by anthropogenic activity). Thus, N_2O emissions were not reduced by attempting to estimate a natural background emission based on simulating native vegetation, which had been done in the previous Inventory.

There are two main consequences of adopting new methods from IPCC (2006). First, total emissions are higher, in large part because the non-anthropogenic portion was not subtracted from total emissions. Second, indirect emissions are lower because the amount of nitrate N leached and runoff that is assumed to be converted to N_2O in waterways is substantially lower (0.75 versus 2.5 percent of nitrate N in IPCC/UNEP/OECD/IEA [1997]).

The total change following recalculations ranged from a 15 to 42 percent increase in emissions with an average increase of 32.5 percent. As noted above, one reason for the increase is that under the new methods from IPCC (2006) non-anthropogenic emissions were not subtracted from total emissions. The second main reason is that application of the structural uncertainty estimator described above tended to increase direct N_2O estimates, because DAYCENT under-estimated emissions when the annual rate exceeded 6 g N_2O m^{-2}.

Planned Improvements

Two major improvements are planned for the Agricultural Soil Management sector. The first improvement will be to incorporate more land survey data from the National Resources Inventory (NRI) (USDA 2000b) into the DAYCENT simulation analysis, beyond the area estimates for rangeland and pasture that are currently used to estimate emissions from grasslands. NRI has a record of land-use activities since 1982 for all U.S. agricultural land, which is estimated at about 386 Mha. NASS is used as the basis for land-use records in the current Inventory, and there are three major disadvantages to this land survey. First, most crops are grown in rotation with other crops (e.g., corn-soybean), but NASS data provide no information regarding rotation histories. In contrast, NRI is designed to track rotation histories, and this is important because emissions from any particular year can be influenced by the crop that was grown the previous year. Second, NASS does not conduct a complete survey of cropland area each year, leading to gaps in the land base. NRI does provide a complete history of cropland areas for 4 out of every 5 years, and is currently moving to an annualized inventory that will include a full record for each year. Third, the current Inventory based on NASS does not quantify the influence of land-use change on emissions, which can be addressed using the NRI survey records. NRI also provides additional information on pasture land management that can be incorporated into the analysis (particularly the use of irrigation). Using NRI data will also make the Agricultural Soil Management sector methods more consistent with the methods used to estimate C stock changes for agricultural soils. However, the structure of model input files that contain land management data will need to be extensively revised to facilitate use of NRI data.

The second planned improvement is to further refine the uncertainty analysis. New studies are being completed and published evaluating agricultural management impacts on soil N_2O emissions, and these studies can be incorporated into the empirical analysis, leading to a more robust assessment of structural uncertainty in DAYCENT. Moreover, structural uncertainty is only evaluated for emission estimates in croplands, but it is anticipated that the evaluation could be expanded in the near future to include grasslands. In addition, the Monte Carlo analysis will be expanded to address uncertainties in activity data related to crop- and grassland areas, as well as irrigation and tillage histories. Currently, the land-area statistics are treated as certain because the NASS data do not include a measure of uncertainty. Incorporating land survey data from the NRI will facilitate the assessment of uncertainties in agricultural activity data. Finally, uncertainties in 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. Uncertainties in these quantities will be derived and included in future years.

Additional improvements are more minor but will lead to more accurate estimates, including updating DAYMET weather for more recent years and revising manure N application data to not include poultry manure that is used for cattle feed. Currently, it is estimated that approximately 5 percent of poultry manure is used for feed in the United States and, therefore, not applied to soils. Future inventories will also create a time series of poultry manure going to feed, since initial research indicates that the percentage may have changed over time. In addition, some simulations for sorghum did not run to completion. Input files for counties where this occurred will be examined and the errors corrected. Lastly, instead of assuming that a constant 10 percent of total fertilizer used annually in the United States is applied to settlements, an attempt will be made in the future to recognize that this value varies through the time series because of increasing urbanization, particularly in metropolitan areas. This improvement will be accomplished by exploring the possibility of developing a database that has county-level nitrogen fertilizer data partitioned by farm and non-farm use.

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 carbon 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 wheat, rice, sugarcane, corn, barley, soybeans, and peanuts. Less than 5 percent of the residue for each of these crops is burned each year, except for rice.[13] Annual emissions from this source over the period 1990 to 2005 have remained relatively constant, averaging approximately 0.9 Tg CO_2 Eq. (41 Gg) of CH_4, 0.5 Tg CO_2 Eq. (2 Gg) of N_2O (see Table 6-18 and Table 6-19).

Table 6-18: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq.)

Gas/Crop Type	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**0.7**	**0.7**	**0.8**	**0.8**	**0.7**	**0.8**	**0.9**	**0.9**
Wheat	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sugarcane	+	+	+	+	+	+	+	+
Corn	0.3	0.3	0.4	0.3	0.3	0.4	0.4	0.4
Barley	+	+	+	+	+	+	+	+
Soybeans	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Peanuts	+	+	+	+	+	+	+	+
N_2O	**0.4**	**0.4**	**0.5**	**0.5**	**0.4**	**0.4**	**0.5**	**0.5**
Wheat	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+
Corn	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Barley	+	+	+	+	+	+	+	+
Soybeans	0.2	0.2	0.3	0.3	0.3	0.2	0.3	0.3
Peanuts	+	+	+	+	+	+	+	+
Total	**1.1**	**1.0**	**1.3**	**1.2**	**1.1**	**1.2**	**1.4**	**1.4**

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

Table 6-19: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (Gg)

Gas/Crop Type	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**33**	**32**	**38**	**37**	**34**	**38**	**42**	**41**
Wheat	7	5	5	5	4	6	5	5
Rice	4	4	4	4	3	5	4	4
Sugarcane	1	1	1	1	1	1	1	1
Corn	13	13	17	16	15	17	20	19
Barley	1	1	1	+	+	+	+	+
Soybeans	7	8	10	11	10	9	11	11
Peanuts	+	0	+	+	+	+	+	+
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**2**
Wheat	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+	+
Soybeans	1	1	1	1	1	1	1	1
Peanuts	+	+	+	+	+	+	+	+
CO	**691**	**663**	**792**	**774**	**709**	**800**	**879**	**858**
NO_x	**28**	**29**	**35**	**35**	**33**	**34**	**39**	**39**

+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

---

[13] The fraction of rice straw burned each year is significantly higher than that for other crops (see "Methodology" discussion below).

Methodology

The methodology for estimating greenhouse gas emissions from field burning of agricultural residues is consistent with IPCC/UNEP/OECD/IEA (1997). In order to estimate the amounts of C and N released during burning, the following equations were used:[14]

[C or N] Released = (Annual Crop Production) ×
(Residue/Crop Product Ratio) ×
(Fraction of Residues Burned in situ) ×
(Dry Matter Content of the Residue) ×
(Burning Efficiency) × ([C or N] Content of the Residue) ×
(Combustion Efficiency)[15]

Emissions were calculated by multiplying the amount of C or N released by the appropriate IPCC default emission ratio (i.e., CH_4-C/C and N_2O-N/N).

The types of crop residues burned in the United States were determined from various state-level greenhouse gas emission inventories (ILENR 1993, Oregon Department of Energy 1995, Wisconsin Department of Natural Resources 1993) and publications on agricultural burning in the United States (Jenkins et al. 1992, Turn et al. 1997, EPA 1992).

Crop production data for all crops except rice in Florida and Oklahoma were taken from the USDA's *Field Crops, Final Estimates 1987–1992, 1992–1997, 1997–2002* (USDA 1994, 1998, 2003), and *Crop Production Summary* (USDA 2005, 2006). Rice production 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 1999b, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005), and crop yields for Arkansas (USDA 1994, 1998, 2003, 2005, 2006) were applied to Oklahoma acreages[16] (Lee 2003, 2004, 2005, 2006). The production data for the crop types whose residues are burned are presented in Table 6-20.

The percentage of crop residue burned was assumed to be 3 percent for all crops in all years, except rice, based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996). Estimates of the percentage of rice residue burned were derived from state-level estimates of the percentage of rice area burned each year, which were multiplied by state-level, annual rice production statistics. The annual percentages of rice area burned in each state were obtained from the agricultural extension agents in each state and reports of the California Air Resources Board (Anonymous 2006; Bollich 2000; California Air Resources Board 1999, 2001; Cantens 2005; Deren 2002; Fife 1999; Klosterboer 1999a, 1999b, 2000, 2001, 2002, 2003; Lancero 2006; Lee 2005, 2006; Lindberg 2002, 2003, 2004, 2005; Linscombe 1999a, 1999b, 2001, 2002, 2003, 2004, 2005, 2006; Najita 2000, 2001; Sacramento Valley Basinwide Air Pollution Control Council 2005; Schueneman 1999a, 1999b, 2001; Stansel 2004, 2005; Street 2001, 2002, 2003; Walker 2004, 2005, 2006; Wilson 2003, 2004, 2005, 2006) (see Table 6-21 and Table 6-22). The estimates provided for Florida and Missouri remained constant over the entire

Table 6-20: Agricultural Crop Production (Gg of Product)

Crop	1990	1995	2000	2001	2002	2003	2004	2005
Wheat	74,292	59,404	60,641	53,001	43,705	63,814	58,738	57,280
Rice	7,114	7,947	8,705	9,794	9,601	9,084	10,565	10,152
Sugarcane	25,525	27,922	32,762	31,377	32,253	30,715	26,320	25,308
Corn	201,534	187,970	251,854	241,377	227,767	256,278	299,914	282,260
Barley	9,192	7,824	6,919	5,407	4,940	6,059	6,091	4,613
Soybeans	52,416	59,174	75,055	78,671	75,010	66,778	85,013	83,999
Peanuts	1,635	1,570	1,481	1,940	1,506	1,880	1,945	2,187

*Corn for grain (i.e., excludes corn for silage).

---

[14] As is explained later in this section, the fraction of rice residues burned varies among states, so these equations were applied at the state level for rice. These equations were applied at the national level for all other crop types.

[15] Burning Efficiency is defined as the fraction of dry biomass exposed to burning that actually burns. Combustion Efficiency is defined as the fraction of carbon in the fire that is oxidized completely to CO_2. In the methodology recommended by the IPCC, the "burning efficiency" is assumed to be contained in the "fraction of residues burned" factor. However, the number used here to estimate the "fraction of residues burned" does not account for the fraction of exposed residue that does not burn. Therefore, a "burning efficiency factor" was added to the calculations.

[16] Rice production yield data are not available for Oklahoma, so the Arkansas values are used as a proxy.

Table 6-21: Percent of Rice Area Burned by State

State	1990–1998	1999	2000	2001	2002	2003	2004	2005
Arkansas	13%	13%	13%	13%	16%	22%	17%	22%
California	Variable[a]	27%	27%	23%	13%	14%	11%	12%
Florida[b]	0%	0%	0%	0%	0%	0%	0%	0%
Louisiana	6%	0%	5%	4%	3%	3%	3%	3%
Mississippi	10%	40%	40%	40%	8%	65%	23%	23%
Missouri	18%	18%	18%	18%	18%	18%	18%	18%
Oklahoma	90%	90%	90%	90%	90%	100%	88%	94%
Texas	1%	2%	0%	0%	0%	0%	0%	0%

[a] Values provided in Table 6-22.

[b] Although rice is cultivated in Florida, crop residue burning is illegal. Therefore, emissions remain zero throughout the time series.

1990 through 2005 period, while the estimates for all other states varied over the time series. For California, the annual percentages of rice area burned in the Sacramento Valley are assumed to be representative of burning in the entire state, because the Sacramento Valley accounts for over 95 percent of the rice acreage in California (Fife 1999). These values generally declined between 1990 and 2005 because of a legislated reduction in rice straw burning (Lindberg 2002), although there was a slight increase from 2004 to 2005 (see Table 6-21 and Table 6-22).

All residue/crop product mass ratios except sugarcane were obtained from Strehler and Stützle (1987). The datum for sugarcane is from University of California (1977).

Table 6-22: Percent of Rice Area Burned in California, 1990–1998

Year	Percentage
1990	75%
1991	75%
1992	66%
1993	60%
1994	69%
1995	59%
1996	63%
1997	34%
1998	35%

Residue dry matter contents for all crops except soybeans and peanuts were obtained from Turn et al. (1997). Soybean dry matter content was obtained from Strehler and Stützle (1987). Peanut dry matter content was obtained through personal communications with Jen Ketzis (1999), who accessed Cornell University's Department of Animal Science's computer model, Cornell Net Carbohydrate and Protein System. The residue carbon contents and nitrogen contents for all crops except soybeans and peanuts are from Turn et al. (1997). The residue C content for soybeans and peanuts is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The N content of soybeans is from Barnard and Kristoferson (1985). The nitrogen content of peanuts is from Ketzis (1999). These data are listed in Table 6-23. The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent, for all crop types (EPA 1994). Emission ratios for all gases (see Table 6-24) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Uncertainty

A significant source of uncertainty in the calculation of non-CO_2 emissions from field burning of agricultural residues is in the estimates of the fraction of residue of each

Table 6-23: Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue/Crop Ratio	Fraction of Residue Burned	Dry Matter Fraction	C Fraction	N Fraction	Burning Efficiency	Combustion Efficiency
Wheat	1.3	0.03	0.93	0.4428	0.0062	0.93	0.88
Rice	1.4	Variable	0.91	0.3806	0.0072	0.93	0.88
Sugarcane	0.8	0.03	0.62	0.4235	0.0040	0.93	0.88
Corn	1.0	0.03	0.91	0.4478	0.0058	0.93	0.88
Barley	1.2	0.03	0.93	0.4485	0.0077	0.93	0.88
Soybeans	2.1	0.03	0.87	0.4500	0.0230	0.93	0.88
Peanuts	1.0	0.03	0.86	0.4500	0.0106	0.93	0.88

Table 6-24: Greenhouse Gas Emission Ratios

Gas	Emission Ratio
CH_4[a]	0.005
CO[a]	0.060
N_2O[b]	0.007
NO_x[b]	0.121

[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).

crop type burned each year. Data on the fraction burned, as well as the gross amount of residue burned each year, are not collected at either the national or state level. In addition, burning practices are highly variable among crops, as well as among states. The fractions of residue burned used in these calculations were based upon information collected by state agencies and in published literature. Based on expert judgment, uncertainty in the fraction of crop residue burned ranged from zero to 100 percent, depending on the state and crop type.

The results of the Tier 2 Monte Carlo uncertainty analysis are summarized in Table 6-25. CH_4 emissions from field burning of agricultural residues in 2005 were estimated to be between 0.75 and 0.97 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 13 percent below and 13 percent above the 2005 emission estimate of 0.9 Tg CO_2 Eq. Also at the 95 percent confidence level, N_2O emissions were estimated to be between 0.45 and 0.57 Tg CO_2 Eq. (or approximately 11 percent below and 12 percent above the 2005 emission estimate of 0.5 Tg CO_2 Eq.).

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. No problems were found.

Recalculations Discussion

The crop production data for 2004 were updated using data from USDA (2006). Data on the percentage of rice residue burned in Missouri were revised for all years to 17.5 percent based on new information (Anonymous 2006). Similarly, the percentage of rice residue burned in Mississippi was revised to 22.5 percent for 2004 based on new information provided by Walker (2006). New data for acres of rice harvested in Arkansas in 2005 changed the average rice yield for Arkansas for all years. Subsequently, this change resulted in a change in the rice production data for Oklahoma for all years, since Arkansas data are used as a proxy to calculate rice production in Oklahoma.

These modifications resulted in a change in emissions estimates for CH_4 and N_2O for all years. From 1990 to 2004, emission estimates for CH_4 increased by amounts ranging between 0.18 and 0.51 percent. From 1990 to 2003, N_2O emission estimates increased by amounts ranging between 0.15 and 0.39 percent. In 2004, N_2O emission estimates decreased by 0.05 percent.

Planned Improvements

Preliminary research on agricultural burning in the United States indicates that residues from several additional crop types (e.g., grass for seed, blueberries, and fruit and nut trees) are burned. Whether sufficient information exists for inclusion of these additional crop types in future inventories is being investigated. The extent of recent state crop-burning regulations is also being investigated.

Table 6-25: Tier 2 Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	0.9	0.75	0.97	-13%	+13%
Field Burning of Agricultural Residues	N_2O	0.5	0.45	0.57	-11%	+12%

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

7. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the net greenhouse gas flux[1] resulting from the uses and changes in land types and forests in the United States. The Intergovernmental Panel on Climate Change (IPCC) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003) 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). 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 flux estimates in this chapter, with the exception of CO_2 fluxes from wood products, urban trees, and liming, 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. Agricultural mineral and organic soil C flux calculations are based primarily on national surveys, so these results are largely constant over multi-year intervals, with large discontinuities between intervals. For the landfilled yard trimmings and food scraps source, periodic solid waste survey data were interpolated so that annual storage estimates could be derived. In addition, because the most recent national forest, land-use, and municipal solid waste surveys were completed prior to 2005, the estimates of CO_2 flux from forests, agricultural soils, and landfilled yard trimmings and food scraps are based in part on extrapolation. Carbon dioxide flux from urban trees is based on neither annual data nor periodic survey data, but instead on data collected over the period 1990 through 1999. 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 2005 resulted in a net C sequestration of 828.5 Tg CO_2 Eq. (225.9 Tg C) (Table 7-1 and Table 7-2). This represents an offset of approximately 14 percent of total U.S. CO_2 emissions. Total

---

[1] 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."

Table 7-1: Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Land-Use Category	1990	1995	2000	2001	2002	2003	2004	2005
Forest Land Remaining Forest Land	**(598.5)**	**(717.5)**	**(638.7)**	**(645.7)**	**(688.1)**	**(687.0)**	**(697.3)**	**(698.7)**
Changes in Forest C Stocks[a]	(598.5)	(717.5)	(638.7)	(645.7)	(688.1)	(687.0)	(697.3)	(698.7)
Cropland Remaining Cropland	**(28.1)**	**(37.4)**	**(36.5)**	**(38.0)**	**(37.8)**	**(38.3)**	**(39.4)**	**(39.4)**
Changes in Agricultural Soil C Stocks and Liming Emissions[b]	(28.1)	(37.4)	(36.5)	(38.0)	(37.8)	(38.3)	(39.4)	(39.4)
Land Converted to Cropland	**8.7**	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**
Changes in Agricultural Soil C Stocks[c]	8.7	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Grassland Remaining Grassland	**0.1**	**16.4**	**16.3**	**16.2**	**16.2**	**16.2**	**16.1**	**16.1**
Changes in Agricultural Soil C Stocks[d]	0.1	16.4	16.3	16.2	16.2	16.2	16.1	16.1
Land Converted to Grassland	**(14.6)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**
Changes in Agricultural Soil C Stocks[e]	(14.6)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)
Settlements Remaining Settlements[f]	**(57.5)**	**(67.8)**	**(78.2)**	**(80.2)**	**(82.3)**	**(84.4)**	**(86.4)**	**(88.5)**
Urban Trees	(57.5)	(67.8)	(78.2)	(80.2)	(82.3)	(84.4)	(86.4)	(88.5)
Other	**(22.8)**	**(13.3)**	**(10.5)**	**(10.6)**	**(10.8)**	**(9.3)**	**(8.7)**	**(8.8)**
Landfilled Yard Trimmings and Food Scraps	(22.8)	(13.3)	(10.5)	(10.6)	(10.8)	(9.3)	(8.7)	(8.8)
Total	**(712.8)**	**(828.8)**	**(756.7)**	**(767.5)**	**(811.9)**	**(811.9)**	**(824.8)**	**(828.5)**

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

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

[b] Estimates include C stock changes in mineral soils and organic soils on *Cropland Remaining Cropland*, C stock changes in organic soils on *Land Converted to Cropland*, and liming emissions from all managed land.

[c] Estimates include C stock changes in mineral soils only; organic soil C stock changes and liming emissions for this land use/land-use change category are reported under *Cropland Remaining Cropland*.

[d] Estimates include C stock changes in mineral soils and organic soils on *Grassland Remaining Grassland*, and C stock changes in organic soils on *Land Converted to Grassland*. Liming emissions for this land use/land-use change category are reported under *Cropland Remaining Cropland*.

[e] Estimates include C stock changes in mineral soils only; organic soil C stock changes and liming emissions for this land use/land-use change category are reported under *Grassland Remaining Grassland* and *Cropland Remaining Cropland*, respectively.

[f] Estimates include C stock changes on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*. Liming emissions for this land use/land-use change category are reported under *Cropland Remaining Cropland*.

land use, land-use change, and forestry net C sequestration[2] increased by approximately 16 percent between 1990 and 2005. This increase was primarily due to an increase in the rate of net C accumulation in forest C stocks. Net C accumulation in *Settlements Remaining Settlements*, *Land Converted to Grassland*, and *Cropland Remaining Cropland* increased, while net C accumulation in landfilled yard trimmings and food scraps slowed over this period. The *Grassland Remaining Grassland* land-use category resulted in net C emissions in 1990 and 1991, became a net C sink from 1992 to 1994, and then remained a fairly constant emission source. Emissions from *Land Converted to Cropland* declined between 1990 and 2005.

Non-CO_2 emissions from Land Use, Land-Use Change, and Forestry are shown in Table 7-3 and Table 7-4. The application of synthetic fertilizers to forest and settlement soils in 2005 resulted in direct N_2O emissions of 6.2 Tg CO_2 Eq. (20 Gg N_2O). Direct N_2O emissions from fertilizer application increased by approximately 19 percent between 1990 and 2005. Non-CO_2 emissions from forest fires in 2005 resulted in methane (CH_4) emissions of 11.6 Tg CO_2 Eq. (551 Gg), and in N_2O emissions of 1.2 Tg CO_2 Eq. (4 Gg).

7.1. 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,

---

[2] 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.

Table 7-2: Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Tg C)

Land-Use Category	1990	1995	2000	2001	2002	2003	2004	2005
Forest Land Remaining Forest Land	**(163.2)**	**(195.7)**	**(174.2)**	**(176.1)**	**(187.7)**	**(187.4)**	**(190.2)**	**(190.6)**
Changes in Forest C Stocks[a]	(163.2)	(195.7)	(174.2)	(176.1)	(187.7)	(187.4)	(190.2)	(190.6)
Cropland Remaining Cropland	**(7.7)**	**(10.2)**	**(10.0)**	**(10.4)**	**(10.3)**	**(10.4)**	**(10.7)**	**(10.7)**
Changes in Agricultural Soil C Stocks and Liming Emissions[b]	(7.7)	(10.2)	(10.0)	(10.4)	(10.3)	(10.4)	(10.7)	(10.7)
Land Converted to Cropland	**2.4**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
Changes in Agricultural Soil C Stocks[c]	2.4	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Grassland Remaining Grassland	**0.0**	**4.5**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**
Changes in Agricultural Soil C Stocks[d]	0.0	4.5	4.4	4.4	4.4	4.4	4.4	4.4
Land Converted to Grassland	**(4.0)**	**(4.5)**	**(4.5)**	**(4.5)**	**(4.5)**	**(4.5)**	**(4.5)**	**(4.5)**
Changes in Agricultural Soil C Stocks[e]	(4.0)	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)
Settlements Remaining Settlements[f]	**(15.7)**	**(18.5)**	**(21.3)**	**(21.9)**	**(22.4)**	**(23.0)**	**(23.6)**	**(24.1)**
Urban Trees	(15.7)	(18.5)	(21.3)	(21.9)	(22.4)	(23.0)	(23.6)	(24.1)
Other	**(6.2)**	**(3.6)**	**(2.9)**	**(2.9)**	**(3.0)**	**(2.5)**	**(2.4)**	**(2.4)**
Landfilled Yard Trimmings and Food Scraps	(6.2)	(3.6)	(2.9)	(2.9)	(3.0)	(2.5)	(2.4)	(2.4)
Total	**(194.4)**	**(226.0)**	**(206.4)**	**(209.3)**	**(221.4)**	**(221.4)**	**(224.9)**	**(225.9)**

Note: 1 Tg C = 1 teragram C = 1 million metric tons C. Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

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

[b] Estimates include C stock changes in mineral soils and organic soils on *Cropland Remaining Cropland*, C stock changes in organic soils on *Land Converted to Cropland*, and liming emissions from all managed land.

[c] Estimates include C stock changes in mineral soils only; organic soil C stock changes and liming emissions for this land use/land-use change category are reported under *Cropland Remaining Cropland*.

[d] Estimates include C stock changes in mineral soils and organic soils on *Grassland Remaining Grassland*, and C stock changes in organic soils on *Land Converted to Grassland*. Liming emissions for this land use/land-use change category are reported under *Cropland Remaining Cropland*.

[e] Estimates include C stock changes in mineral soils only; organic soil C stock changes and liming emissions for this land use/land-use change category are reported under *Grassland Remaining Grassland* and *Cropland Remaining Cropland*, respectively.

[f] Estimates include C stock changes on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*. Liming emissions for this land use/land-use change category are reported under *Cropland Remaining Cropland*.

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 carbon (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 also necessary for estimating C flux, which are:

- Harvested wood products in use.
- Harvested wood products 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 to the atmosphere. Instead, harvesting transfers C 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

Table 7-3: Non-CO_2 Emissions from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Land-Use Category	1990	1995	2000	2001	2002	2003	2004	2005
Forest Land Remaining Forest Land	**7.8**	**4.5**	**15.7**	**6.9**	**11.8**	**9.2**	**8.0**	**13.1**
CH_4 Emissions from Forest Fires	7.1	4.0	14.0	6.0	10.4	8.1	6.9	11.6
N_2O Emissions from Forest Fires	0.7	0.4	1.4	0.6	1.1	0.8	0.7	1.2
N_2O Emissions from Soils[a]	0.1	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Settlements Remaining Settlements	**5.1**	**5.5**	**5.6**	**5.5**	**5.6**	**5.8**	**6.0**	**5.8**
N_2O Emissions from Soils[b]	5.1	5.5	5.6	5.5	5.6	5.8	6.0	5.8
Total	**13.0**	**10.1**	**21.3**	**12.4**	**17.4**	**15.0**	**13.9**	**18.9**

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.

[a] 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.

[b] 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: Non-CO_2 Emissions from Land Use, Land-Use Change, and Forestry (Gg)

Land-Use Category	1990	1995	2000	2001	2002	2003	2004	2005
Forest Land Remaining Forest Land								
CH_4 Emissions from Forest Fires	337	189	667	285	494	384	330	551
N_2O Emissions from Forest Fires	2	1	5	2	3	3	2	4
N_2O Emissions from Soils[a]	0	1	1	1	1	1	1	1
Settlements Remaining Settlements								
N_2O Emissions from Soils[b]	17	18	18	18	18	19	19	19

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.

[a] 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.

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

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.

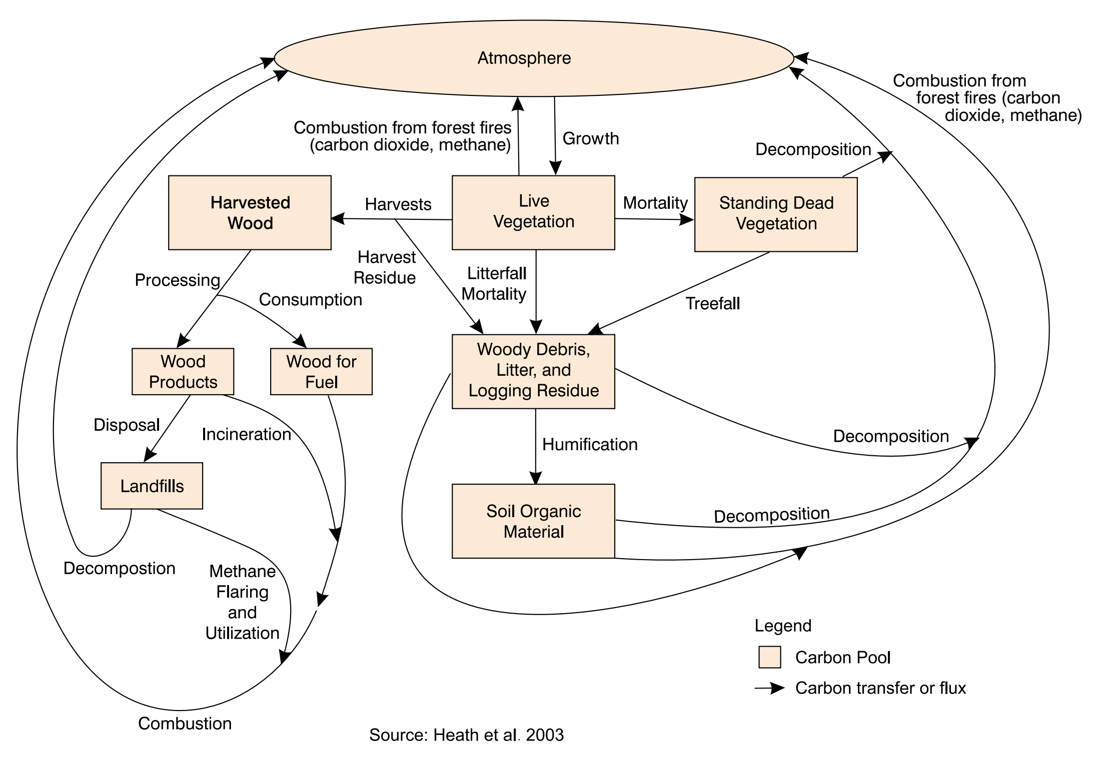
This section quantifies the net changes in C stocks in the five forest C pools and two harvested wood pools. The net change in stocks for each pool is estimated, and then the changes in stocks are summed over all pools to estimate total net flux. Thus, the focus on C implies that all C-based greenhouse gases are included, and the focus on stock change suggests that specific ecosystem fluxes do not need to be separately itemized in this report. Disturbances from forest fires and pest outbreaks are implicitly included in the net changes. For instance, an inventory conducted after fire counts only trees 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. 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 not available for the entire United States to allow results to be partitioned in this way. Instead, 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 7-1. 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 altered in this graphic to better illustrate the processes that result in transfers of C from one pool to another, and emissions to the atmosphere as well as uptake from the atmosphere.

Approximately 33 percent (303 million hectares) of the U.S. land area is forested, of which approximately 250 million hectares are located in the conterminous 48 states. An additional 52 million hectares are located in Alaska and Hawaii, though this inventory does not currently account for these stocks and fluxes due to data limitations. Hawaii

Figure 7-1

Forest Sector Carbon Pools and Flows



Source: Heath et al. 2003

and U.S. territories have relatively small areas of forest land and will probably not affect the overall C budget to a great degree. Alaska has over 50 million hectares of forest land, however, and more efforts will be made to account for this area in the future (see Planned Improvements for more details). Agroforestry systems are also not currently accounted for in the U.S. Inventory, since they are not explicitly inventoried by either of the two primary national natural resource inventory programs: the Forest Inventory and Analysis (FIA) program of the U.S. Department of Agriculture (USDA) Forest Service and the National Resources Inventory (NRI) of the USDA Natural Resources Conservation Service (Perry et al. 2005).

Seventy-nine percent of the 250 million hectares are classified as timberland, meaning they meet minimum levels of productivity and are available for timber harvest. Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than other forest lands. Of the remaining 51 million hectares, 16 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 35 million hectares are lower productivity forest lands (Smith et al. 2004b). From the early 1970s to the early 1980s, forest land declined by approximately 2.4 million hectares. During the 1980s and 1990s, forest area increased by about 3.7 million hectares. These net changes in forest area represent average annual fluctuations of only about 0.1 percent. Given the low rate of change in U.S. forest land 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 can increase both the rate of growth and the eventual biomass density of the forest, thereby increasing the uptake of C.[3] Harvesting forests removes much of the aboveground C, but trees can grow on this area again and sequester C. 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.

---

[3] The term “biomass density” refers to the mass of vegetation per unit area. It is usually measured on a dry-weight basis. Dry biomass is 50 percent carbon by weight.

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, as well as timber harvesting and use have resulted in net uptake (i.e., net sequestration) of C each year from 1990 through 2005. Due to improvements in U.S. agricultural productivity, the rate of forest clearing for crop cultivation and pasture slowed in the late 19th century, and by 1920, this practice had all but ceased. As farming expanded in the Midwest and West, large areas of previously cultivated land in the East were taken out of crop production, primarily between 1920 and 1950, and were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still affect C fluxes from forests in the East. In addition, C fluxes from eastern forests have been affected by a trend toward managed growth on private land. Collectively, these changes have nearly doubled the biomass density in eastern forests since the early 1950s. 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 in preparation). The size of these long-term C storage pools has increased during the last century.

Table 7-5: Net Annual Changes in C Stocks (Tg CO_2/yr) in Forest and Harvested Wood Pools

Carbon Pool	1990	1995	2000	2001	2002	2003	2004	2005
Forest	**(466.5)**	**(602.0)**	**(529.4)**	**(555.5)**	**(595.3)**	**(595.3)**	**(595.3)**	**(595.3)**
Aboveground Biomass	(251.8)	(331.0)	(347.1)	(360.4)	(376.4)	(376.4)	(376.4)	(376.4)
Belowground Biomass	(63.9)	(69.8)	(73.9)	(76.4)	(79.5)	(79.5)	(79.5)	(79.5)
Dead Wood	(36.7)	(60.9)	(48.2)	(50.0)	(52.4)	(52.4)	(52.4)	(52.4)
Litter	(65.6)	(49.5)	(35.8)	(47.1)	(52.2)	(52.2)	(52.2)	(52.2)
Soil Organic Carbon	(48.5)	(90.8)	(24.5)	(21.6)	(34.8)	(34.8)	(34.8)	(34.8)
Harvested Wood	**(132.0)**	**(115.5)**	**(109.3)**	**(90.2)**	**(92.8)**	**(91.7)**	**(101.9)**	**(103.4)**
Products in use	(63.1)	(53.5)	(46.2)	(31.2)	(34.1)	(33.4)	(43.3)	(44.4)
SWDS	(68.9)	(62.0)	(63.1)	(59.0)	(58.7)	(58.3)	(58.7)	(59.0)
Total Net Flux	**(598.5)**	**(717.5)**	**(638.7)**	**(645.7)**	**(688.1)**	**(687.0)**	**(697.3)**	**(698.7)**

Note: Forest C stocks do not include forest stocks in Alaska, Hawaii, or U.S. territories, 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.

Table 7-6: Net Annual Changes in C Stocks (Tg C/yr) in Forest and Harvested Wood Pools

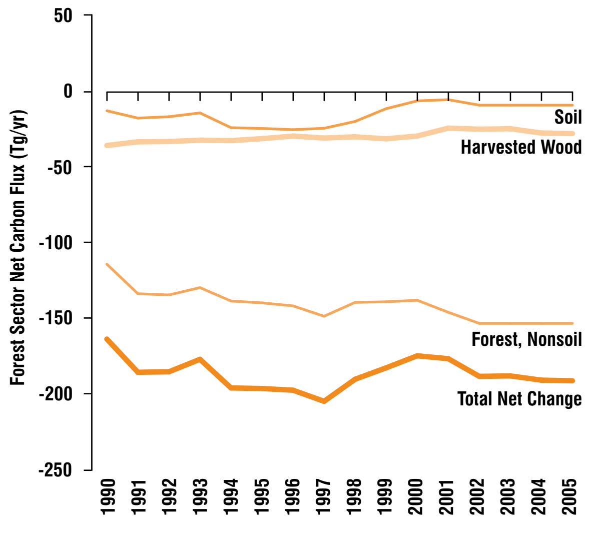
Carbon Pool	1990	1995	2000	2001	2002	2003	2004	2005
Forest	**(127.2)**	**(164.2)**	**(144.4)**	**(151.5)**	**(162.4)**	**(162.4)**	**(162.4)**	**(162.4)**
Aboveground Biomass	(68.7)	(90.3)	(94.7)	(98.3)	(102.7)	(102.7)	(102.7)	(102.7)
Belowground Biomass	(17.4)	(19.0)	(20.1)	(20.8)	(21.7)	(21.7)	(21.7)	(21.7)
Dead Wood	(10.0)	(16.6)	(13.1)	(13.6)	(14.3)	(14.3)	(14.3)	(14.3)
Litter	(17.9)	(13.5)	(9.8)	(12.9)	(14.2)	(14.2)	(14.2)	(14.2)
Soil Organic Carbon	(13.2)	(24.8)	(6.7)	(5.9)	(9.5)	(9.5)	(9.5)	(9.5)
Harvested Wood	**(36.0)**	**(31.5)**	**(29.8)**	**(24.6)**	**(25.3)**	**(25.0)**	**(27.8)**	**(28.2)**
Products in use	(17.2)	(14.6)	(12.6)	(8.5)	(9.3)	(9.1)	(11.8)	(12.1)
SWDS	(18.8)	(16.9)	(17.2)	(16.1)	(16.0)	(15.9)	(16.0)	(16.1)
Total Net Flux	**(163.2)**	**(195.7)**	**(174.2)**	**(176.1)**	**(187.7)**	**(187.4)**	**(190.2)**	**(190.6)**

Note: Forest C stocks do not include forest stocks in Alaska, Hawaii, or U.S. territories, 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.

Changes in C stocks in U.S. forests and harvested wood were estimated to account for net sequestration of 698.7 Tg CO_2 Eq. (190.6 Tg C) in 2005 (Table 7-5, Table 7-6, and Figure 7-2). 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, though the increase in forest sequestration is due more to an increasing C density per area than to the increase in area of forest land. Forest land in the conterminous United States was approximately 246, 250, and 251 million hectares for 1987, 1997, and 2002, respectively, which amounts to only a 2 percent increase over the period (Smith et al. 2004b). 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. National estimates are a composite of individual state surveys. Total sequestration increased by 17 percent between 1990 and 2005 (see *Recalculations Discussion*). Estimated sequestration in the aboveground biomass C pool had the greatest effect on total change. This was primarily due to an increase in the rate of net C accumulation as density, or the rate of change in metric tons of C per hectare per year, approximately a 21 percent increase over the 1990 through 2005 time series. This increase is particularly evident for the aboveground and belowground tree biomass pools, for which rate of C accumulation increased by about 37 percent.

Figure 7-2

Estimates of Net Annual Changes in Carbon Stocks for Major Carbon Pools



Stock estimates for forest and harvested wood C storage pools are presented in Table 7-7. Together, the aboveground live and forest soil pools account for a large proportion of total forest C stocks. C stocks in all non-soil pools increased over time. Therefore, C sequestration was greater than C emissions from forests, as discussed above. Figure 7-3 shows county-average C densities for live trees on forest land, including both above- and belowground biomass.

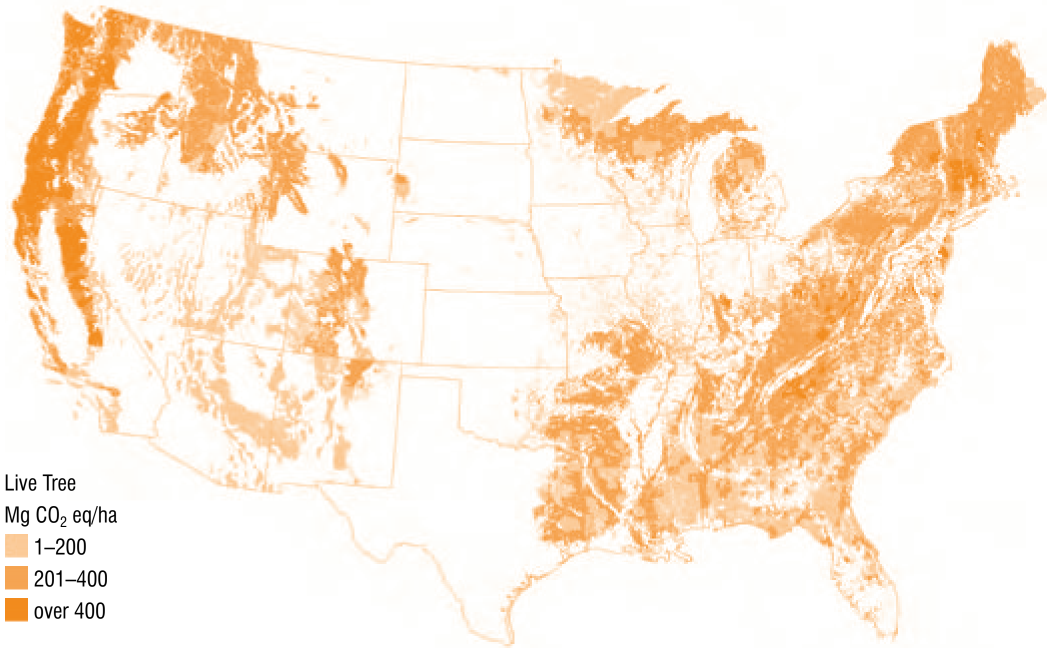
Table 7-7: Forest area (1,000 ha) and C Stocks (Tg C) in Forest and Harvested Wood Pools

Carbon Pool	1990	1995	2000	2001	2002	2003	2004	2005	2006
Forest Area (1,000 ha)	**242,300**	**245,946**	**250,275**	**251,110**	**251,977**	**252,879**	**253,782**	**254,684**	**255,587**
Carbon Pools (Tg C)									
Forest	**39,026**	**39,762**	**40,576**	**40,721**	**40,872**	**41,035**	**41,197**	**41,359**	**41,522**
Aboveground Biomass	14,164	14,565	15,031	15,125	15,224	15,326	15,429	15,532	15,634
Belowground Biomass	2,794	2,885	2,983	3,003	3,024	3,045	3,067	3,089	3,110
Dead Wood	2,354	2,418	2,499	2,512	2,526	2,540	2,555	2,569	2,583
Litter	4,404	4,497	4,559	4,569	4,582	4,596	4,610	4,625	4,639
Soil Organic C	15,310	15,398	15,505	15,511	15,517	15,527	15,536	15,546	15,555
Harvested Wood	**1,888**	**2,067**	**2,225**	**2,255**	**2,287**	**2,317**	**2,341**	**2,367**	**2,395**
Products in use	1,184	1,268	1,341	1,354	1,368	1,381	1,389	1,399	1,411
SWDS	704	799	884	901	919	936	952	968	984
Total C Stock	**40,914**	**41,829**	**42,801**	**42,976**	**43,159**	**43,352**	**43,538**	**43,726**	**43,917**

Note: Forest area estimates are based on interpolation and extrapolation of inventory data as described in the text and in Annex 3.12. Forest C stocks do not include forest stocks in Alaska, Hawaii, or U.S. territories, 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 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. 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 2005 requires estimates of C stocks for 2005 and 2006.

Figure 7-3

Average C Density in the Forest Tree Pool in the Conterminous United States During 2005



Note: This graphic shows county-average carbon densities for live trees on forestland, including both above- and belowground biomass. These data are based on the most recent forest inventory survey in each state. (See Table A-3 for the most recent inventory year for each state or substate.)

Box 7-1: 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 fire, but only for the lower 48 states. As detailed previously, Alaska is not yet included in national estimates of forest C stocks and fluxes, due to lack of forest inventory data at this time (see *Planned Improvements*). Wildfire data is, however, available for Alaska, so it has been included in these calculations. 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 (Table 7-8). Non-CO_2 greenhouse gas emissions from forest fires are also quantified in a separate section below.

Table 7-8: Estimates of CO_2 (Tg/yr) Emissions for the Lower 48 States and Alaska[a]

Year	CO_2 emitted in the Lower 48 States (Tg/yr)	CO_2 emitted in Alaska (Tg/yr)	Total CO_2 emitted (Tg/yr)
1990	42.7	34.5	77.2
1995	42.9	0.5	43.3
2000	144.6	8.2	152.8
2001	63.0	2.4	65.3
2002	89.7	23.6	113.3
2003	81.4	6.5	87.9
2004	5.0	70.6	75.6
2005	75.9	50.5	126.4

[a] Note that these emissions have already been accounted for in the net C sequestration estimates (i.e., net flux already accounts for the amount sequestered minus any emissions).

The IPCC (2003) methodology was employed to estimate CO_2 emissions from forest fires. CO_2 emissions for the lower 48 states and Alaska in 2005 were estimated to be 126.4 Tg CO_2/yr. This amount is masked in the estimates of total flux for 2005, however, by an additional 126.4 Tg CO_2/yr being sequestered (i.e., flux already accounts for the amount sequestered minus any emissions).

Methodology

The methodology described herein is consistent with IPCC (2003) and IPCC/UNEP/OECD/IEA (1997). Estimates of net annual C stock change, or flux, of forest ecosystems are derived from applying C estimation factors to forest inventory data and interpolating between successive inventory-based estimates of C stocks. C emissions from harvested wood 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). Different data sources are used to estimate the C stocks and stock change in forest ecosystems or harvested wood products. See Annex 3.12 for details and additional information related to the methods described below.

Forest Carbon Stocks and Fluxes

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, Forest Inventory and Analysis (FIA) program (Frayer and Furnival 1999, USDA Forest Service 2006a). Inventories include forest lands[4] of the conterminous United States and are organized as a number of separate datasets, each representing a complete inventory, or survey, of an individual state at a specified time. Forest C calculations are organized according to these state surveys, and the frequency of surveys varies by state. To calculate a C stock change, at least two surveys are needed in each state. Thus, the most recent surveys for each state are used as well as all additional consistent inventory data back through 1990. Because C flux is based on change between successive C stocks, consistent representation of forest land in successive inventories is necessary. In order to achieve accurate representation of forests from 1990 to the present, sometimes state-level data are subdivided or additional inventory sources are used to produce the consistent state or sub-state inventories.

The principal FIA forest inventory datasets employed are freely available for download at USDA Forest Service (2006b) as the Forest Inventory and Analysis Database (FIADB) Version 2.1. These data are identified as "snapshot" files, also identified as FISDB 2.1, and include detailed plot information, including individual-tree data. However, to achieve consistent representation (spatial and temporal), two other general sources of past FIA data are included as necessary. Firstly, older FIA plot- and tree-level data—not in the FIADB format—are used if available. Secondly, 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. A detailed list of the specific inventory data used here is in Table A-188 of Annex 3.12.

Forest C stocks are estimated from inventory data by a collection of conversion factors and models referred to as FORCARB2 (Birdsey and Heath 1995, Birdsey and Heath 2001, Heath et al. 2003, Smith et al. 2004a), which have been formalized in an application referred to as the Carbon Calculation Tool (CCT), (Smith et al. in preparation). The conversion factors and model coefficients are usually categorized by region and forest type, and forest C stock estimates are dependent on these particular sets of factors. Factors are applied to the data at the scale of FIA inventory plots. The results are estimates of C density (Mg per hectare) for the various forest pools. C density for live trees, standing dead trees, understory vegetation, down dead wood, forest floor, and soil organic matter are estimated. All non-soil pools except forest floor can be separated into aboveground and belowground components. The live tree and understory C pools are pooled as biomass in this Inventory. Similarly, standing dead trees and down dead wood are pooled as dead wood in this Inventory. Definitions of ecosystem pools and the C conversion process follow, with additional information in Annex 3.12.

Live Biomass, Dead Wood, and Litter Carbon

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 full-tree and aboveground-only biomass in order to estimate the belowground component. If inventory plots include data on individual trees, tree C is based on Jenkins et al. (2003) and is a function of species and diameter. Some inventory data do not provide measurements of individual trees; tree

---

[4] 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.

C in these plots is estimated from plot-level volume of merchantable wood, or growing-stock volume, of live trees, which is calculated from updates of Smith et al. (2003). Some inventory data, particularly some of the older datasets, may not include sufficient information to calculate tree C because of incomplete or missing tree or volume data; C estimates for these plots are based on averages from similar, but more complete, inventory data.

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 this 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).

The two components of dead wood—standing dead trees and down dead wood—are estimated separately. The standing dead tree C pools include aboveground and belowground (coarse root) mass and include trees of at least 2.54 cm d.b.h. 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 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).

Forest Soil C

Soil organic carbon (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), and 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. Thus, SOC is defined by region and forest type group.

C stocks and fluxes for *Forest Land Remaining Forest Land* are reported in pools following IPCC (2003). Total forest C stock and flux estimates start with the plot-level calculations described above. The separate C densities are summed and multiplied by the appropriate expansion factors to obtain a C stock estimate for the plot. In turn, these are summed to state or sub-state total C stocks. Annualized estimates of C stocks are based on interpolating or extrapolating as necessary to assign a C stock to each year. For example, the C stock of Alabama for 2005 is an extrapolation of the two most recent inventory datasets for that particular state, which are from 1999 and 2003. Flux, or net annual stock change, is simply the difference between two successive years with the appropriate sign convention so that net increases in ecosystem C are identified as negative flux. This methodological detail accounts for the constant estimates of flux from the second most recent Inventory to the present (see 2002 through 2005 on Table 7-5 as an example).

Harvested Wood Carbon

Estimates of the harvested wood product (HWP) contribution to forest C sinks and emissions (hereafter called “HWP Contribution”) are based on methods described in Skog (in preparation) using the WOODCARB II model. These are based on the methods suggested in IPCC (2006) for estimating HWP carbon. The United States uses the production accounting approach to report HWP Contribution. This means that 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 the production approach is used in this Inventory, 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 in four HWP summary quantities 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]). These four categories of annual change of C in wood and paper products are (1) all products in use in the United States; (2) all products in SWDS in the United States; (3) products in use in the United States and other countries where the wood came from trees harvested in the United States; and (4) products in SWDS in the United States and other countries where the wood came from trees harvested in the United States.

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 & forthcoming). 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.

Summary categories 3 and 4 (above) are used to estimate 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

The forest survey data that underlie the forest C estimates are based on a statistical sample designed to represent the wide variety of growth conditions present over large territories. The USDA Forest Service inventories are designed to be accurate within 3 percent at the 67 percent confidence level (one standard error) per 405,000 ha (1 million acres) of timberland (USDA Forest Service 2006c). For larger areas, the uncertainty in area is concomitantly smaller, and precision at plot levels is larger. An analysis of uncertainty in growing stock volume data for timber producing land in the Southeast by Phillips et al. (2000) found that nearly all of the uncertainty in their analysis was due to sampling rather than the regression equations used to estimate volume from tree height and diameter. The quantitative uncertainty analysis summarized here (and in Table 7-9) primarily focuses on uncertainties associated with the estimates of specific C stocks at the plot level and does not address error in tree diameters or volumes.

Estimates for stand-level C pools are derived from extrapolations of site-specific studies to all forest land, because survey data on these pools are not generally available. Such extrapolation introduces uncertainty because available studies may not adequately represent regional or national averages. Uncertainty may also arise due to: (1) modeling errors (e.g., relying on coefficients or relationships that are not well known); and (2) errors in converting estimates from one reporting unit to another (Birdsey and Heath 1995). An important source of uncertainty is that there is little consensus from available data sets on the effect of land-use change and forest management activities (such as harvest) on soil C stocks. For example, while Johnson and Curtis (2001) found little or no net change in soil C following harvest, on average, across a number of studies, many of the individual studies did exhibit differences. Heath and Smith (2000) noted that the experimental design in a number of soil studies limited their usefulness for determining effects of harvesting on soil C. Because soil C stocks are large, estimates need to be very precise, since even small relative changes in soil C sum to large differences when integrated over large areas. The soil C stock and stock change estimates presented here are based on the assumption that soil C density for each broad forest type group stays constant over time. The state of information and modeling are improving in this regard (Woodbury et al. 2006); the effects of land use and of changes in land use and forest management will be better accounted for in future estimates of soil C.

Uncertainty in estimates about the HWP Contribution is based on Monte Carlo simulation of the production

Table 7-9: 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	2005 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	(595.3)	(785.2)	(410.5)	-32%	+31%
Harvested Wood Products	CO_2	(103.4)	(130.2)	(78.9)	-26%	+24%
Total Forest	**CO_2**	**(698.7)**	**(889.5)**	**(513.1)**	**-27%**	**+27%**

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.

approach. The uncertainty analysis is based on Skog et al. (2004). However, the uncertainty analysis simulation has been revised in conjunction with overall revisions in the HWP model (Skog in preparation). The analysis includes an evaluation of the effect of uncertainty in 13 sources including production and trade data, factors to convert products to quantities of C, rates at which wood and paper are discarded, and rates and limits for decay of wood and paper in SWDS.

The 2005 flux estimate for forest C stocks is estimated to be between -513.1 and -889.5 Tg CO_2 Eq. at a 95 percent confidence level. This includes a range of -410.5 to -785.2 Tg CO_2 Eq. in forest ecosystems and -78.9 to -130.2 Tg CO_2 Eq. for HWP. The relatively smaller range of uncertainty, in terms of percentage, for the total relative to the two separate parts is because the total is based on summing the two independent uncertain parts, as discussed 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 main purpose of the FIA program has been to estimate areas, volume of growing stock, and timber products output and utilization factors. 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 2006b).

Many key calculations for estimating current forest C stocks based on FIA data are based on coefficients from the FORCARB2 model (see additional discussion in the Methodology section above and in Annex 3.12). The model has been used for many years to produce national assessments of forest C stocks and stock changes. 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 with standard inventory summaries such as Resources Planning Act (RPA) Forest Resource Tables or selected population estimates generated from the FIA Database (FIADB), which are available at an FIA Internet site (USDA Forest Service 2006b). 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 from original units to C units are based on estimates by industry and Forest Service published sources. The WOODCARB II model uses estimation methods suggested by the IPCC (2006). Estimates of annual C change in solidwood and paper products in use were verified by two independent criteria. The first criteria 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 criteria 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 criteria 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. 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 reduces uncertainty in estimates of annual change in C in products made from wood harvested in the United States.

Recalculations Discussion

The overall scheme for developing annualized estimates of forest ecosystem C stocks based on the individual state surveys and the C conversion factors used are similar to that presented in the previous Inventory (EPA 2006a). The principal change from the previous year's methods involves the increased use of sub-state classification of the survey data as indicated in Table A-188 in Annex 3.12, which details the survey data used for the current Inventory. For the current Inventory, the emphasis was on improving consistency between successive surveys or portions of surveys when sub-state portions of inventory data provided better continuity. The FIADB "snapshot" datasets were the primary source of FIA inventory data. Secondary sources included the plot and tree data from older, pre-FIADB, inventories and the plot-level RPA datasets. By improving the consistency of these datasets, substantial revisions were made to previous estimates, which primarily affected early years in the calculations. The new calculations of forest C stocks in 1990 decreased the estimate of C sequestration by 23 percent (174.9 Tg CO_2 Eq.), while increasing C sequestration estimates for forest C stocks in 2004 by 9 percent (60.1 Tg CO_2 Eq.).

The change in stock and flux estimates for the period since 1990, as compared to the estimates presented in the previous Inventory, is based on the cumulative effects of (1) additional inventory data, and (2) how the state or sub-state inventories are classified. State-level inventory data changed more dramatically for some particular states as compared to others. As an example, stock and flux estimates for the state of California are based on the FIA datasets specified in Table A-188 in Annex 3.12. In past inventories (for example, EPA 2006a), chaparral ecosystems were included in forest inventory data and, therefore, forest C stock estimates. However, much of this ecological community type fails to meet the definition of forestland. Current FIA forest inventory data does not include non-forest land of this ecological community. In order to maintain consistency across the time series, non-forest chaparral estimates had to be removed from California's total stock estimates in earlier inventories. This caused a dramatic decrease in forest C stock estimates at the early part of the time series for the state of California compared to those California estimates used for the previous inventory submission.

The estimate of HWP contribution under the production account approach has been revised. Estimates of the 5 HWP variables have been added (see Annex 3.12), which allow estimates using the alternate accounting approaches for which the IPCC provides accounting guidance (IPCC 2006). The basic method used to estimate the HWP variables has not changed—tracking additions to and removals from pools—but more detailed product and trade data are used and discard and decay parameters have been revised. With use of more detailed production and trade data and modification in half lives for solidwood and paper product in use (to meet calibration criteria), the estimates of C additions to product in use (under the production approach) varies differently from year to year. With calibration based on two criteria (See Annex 3.12 for more details), the use of revised curves to describe discards from products in use (first order decay) did not affect recent year estimates of annual additions to products in use, when compared to the curves previously used. Average annual total additions due to HWP from the period 1990 through 2004 (111 Tg CO_2 Eq.) is about 47 percent less than the previous estimate of 209 Tg CO_2 Eq. Virtually all of the decrease in annual additions is due to a decrease in estimates of annual additions to landfills and dumps. The estimate of total C in products in use in 2004 has increased from 1344 Tg to 1389 Tg. The estimate of total C in products in landfills and dumps in 2004 decreased from 1369 Tg to 952 Tg. There are several revisions that contributed to the decrease in annual additions to landfills and dumps. Changes have been greater for estimates of C additions to SWDS. Estimates of the fractions of discarded wood going to landfills and dumps were revised using data from EPA (2006b and prior years), Melosi (1981, 2000) and other sources. Estimates of the fraction of wood and paper not subject to decay in landfills were revised, based on Freed and Mintz (2003), using data from studies by Eleazer et al. (1997) and Barlaz (1998). The estimated fraction of C in wood subject to decay in landfills was revised from 3 percent to 23 percent, while the estimated fraction of C in paper subject to decay in landfills increased from 26 percent to 56 percent. Those fractions of wood and paper not subject to decay, therefore, decreased. Previous estimates of wood and paper subject to decay in landfills had been based on Micales and Skog (1997). Estimates of the rates of decay in landfills and dumps were also updated to 29 years and 14.5 years, respectively, using values from IPCC (2006). These half-lives are the midpoints of the estimated ranges of decay for wood and paper in temperate regions. The estimate of total C additions in SWDS over the period 1990 through 2004 decreased from 630 Tg to 256 Tg. Overall, the estimate of C additions under the production accounting approach over the period 1990 to 2004 has decreased from 857 Tg to 455 Tg, or 47 percent.

Another change in the current Inventory is the inclusion of estimates of C emissions caused by fire disturbance. Although these emissions are implicitly included in total forest C flux estimates, expert and public reviews of previous Inventories indicated an interest in the magnitude of this flux. An estimate of C emissions was, therefore, calculated and included in Box 7-1 in the current Inventory. C emissions caused by fire disturbance are still implicitly included as part of the overall forest C flux estimate, and, thus, not treated as a separate estimate in the current Inventory.

Non-CO_2 emissions from forest fires is a new source included in the current Inventory. CH_4 and N_2O emissions resulting from forest fires were not previously calculated, but these estimates are now included in their own subsection of *Forest Land Remaining Forest Land*.

Planned Improvements

The ongoing annual surveys by the FIA Program will improve precision of forest C estimates as new state surveys become available (Gillespie 1999). The annual surveys will eventually include all states. Therefore, inventory-based estimates of net annual flux for Alaska will become available, starting with the more productive forest in the southeastern portion of the state. Forest inventory data is limited in Alaska and, in the past, a net C change of zero was assumed. Alaska has over 50 million hectares of forest land, however, and could have a significant effect on estimates of total C emissions and sinks. A review of the scientific literature indicates Alaskan forests could change U.S. national forest C flux estimates by 5 to 10 percent (not including harvested wood). In addition, the more intensive sampling of down dead wood, litter, and soil organic C on some of the permanent FIA plots will substantially improve resolution of C pools at the plot level for all U.S. forest land.

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). 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. However, many forests in the Eastern United States are re-growing on abandoned agricultural land. During such regrowth, soil and forest floor C stocks often increase substantially over many years or even decades, especially on highly eroded agricultural land. In addition, with deforestation, soil C stocks often decrease over many years. A new methodology is being developed to account for these changes in soil C over time. This methodology includes estimates of area changes among land uses (especially forest and agriculture), estimates of the rate of soil C stock gain with afforestation, and estimates of the rate of soil C stock loss with deforestation over time. This topic is important because soil C stocks are large, and soil C flux estimates contribute substantially to total forest C flux.

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 into a nation-wide inventory, as well as the means for entity-level reporting.

An additional planned improvement is to develop a consistent representation of the U.S. managed land base. Currently, the forest C and the agricultural soil C inventories are the two major analyses addressing land-use and management impacts on C stocks. The forest inventory relies on the activity data from the FIA Program to estimate anthropogenic impacts on forest land, while the agricultural soil C inventory relies on the USDA National Resources Inventory (NRI). Recent research has revealed that the classification of forest land is not consistent between the FIA and NRI, leading to some double-counting and gaps in the current forest C and agricultural soil C inventories (e.g., some areas classified as forest land in the FIA are considered rangeland in the NRI). Consequently, the land bases are in the process of being compared between the inventories to determine where overlap or gaps occur, and then ensure that the inventories are revised to have a consistent and complete accounting of land-use and management impacts across all managed land in the United States.

Non-CO_2 Emissions From Forest Fires

Emissions of non-CO_2 gases from forest fires were estimated using the default IPCC (2003) methodology. Emissions from this source in 2005 were estimated to be 11.6 Tg CO_2 Eq. of CH_4 and 1.2 Tg CO_2 Eq. of N_2O, as shown in Table 7-10 and Table 7-11. The non-CO_2 estimates of forest fire emissions account for both the lower 48 states and Alaska, while the national inventory estimates of forest C stocks and fluxes currently include only the conterminous states.

Table 7-10: Estimated Non-CO_2 Emissions from Forest Fires (Tg CO_2 Eq.) for U.S. Forests[a]

Gas	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	7.1	4.0	14.0	6.0	10.4	8.1	6.9	11.6
N_2O	0.7	0.4	1.4	0.6	1.1	0.8	0.7	1.2
Total	**7.8**	**4.4**	**15.4**	**6.6**	**11.4**	**8.9**	**7.6**	**12.8**

[a] Calculated based on C emission estimates in *Changes in Forest Carbon Stocks* and default factors in IPCC (2003).

Table 7-11: Estimated Non-CO_2 Emissions from Forest Fires (Gg Gas) for U.S. Forests[a]

Gas	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	337	189	667	285	494	384	330	551
N_2O	2	1	5	2	3	3	2	4

[a] Calculated based on C emission estimates in *Changes in Forest Carbon Stocks* and default factors in IPCC (2003).

Methodology

The IPCC (2003) Tier 2 default methodology was used to calculate non-CO_2 emissions from forest fires. Estimates for CH_4 emissions were calculated by multiplying the total estimated C emitted (see Table 7-12) from forest burned by gas-specific emissions ratios and conversion factors. N_2O emissions were calculated in the same manner, but were also multiplied by a N-C ratio of 0.01 as recommended by IPCC (2003). The equations used were:

$$CH_4 \text{ Emissions} = (\text{C released}) \times (\text{emission ratio}) \times 16/12$$

$$N_2O \text{ Emissions} = (\text{C released}) \times (\text{N/C ratio}) \times (\text{emission ratio}) \times 44/28$$

Estimates for C emitted from forest fires, presented in Table 7-12 below, are the same estimates used to generate estimates of CO_2 emissions from forest fires, presented earlier in Box 7-1. See Table A-197 and explanation in Annex 3.12 for more details on the methodology used to estimate C emitted from forest fires.

Table 7-12: Estimated Carbon Released from Forest Fires for U.S. Forests

Year	C Emitted (Tg/yr)
1990	21.1
1995	11.8
2000	41.7
2001	17.8
2002	30.9
2003	24.0
2004	20.6
2005	34.5

Uncertainty

Non-CO_2 gases emitted from forest fires depend on several variables, including forest area and average C density for forest land in both Alaska and 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 the information provided above. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-13.

Table 7-13: 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	2005 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
Non-CO_2 Emissions from Forest Fires	CH_4	11.6	3.2	21.5	-71%	+92%
Non-CO_2 Emissions from Forest Fires	N_2O	1.2	0.3	2.2	-70%	+93%

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

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, although the rate of N fertilizer application for the area of forests that receives N fertilizer in any given year is relatively high, average annual applications, 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, is quite low. Nitrous oxide emissions from forest soils are estimated to have increased by a multiple of 5.5 from 1990 to 2005. The trend toward increasing N_2O emissions is a result of an increase in the area of N fertilized pine plantations in the southeastern United States. Total forest soil N_2O emissions are summarized in Table 7-14.

Table 7-14: N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	0.1	<1
1995	0.2	1
2000	0.3	1
2001	0.3	1
2002	0.3	1
2003	0.3	1
2004	0.3	1
2005	0.3	1

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 are in the southeastern United States. Consequently, it was assumed that southeastern pine plantations represent the vast majority of fertilized forests in the United States. Therefore, 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 (North Carolina State Forest Nutrition Cooperative 2002). 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 midpoint of the reported range of N fertilization rates (150 lbs. N per acre). Data for areas of forests receiving fertilizer outside the southeastern United States were not available, so N additions to non-southeastern forests are not included here. It should be expected, however, that emissions from the small areas of fertilized forests in other regions would be insubstantial because the majority of trees planted and harvested for timber are in the southeastern United States (USDA Forest Service 2001). Area data for pine plantations receiving fertilizer in the Southeast were not available for 2002, 2003, 2004, and 2005, so data from 2001 were used for these years. The 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 fractions, calculated according to the IPCC default factors of 10 percent and 30 percent, respectively, were included with all sources of indirect emissions in the Agricultural Soil Management source category of the Agriculture chapter.

Uncertainty

The amount of N_2O emitted from forests depends not only on N inputs, but also on a large number of variables, including organic C availability, O_2 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. The IPCC default methodology used here does not incorporate any of these variables and only accounts for variations 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 accounted for here. However, the total quantity of organic N inputs to soils

Table 7-15: Tier 2 Quantitative Uncertainty Estimates of N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	0.3	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*.

is accounted for in the Agricultural Soil Management and *Settlements Remaining Settlements* sections.

Uncertainties exist in the fertilizer application rates, the area of forested land receiving fertilizer, and the emission factors used to derive emission estimates.

To quantify the uncertainties for N_2O fluxes from forest soils, 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 7-15. 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 2005 emission estimate of 0.3 Tg CO_2 Eq.

Recalculations Discussion

The IPCC default emission factor of 1.25 percent for direct emissions from applied N was updated to 1 percent based on IPCC (2006). Additionally, because the direct emission factor was developed based on total N inputs, the new method has been revised to estimate direct N_2O emissions based on total N input. Previously, a portion of the N inputs were removed from the calculation of direct N_2O emissions, because it was assumed to be lost through volatilization before direct emissions occurred.

Planned Improvements

Area data for southeastern pine plantations receiving fertilizer will be updated with more recent datasets.

7.2. 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.

7.3. Cropland Remaining Cropland (IPCC Source Category 5B1)

Soils contain both organic and inorganic forms of C, but soil organic carbon (SOC) stocks are the main source or sink for atmospheric CO_2 in most soils. Changes in inorganic C stocks are typically minor. 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/UNEP/OECD/IEA (1997) recommends reporting changes in soil organic C stocks due to agricultural land-use and management activities on mineral soils and organic soils. In addition, the IPCC Guidelines recommend reporting CO_2 emissions that result from liming of soils with dolomite and limestone.

Typical well-drained mineral soils contain from 1 to 6 percent organic C by weight, although some mineral soils that are saturated with water for substantial periods during the year may contain significantly more C (NRCS 1999). When mineral soils undergo conversion from their native state to agricultural uses, as much as half the SOC can be 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). C losses are estimated from drained organic soils under both grassland and cropland management in this inventory.

The last category of the IPCC methodology addresses emissions from lime additions (in the form of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) to agricultural soils. Lime 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.

Cropland Remaining Cropland includes all areas designated as cropland that had been cropland since 1982 according to the USDA NRI land use survey (USDA-NRCS 2000). Consequently, the area of *Cropland Remaining Cropland* changes through time with land-use change. For this area, CO_2 emissions and removals[5] 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 2 or 3 approaches (i.e., change in C stocks after 1997 due to Conservation Reserve Program enrollment). Emissions from organic soils are estimated using a Tier 2 IPCC method. Emissions from liming are estimated using a Tier 2 IPCC method that relies on national aggregate statistics of lime application and emissions factors developed by West and McBride (2005).

Of the three 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 2005 (see Table 7-16 and Table 7-17). In 2005, mineral soils were estimated to remove about 71.1 Tg CO_2 Eq. (19.4 Tg C). This rate of C storage in mineral soils represented about an 18 percent increase in the rate since the initial reporting year of 1990. Emissions from organic soils had the second largest flux, emitting about 27.7 Tg CO_2 Eq. (7.5 Tg C) in 2005. Liming emitted another 4.0 Tg CO_2 Eq. (1.1 Tg C) in 2005. In total, U.S. agricultural soils in *Cropland Remaining Cropland* removed approximately 39.4 Tg CO_2 Eq. (10.7 Tg C) in 2005.

The net increase in soil C stocks over the period from 1990 through 2005 was largely due to an increase in annual cropland enrolled in the Conservation Reserve Program, intensification of crop production by limiting the use of bare-summer fallow in semi-arid regions, increased hay production, and adoption of conservation tillage (i.e., reduced- and no-till practices). At present (2005), cropland enrolled in the Conservation Reserve Program accounts

---

[5] Note that removals occur through crop and forage uptake of CO_2 into biomass C that is later incorporated into soils pools.

Table 7-16: Net Soil C Stock Changes and Liming Emissions in *Cropland Remaining Cropland* (Tg CO_2 Eq.)

Soil Type	1990	1995	2000	2001	2002	2003	2004	2005
Mineral Soils	(60.2)	(69.5)	(68.5)	(70.1)	(70.4)	(70.5)	(71.0)	(71.1)
Organic Soils	27.4	27.7	27.7	27.7	27.7	27.7	27.7	27.7
Liming of Soils[a]	4.7	4.4	4.3	4.4	5.0	4.6	3.9	4.0
Total Net Flux	**(28.1)**	**(37.4)**	**(36.5)**	**(38.0)**	**(37.8)**	**(38.3)**	**(39.4)**	**(39.4)**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

[a] Also includes emissions from liming on *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*.

Table 7-17: Net Soil C Stock Changes and Liming Emissions in *Cropland Remaining Cropland* (Tg C)

Soil Type	1990	1995	2000	2001	2002	2003	2004	2005
Mineral Soils	(16.4)	(18.9)	(18.7)	(19.1)	(19.2)	(19.2)	(19.4)	(19.4)
Organic Soils	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Liming of Soils[a]	1.3	1.2	1.2	1.2	1.4	1.2	1.1	1.1
Total Net Flux	**(7.7)**	**(10.2)**	**(10.0)**	**(10.4)**	**(10.3)**	**(10.4)**	**(10.7)**	**(10.7)**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

[a] Also includes emissions from liming in *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*.

for 32 percent of the increase of C stocks for *Cropland Remaining Cropland* on mineral soils (Table 7-17).

The spatial variability in annual CO_2 flux associated with C stock changes in mineral and organic soils is displayed in Figure 7-4 and Figure 7-5. The highest rates of sequestration in mineral soils occurred in the Midwest, where there were the largest amounts of cropland managed with conservation tillage adoption. Rates were also high in the Great Plains due to enrollment in the Conservation Reserve Program. Emission rates from drained organic soils were highest along the southeastern coastal region, in the northeast central United States surrounding the Great Lakes, and along the central and northern portions of the West Coast.

The estimates presented here are restricted to C stock changes in agricultural soils. Agricultural soils are also important sources of other greenhouse gases, particularly N_2O from application of fertilizers, manure, and crop residues and from cultivation of legumes, as well as CH_4 from flooded rice cultivation. These emissions are accounted for in the Agriculture chapter, along with non-CO_2 greenhouse gas emissions from field burning of crop residues and CH_4 and N_2O emissions from livestock digestion and manure management.

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; (2) agricultural land-use and management activities on organic soils; and (3) CO_2 emissions that result from liming of soils with dolomite and limestone for *Cropland Remaining Cropland*.

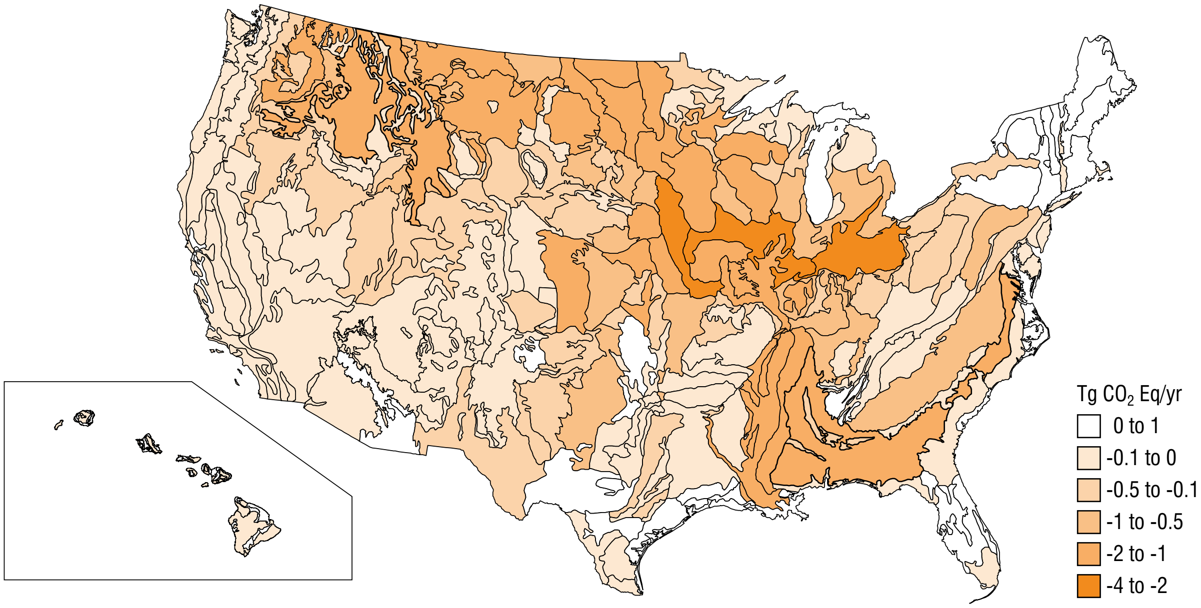
Soil C stock changes were estimated for *Cropland Remaining Cropland* (as well as agricultural land falling into the IPCC categories *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*) according to land use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2000). The NRI is a statistically-based sample of all non-federal land, and includes ca. 400,000 points in agricultural land of the conterminous United States and Hawaii.[6] 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 collected for each NRI point on a 5-year cycle beginning in 1982, and

---

[6] NRI points were classified as agricultural if under grassland or cropland management in 1992 and/or 1997.

Figure 7-4

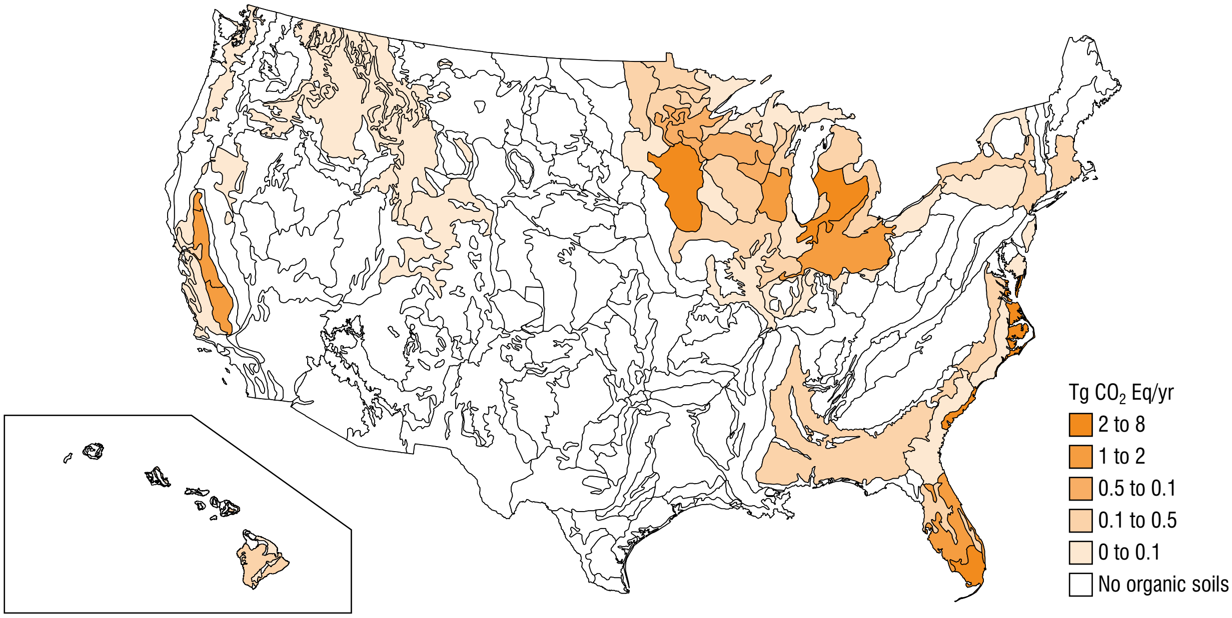
Net Soil C Stock Change for Mineral Soils in *Cropland Remaining Cropland*, 2005



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 Inventory computations. See Methodology for additional details.

Figure 7-5

Net Soil C Stock Change for Organic Soils in *Cropland Remaining Cropland*, 2005



Note: Values greater than zero represent emissions.

were subdivided into four inventory time periods, 1980–84, 1985–1989, 1990–94 and 1995–2000. Currently, the NRI is being revised to collect data annually from a subset of points. However, at present, no additional inventory point data are available for years after 1997.

NRI points were classified as *Cropland Remaining Cropland* for an inventory time period (e.g., 1990-1994 and 1995-2000) if the land use had been cropland since the first year of the NRI survey in 1982 through the end of the respective time period. Cropland includes all land used to produce food or fiber, as well as 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 used to estimate C stock changes for mineral soils used to produce a majority of annual crops in the United States (i.e., all crops except vegetables, tobacco, perennial/horticultural crops, and rice, in addition to lands with very gravelly, cobbly or shaley soils (greater than 35 percent by volume)). An IPCC Tier 2 method (see Ogle et al. 2003) was used to estimate C stock changes for cropland on mineral soils that were not addressed with the Tier 3 method: 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. Mineral SOC stocks were estimated using a Tier 2 method for these areas, because the Century model 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. These calculations accounted for enrollment patterns in the Conservation Reserve Program after 1997, which was not addressed by the Tier 3 methods.

Further elaboration on the methodology and data used to estimate stock changes from mineral are described below and in Annex 3.13.

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the Century biogeochemical model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), which simulates the dynamics of C and other elements in cropland, grassland, forest, and savanna ecosystems. It uses monthly weather data as input, along with information about soil physical properties. Input data on land use and management can be specified at monthly 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, 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 7-2 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. Land-use and management activities were grouped into inventory time periods (i.e., time "blocks") for 1980–84, 1985–89, 1990–94 and 1995–2000, using NRI data from 1982, 1987, 1992, and 1997, respectively.

Additional sources of activity data were used to supplement the land-use information from NRI. The Conservation Technology Information Center (CTIC 1998) 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 (ERS 1997) 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 adjusted based on county-level manure production rates for other years in the Inventory. Specifically, county-scale ratios of manure production in other years relative to 1997 were used to estimate the area amended in the other years, essentially scaling the amendment data compiled by USDA in 1997 across the time series (see Annex 3.13 for further details). Higher managed manure N production relative to 1997 was, thus, assumed to increase the amount of area amended with manure, while less managed manure N production relative to 1997 was assumed to reduce the amended area. The amount of managed manure produced

Box 7-2: Tier 3 Inventory for Soil C Stocks compared to Tier 1 or 2 Approaches

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 states 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). 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 Century model, soil C dynamics (and CO_2 emissions and uptake) are treated as continuous variables, which change on a monthly time step. C 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 as an equilibrium step change used in the IPCC methodology (Tier 1 and 2), the Tier 3 model addresses the delayed response of the soil to management and land-use changes, which 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 soil C stocks change only with discrete changes in management and/or land use, rather than a longer term trend such as gradual increases in crop productivity.

by each livestock type was calculated by determining the population of animals that were on feedlots or otherwise housed (requiring manure to be collected and managed). Annual animal population data for all livestock types, except horses and goats, were obtained for all years from the U.S. Department of Agriculture-National Agricultural Statistics Service (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000, 2004a-e, 2005a-e, 2006a-e). Horse population data were obtained from the FAOSTAT database (FAO 2006). Goat population data for 1992, 1997, and 2002 were obtained from the *Census of Agriculture* (USDA 2005f); these data were interpolated and extrapolated to derive estimates for the other years. Information regarding poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service personnel (Lange 2000). Additional population data for different farm size categories for dairy and swine were obtained from the 1992 and 1997 *Census of Agriculture* (USDA 2005g).

Monthly weather data, aggregated to county-scale from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) database (Daly et al. 1994), were used as an input in the model simulations. Soil attributes were obtained from an NRI database, which were assigned based on field visits and soil series descriptions. Where more than one inventory point was located in the same county (i.e., same weather) and having the same land-use/management histories and soil type, data inputs to the model were identical and, therefore, these points were clustered for simulation purposes. For the 370,738 NRI points representing non-federal cropland and grassland, there were a total of 170,279 clustered points that represent the unique combinations of climate, soils, land use, and management in the modeled data set. Each NRI cluster point was run 100 times as part of the uncertainty assessment, yielding a total of over 14 million simulation runs for the analysis. C stock estimates from Century were adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Ogle et al. 2007). Mean changes in C stocks and 95 percent confidence intervals were estimated for 1990 to 1994 and 1995 to 2000 (see Uncertainty section for more details). C stock changes from 2001 to 2005 were assumed to be similar to the 1995 to 2000 block, because no additional activity data are currently available from the NRI for the latter years.

Tier 2 Approach

In the 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).[7] 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/UNEP/OECD/IEA (1997) and IPCC (2003). 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).[8] U.S. factors associated with organic matter amendments were not estimated because of 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.

Similar to the Tier 3 Century method, 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 Tillage Information Center (CTIC 1998, 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, and 1997, using a Monte Carlo 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). 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 2005 was determined by calculating the average annual change in stocks between 1992 and 1997.

Additional Mineral C Stock Change

Annual C flux estimates for mineral soils between 1990 and 2005 were adjusted to account for additional C stock changes associated with gains or losses in soil C after 1997 due to changes in Conservation Reserve Program enrollment. The change in enrollment acreage relative to 1997 was based on data from FSA (2006) for 1998 through 2005, 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/UNEP/OECD/IEA (1997) and IPCC (2003), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. Similar to the Tier 2 analysis for mineral soils, the final estimates included a measure of uncertainty as determined from the Monte Carlo simulation with 50,000 iterations. Emissions were based on the 1992 and 1997 *Cropland Remaining Cropland* areas from the *1997 National Resources Inventory* (USDA-NRCS

---

[7] The polygons displayed in Figure 7-7 through Figure 7-10 are the Major Land Resource Areas.

[8] Stock change factors have been derived from published literature to reflect changes in tillage, cropping rotations and intensification, land-use change between cultivated and uncultivated conditions, and drainage of organic soils.

2000). The annual flux estimated for 1992 was applied to 1990 through 1992, and the annual flux estimated for 1997 was applied to 1993 through 2005.

CO_2 Emissions from Agricultural Liming

Carbon dioxide emissions from degradation of limestone and dolomite applied to agricultural soils were estimated using a Tier 2 methodology. The annual amounts of limestone and dolomite applied (see Table 7-18) 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). 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, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006; USGS 2006). 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 2005 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 2005 data, the previous year's fractions were applied to a 2005 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2006* (USGS 2006).

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) 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.

Uncertainty

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) and soil liming emissions. Uncertainty estimates are presented in Table 7-19 for each subsource (i.e., mineral soil C stocks, organic soil C stocks, soil liming) disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). A combined uncertainty estimate for changes in soil C stocks occurring within *Cropland Remaining Cropland* is also included. Uncertainty estimates from each component

Table 7-18: Applied Minerals (Million Metric Tons)

Mineral	1990	1995	2000	2001	2002	2003	2004	2005
Limestone	19.01	17.30	15.86	16.10	20.45	18.71	15.50	16.10
Dolomite	2.36	2.77	3.81	3.95	2.35	2.25	2.33	2.42

Note: These numbers represent amounts applied to all agricultural land, not just *Cropland Remaining Cropland*.

Table 7-19: Quantitative Uncertainty Estimates for C Stock Changes occurring within *Cropland Remaining Cropland* (Tg CO_2 Eq. and Percent)

Source	2005 Stock Change Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Stock Change Estimate (Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: *Cropland Remaining Cropland*, Tier 3 Inventory Methodology	(66.4)	(77.0)	(55.9)	-16%	+16%
Mineral Soil C Stocks: *Cropland Remaining Cropland*, Tier 2 Inventory Methodology	(3.0)	(6.9)	0.8	-127%	+128%
Mineral Soil C Stocks: *Cropland Remaining Cropland* (Change in CRP enrollment relative to 1997)	(1.6)	(2.5)	(0.8)	-50%	+50%
Organic Soil C Stocks: *Cropland Remaining Cropland*, Tier 2 Inventory Methodology	27.7	15.8	36.9	-43%	+33%
CO_2 Emissions from Liming	4.0	0.2	8.0	-96%	+98%
Combined Uncertainty for Agricultural Soil C Stocks in *Cropland Remaining Cropland*	**(39.4)**	**(56.2)**	**(24.3)**	**-43%**	**+38%**

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 appear later in this section. The combined uncertainty for soil C stocks in *Cropland Remaining Cropland* ranged from 43 percent below and 38 percent above the 2005 stock change estimate of -39.4 Tg CO_2 Eq.

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. Errors were found in these steps and corrective actions were taken. One of the errors involved a subset of the transitions from full tillage to reduced till between the late 1980s and early 1990s. The reduced tillage transition was not occurring and the script was revised to correct the transition. The second error involved improved estimation of root production in irrigated systems. Root production had been parameterized based on rainfed crops, and so the parameters were adjusted to better approximate C allocation to belowground growth in irrigated lands. In addition, QA/QC activities uncovered that the empirically-based structural uncertainty estimator for the Century model did not address the random variation associated with predicting soil C stock changes at the site level in the previous Inventory, which is equivalent to NRI points. This uncertainty is not insignificant, and, thus, previous uncertainty estimates were unrealistically low because the random variation was not addressed. Adjustments were made in the current Inventory, and the results better reflect the uncertainty in the Tier 3 approach as implemented in the United States.

As discussed in the uncertainty sections, 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.

Recalculations Discussion

Several adjustments were made in the current Inventory to improve the results. First, consistency was achieved in the N inputs data between the agricultural soil C and soil N_2O source categories (see Agricultural Soil Management section of the Agriculture chapter). Although this improvement required several changes to soil N_2O inventory methods, the only change to the soil C source was the scaling of manure amendment data in 1997 based on variation in managed manure N production during other years of the Inventory. Second, scheduling files, (used in the model program to determine when activities such as fertilization, tillage, planting, and harvesting occur) were adjusted in the Tier 3 approach, so that transitions from full tillage to reduced till were properly modeled, and allocation of C to roots was reduced for irrigated systems due to excessively high root biomass discovered through QA/QC checks.

Third, uncertainty was estimated in the current Inventory for the random variation associated with Century model estimates at the site scale. This is a significant uncertainty in the assessment framework, which was not addressed in the previous Inventory. Fourth, annual C emissions from organic cropland soils are subdivided between *Cropland Remaining Cropland* and *Land Converted to Cropland*. In the previous Inventory, all C emissions associated with drainage of organic soils for crop production were reported in the *Cropland Remaining Cropland* category.

The quantity of applied minerals reported in the previous Inventory for 2004 has been revised. Consequently, the reported emissions resulting from liming in 2004 have also changed. In the previous Inventory, to estimate 2004 data, the previous year's fractions were applied to a 2004 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2005* (USGS 2005). 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 2004. These values have replaced those used in the previous Inventory to calculate the quantity of minerals applied to soil and the emissions from liming. Additionally, a correction was made to liming activity data from 2003 that was inaccurately transcribed from the original source.

Overall, the recalculations resulted in an average annual increase in sinks of 5.3 Tg CO_2 Eq. (21 percent) for soil C stock changes in *Cropland Remaining Cropland* for the period 1990 through 2004.

Planned Improvements

Several improvements are planned for the agricultural soil C inventory. The first improvement is to incorporate new land-use and management activity data from the NRI. In the current Inventory, NRI data only provide land-use and management statistics through 1997, but it is anticipated that new statistics will be released in the coming year for 2000 through 2003. The new data will greatly improve the accuracy of land-use and management influences on soil C in the latter part of the time series.

The second improvement is to develop a consistent representation of the U.S. managed land base. More details on this planned improvement are provided in the *Forest Land Remaining Forest Land* section.

The third improvement is to incorporate additional crops into the Tier 3 approach. Currently, crops such as vegetables, rice, and perennial and horticultural crops have not been fully implemented in the Century model application. However, efforts are currently underway to further develop the model application for simulating soil C dynamics in land managed for production of these crops.

The fourth improvement is to incorporate remote sensing in the analysis for estimation of crop and forage production. Specifically, the Enhanced Vegetation Index (EVI) product that is derived from MODIS satellite imagery is being used to refine the production estimation for the Tier 3 assessment framework. EVI reflects changes in plant "greenness" over the growing season and can be used to compute production based on the light use efficiency of the crop or forage (Potter et al. 1993). In the current framework, production is simulated based on the weather data, soil characteristics, and the genetic potential of the crop. While this method produces reasonable results, remote sensing can be used to refine the productivity estimates and reduce biases in crop production and subsequent C input to soil systems. It is anticipated that precision in the Tier 3 assessment framework will be increased by 25 percent or more with the new method.

The fifth improvement is to develop an automated quality control system to evaluate the results from Century model simulations. Currently, there are over 14 million simulations, and it is not possible to manually review each single simulation. Results are aggregated and evaluated at larger scales such as Major Land Resource Areas and States. QA/QC at these larger scales may not uncover errors at the scale of individual NRI points, which is the scale at which the Century model is used to simulate soil C dynamics. An automated system would greatly improve QA/QC, performing checks on the results from each simulation and identifying errors for further refinements.

The last improvement is to further develop the uncertainty analysis for the Tier 3 method by addressing the uncertainty inherent in the Century model results for other agricultural land (i.e., *Grassland Remaining Grassland, Land Converted to Grassland*, and *Land Converted to Cropland*). In addition, uncertainties need to be addressed in the simulation of soil C stocks for the pre-NRI time period (i.e., before 1979). In the current analysis, inventory development focused on uncertainties in the last two decades because the management activity during the most recent time periods will likely have the largest impact on current trends in soil C storage. However, legacy effects of past management can also have a significant effect on current C stock trends, as well as trajectories of those C stocks in the near future. Therefore, a planned improvement is to revise the Inventory to address uncertainties in management activity prior to 1979.

7.4. Land Converted to Cropland (IPCC Source Category 5B2)

Land Converted to Cropland includes all areas designated as cropland that had been another land use in a prior time period according to the USDA NRI land use survey (USDA-NRCS 2000). Consequently, the area considered in *Land Converted to Cropland* changes through time with land-use change. Lands are retained in this category for 20 years as recommended by the IPCC guidelines (IPCC 2006) unless there is another land-use change. 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/UNEP/OECD/IEA (1997) and the IPCC (2003) recommend reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, (2) agricultural land-use and management activities on organic soils, and (3) CO_2 emissions that result from liming of soils with dolomite and limestone. Mineral soil C stock changes and C emissions from drained and cultivated organic soils are reported for *Land Converted to Cropland*. It was not possible, however, to subdivide the liming application estimates by land use/land-use change categories (see Methodology section below for additional discussion).

Land-use and management of mineral soils in *Land Converted to Cropland* led to losses of soil C during the early 1990s but losses declined slightly through the latter part of the time series (Table 7-20 and Table 7-21). The rate of change in soil C stocks was 7.2 Tg CO_2 Eq. (2.0 Tg C) in 2005. Emissions from mineral soils were estimated at 4.6 Tg CO_2 Eq. (1.2 Tg C) in 2005, while drainage and cultivation of organic soils led to annual losses of 2.6 Tg CO_2 Eq. (0.7 Tg C) in 2005.

The spatial variability in annual CO_2 flux associated with C stock changes in mineral and organic soils for *Land Converted to Cropland* is displayed in Figure 7-6 and Figure 7-7. While a large portion of the United States had net losses in soil C for *Land Converted to Cropland*, there were some notable areas with sequestration in the Intermountain

Table 7-20: Net Soil C Stock Changes in *Land Converted to Cropland* (Tg CO_2 Eq.)

Soil Type	1990	1995	2000	2001	2002	2003	2004	2005
Mineral Soils	6.2	4.6	4.6	4.6	4.6	4.6	4.6	4.6
Organic Soils	2.4	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Liming of Soils[a]	-	-	-	-	-	-	-	-
Total Net Flux	**8.7**	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**

[a] Emissions from liming in *Land Converted to Cropland* are reported in *Cropland Remaining Cropland.*
Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

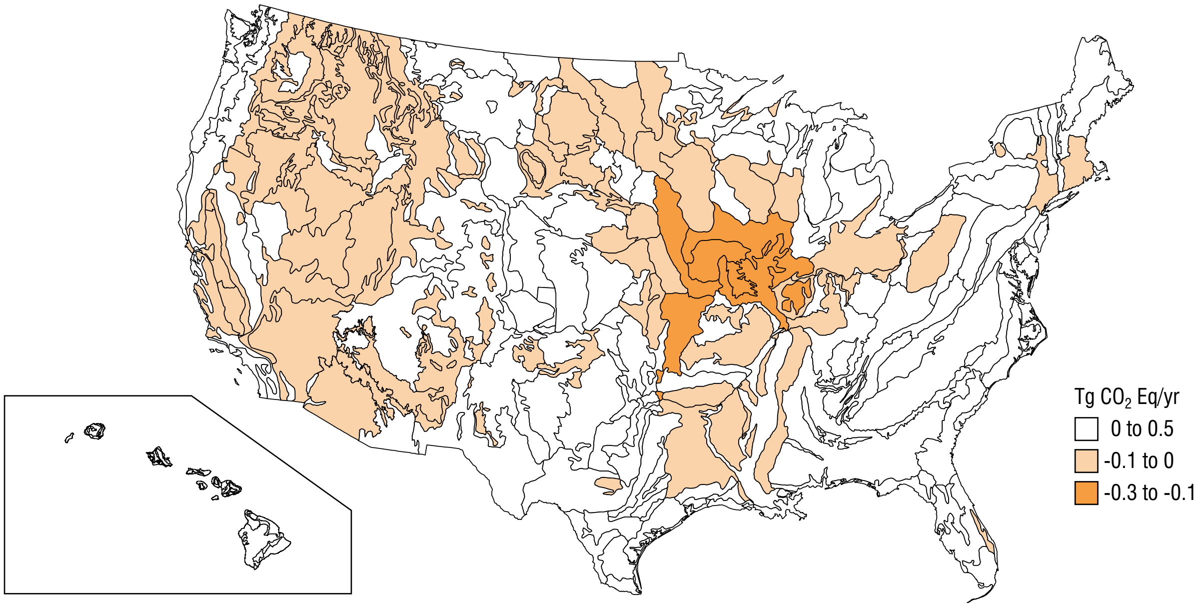
Table 7-21: Net Soil C Stock Changes in *Land Converted to Cropland* (Tg C)

Soil Type	1990	1995	2000	2001	2002	2003	2004	2005
Mineral Soils	1.7	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Organic Soils	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Liming of Soils[a]	-	-	-	-	-	-	-	-
Total Net Flux	**2.4**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**

[a] Emissions from liming in *Land Converted to Cropland* are reported in *Cropland Remaining Cropland.*
Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Figure 7-6

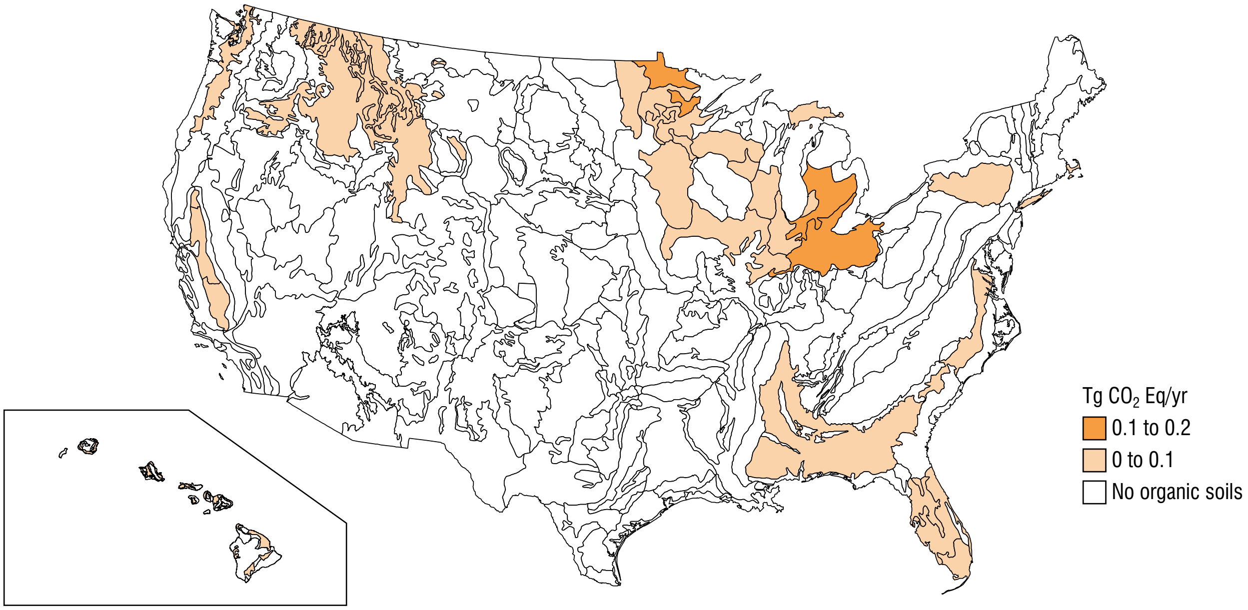
Net Soil C Stock Change for Mineral Soils in *Land Converted to Cropland*, 2005



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 Inventory computations. See Methodology for additional details.

Figure 7-7

Net Soil C Stock Change for Organic Soils in *Land Converted to Cropland*, 2005



Note: Values greater than zero represent emissions.

West and central United States. These areas were gaining C following conversion, because croplands were irrigated or receiving higher fertilizer inputs relative to the previous land use. Emissions from organic soils were largest in California, Florida and the upper Midwest, which coincided with largest concentrations of cultivated organic soils in the United States.

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*.

Soil C stock changes were estimated for *Land Converted to Cropland* according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2000).[9] Land use and some management information (e.g., crop type, soil attributes, and irrigation) were collected for each NRI point on a 5-year cycle beginning in 1982, and were subdivided into four inventory time periods, 1980–84, 1985–1989, 1990–94 and 1995–2000. NRI points were classified as *Land Converted to Cropland* for an inventory time period (e.g., 1990–1994 and 1995–2000) if the land use was cropland at the end of the respective inventory time period but had been another use in a prior inventory time period. Cropland includes all land used to produce food or fiber, as well as forage that is harvested and used as feed (e.g., hay and silage). 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.

Mineral Soil Carbon Stock Changes

A Tier 3 model-based approach was used to estimate C stock changes for soils on *Land Converted to Cropland* used to produce a majority of all crops. Exceptions, which relied on an IPCC Tier 2 method to estimate C stock changes, included: 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 (Ogle et al. 2003).[10]

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the Century biogeochemical model for the Tier 3 methods. 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 2000). 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 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/UNEP/OECD/IEA (1997) and IPCC (2003), which utilizes 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 simulation with 50,000 iterations. Emissions were based on the 1992 and 1997 *Land Converted to Cropland* areas from the *1997 National Resources Inventory* (USDA-NRCS 2000). The annual flux estimated for 1992 was applied to 1990 through 1992, and the annual flux estimated for 1997 was applied to 1993 through 2005.

CO_2 Emissions from Agricultural Liming

Carbon dioxide emissions from degradation of limestone and dolomite applied to *Land Converted to Cropland* are reported in *Cropland Remaining Cropland*, because it was not possible to disaggregate liming application among land use and land-use change categories.

---

[9] NRI points were classified as agricultural if under grassland or cropland management in 1992 and/or 1997.

[10] 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 2000).

Uncertainty

Uncertainty associated with the *Land Converted to Cropland* land-use change category includes the uncertainty associated with changes in mineral and organic soil C stocks. Uncertainty estimates are presented in Table 7-22 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). A combined uncertainty estimate for changes in agricultural soil C stocks occurring within *Land Converted to Cropland* 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 appear later in this section. The combined uncertainty for soil C stocks in *Land Converted to Cropland* was estimated to be 33 percent below and 29 percent above the inventory estimate of 7.2 Tg CO_2 Eq.

Uncertainties in Mineral Soil Carbon Stock Changes

The uncertainty analysis for *Land Converted to Cropland* using the Tier 3 and 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.

Uncertainties in Organic Soil Carbon Stock Changes

Annual C emission estimates from drained organic soils in *Land Converted to Cropland* were estimated using the Tier 2 Approach, as described in the *Cropland Remaining Cropland* section.

QA/QC and Verification

See QA/QC and Verification Section under *Cropland Remaining Cropland*.

Recalculations Discussion

The specific changes in reporting in the current Inventory for *Land Converted to Cropland* are the same as those described in the *Cropland Remaining Cropland* section, except that the uncertainty is not addressed for the random variation associated with Century model estimates at the site scale. The structural uncertainty requires further development before it can be used to address uncertainty inherent in the structure of the Century model for *Land Converted to Cropland*. A further change affecting this section is that organic soil emissions for the *Cropland Remaining Cropland* and *Land Converted to Cropland* sections were previously reported together in the *Cropland Remaining Cropland* section. For the current Inventory, they have been reapportioned between the land use categories and, therefore, a portion of the emissions are now reported in the *Land Converted to Cropland* section. Overall, these recalculations resulted in an average annual increase in emissions of 9.1 Tg CO_2 Eq. (71.4 percent) for soil C stock changes in *Land Converted to Cropland* over the time series from 1990 through 2004. The changes also resulted in a shift from the previous Inventory's reporting of this category as an overall sink to the current reporting as an overall source.

Table 7-22: Quantitative Uncertainty Estimates for C Stock Changes occurring within *Land Converted to Cropland* (Tg CO_2 Eq. and Percent)

Source	2005 Stock Change Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Stock Change 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	0.4	(0.1)	0.9	-124%	+124%
Mineral Soil C Stocks: *Land Converted to Cropland*, Tier 2 Inventory Methodology	4.1	2.3	5.8	-44%	+41%
Organic Soil C Stocks: *Land Converted to Cropland*, Tier 2 Inventory Methodology	2.6	1.2	3.7	-53%	+41%
Combined Uncertainty for Agricultural Soil Carbon Stocks in *Land Converted to Cropland*	**7.2**	**4.9**	**9.3**	**-33%**	**+29%**

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 Century model for *Land Converted to Cropland*, but this is a planned improvement. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.5. Grassland Remaining Grassland (IPCC Source Category 5C1)

Grassland Remaining Grassland includes all areas of grassland that had been designated as grassland since 1982 according to the USDA NRI land use survey (USDA-NRCS 2000). Consequently, the area considered in *Grassland Remaining Grassland* changes through time with land-use change. 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/UNEP/OECD/IEA (1997) and IPCC (2003) recommend reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, (2) agricultural land-use and management activities on organic soils, and (3) CO_2 emissions that result from liming of soils with dolomite and limestone. Mineral and organic soil C stock changes are reported here for *Grassland Remaining Grassland*, but stock changes associated with liming are reported in *Cropland Remaining Cropland*, because it was not possible to subdivide those estimates by land use/land-use change categories (see Methodology section below for additional discussion).

Land-use and management of mineral soils in *Grassland Remaining Grassland* increased soil C during the early 1990s, but this trend was reversed over the decade, with small losses of C prevailing during the latter part of the time series (see Table 7-23 and Table 7-24). Organic soils lost about the same amount of C in each year of the Inventory. The overall trend shifted from small decreases in soil C during 1990 to larger decreases during the latter years, estimated at 16.1 Tg CO_2 Eq. (4.4 Tg C) in 2005.

The spatial variability in annual CO_2 flux associated with C stock changes in mineral and organic soils is displayed in Figure 7-8 and Figure 7-9. Grassland is losing soil organic C in the United States largely due to droughts that are causing small losses of C on a per hectare basis, but are occurring over a large land base. In areas with net gains in

Table 7-23: Net Soil C Stock Changes in *Grassland Remaining Grassland* (Tg CO_2 Eq.)

Soil Type	1990	1995	2000	2001	2002	2003	2004	2005
Mineral Soils	(3.7)	12.7	12.6	12.6	12.5	12.5	12.5	12.4
Organic Soils	3.9	3.7	3.7	3.7	3.7	3.7	3.7	3.7
Liming of Soils[a]	-	-	-	-	-	-	-	-
Total Net Flux	**0.1**	**16.4**	**16.3**	**16.2**	**16.2**	**16.2**	**16.1**	**16.1**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

[a] Emissions from liming in *Grassland Remaining Grassland* are reported in *Cropland Remaining Cropland*.

Table 7-24: Net Soil C Stock Changes in *Grassland Remaining Grassland* (Tg C)

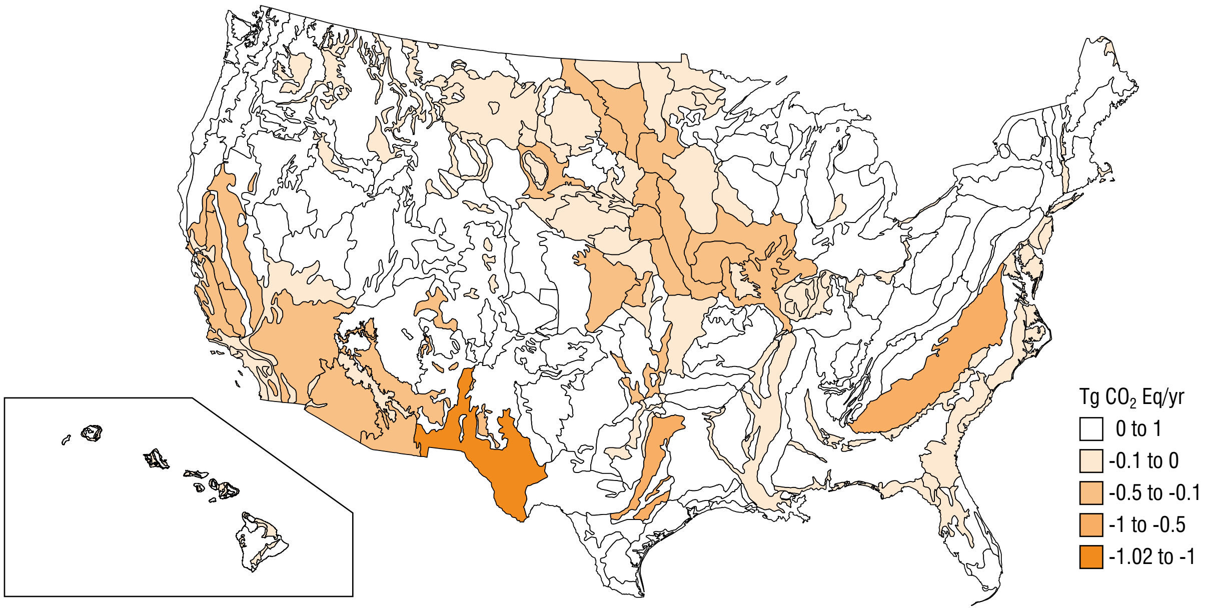
Soil Type	1990	1995	2000	2001	2002	2003	2004	2005
Mineral Soils	(1.0)	3.5	3.4	3.4	3.4	3.4	3.4	3.4
Organic Soils	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Liming of Soils[a]	-	-	-	-	-	-	-	-
Total Net Flux	**0**	**4.5**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

[a] Emissions from liming in *Grassland Remaining Grassland* are reported in *Cropland Remaining Cropland*.

Figure 7-8

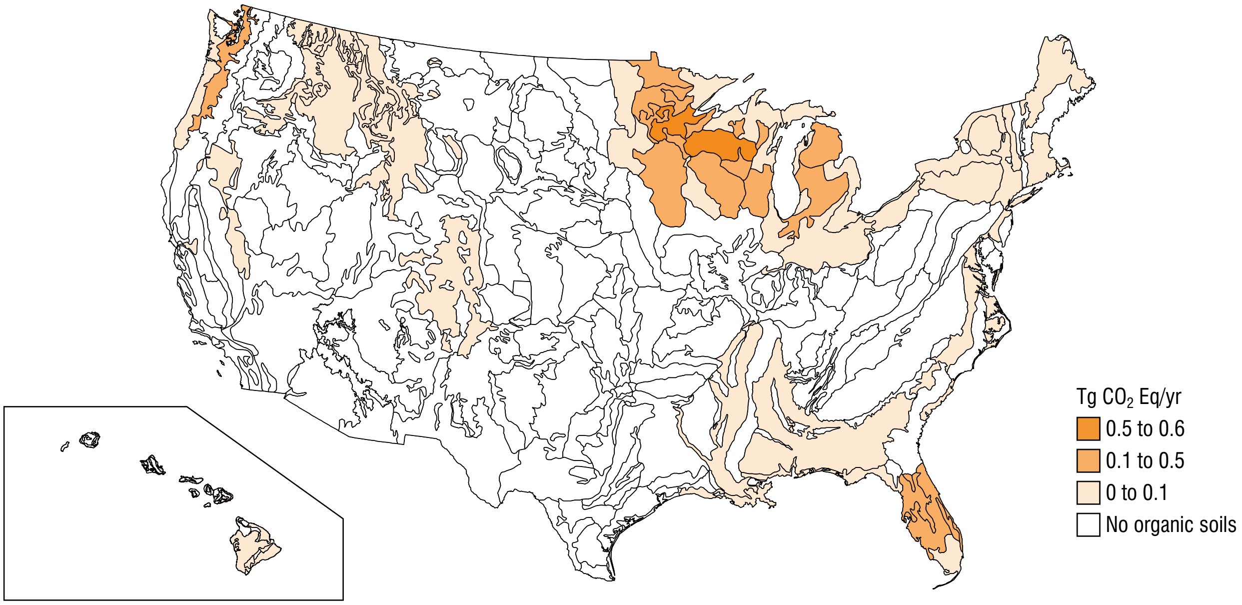
Net Soil C Stock Change for Mineral Soils in *Grassland Remaining Grassland*, 2005



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 Inventory computations. See Methodology for additional details.

Figure 7-9

Net Soil C Stock Change for Organic Soils in *Grassland Remaining Grassland*, 2005



Note: Values greater than zero represent emissions.

soil organic C, sequestration was driven by irrigation and seeding legumes. Similar to *Cropland Remaining Cropland*, emission rates from drained organic soils were highest along the southeastern coastal region, in the northeast central United States surrounding the Great Lakes, and along the central and northern portions of the West Coast.

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*.

Soil C stock changes were estimated for *Grassland Remaining Grassland* according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2000).[11] Land use and some management information (e.g., irrigation, legume pastures) were collected for each NRI point on a 5-year cycle beginning in 1982, 1980–84, 1985–1989, 1990–94 and 1995-2000. NRI points were classified as *Grassland Remaining Grassland* for an inventory time period (e.g., 1990–1994 and 1995–2000) if the land use had been grassland since the first year of the NRI survey in 1982 through the end of the respective time period. 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. 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.

Mineral Soil Carbon Stock Changes

A Tier 3 model-based approach was used to estimate C stock changes for mineral soils in *Grassland Remaining Grassland*, except for lands with very gravelly, cobbly or shaley soils (greater than 35 percent by volume). An IPCC Tier 2 method was used to estimate stock changes for the gravelly, cobbly or shaley soils and additional changes in C stocks in mineral soils. A Tier 2 method was also used to estimate 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 Century biogeochemical model, as described in *Cropland Remaining Cropland*. Historical land-use and management patterns were used in the Century 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 (ERS 1997) 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 manure production rates for other years in the Inventory. Specifically, county-scale ratios of manure production in other years relative to 1997 were used to adjust the area amended with manure for other years in the Inventory (see Annex 3.13 for further details). Higher managed manure N production relative to 1997 was, thus, assumed to increase the amount of area amended with manure, while less managed manure N production relative to 1997 was assumed to reduce the amended area. The amount of managed manure produced by each livestock type was calculated by determining the population of animals that were on feedlots or otherwise housed (requiring manure to be collected and managed). Annual animal population data for all livestock types, except horses and goats, were obtained for all years from the U.S. Department of Agriculture-National Agricultural Statistics Service (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000, 2004a-e, 2005a-d, 2006a-e). Horse population data were obtained from the FAOSTAT database (FAO 2006). Goat population data for 1992, 1997, and 2002 were obtained from the *Census of Agriculture* (USDA 2005g); these data were interpolated and extrapolated to derive estimates for the other years. Information regarding poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service personnel (Lange 2000). Additional population data for different farm size categories for dairy and swine were obtained from the 1992 and 1997 *Census of Agriculture* (USDA 2005g). Pasture/Range/Paddock (PRP) manure N deposition was estimated internally in the Century model, as part of the grassland system simulations (i.e., PRP manure deposition was not

---

[11] NRI points were classified as agricultural if under grassland or cropland management in 1992 and/or 1997.

an external input into the model). 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 for additional information).

Additional Mineral C Stock Change Calculations

Annual C flux estimates for mineral soils between 1990 and 2005 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 nitrogen content. Total sewage sludge generation data for 1988, 1996, and 1998, and a projection for 2000, in dry mass units, were obtained from EPA reports (EPA 1993, 1999), and 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/UNEP/OECD/IEA (1997) and IPCC (2003), which utilizes 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 simulation with 50,000 iterations. Emissions were based on the 1992 and 1997 *Grassland Remaining Grassland* areas from the *1997 National Resources Inventory* (USDA-NRCS 2000). The annual flux estimated for 1992 was applied to 1990 through 1992, and the annual flux estimated for 1997 was applied to 1993 through 2005.

CO_2 Emissions from Agricultural Liming

Carbon dioxide emissions from degradation of limestone and dolomite applied to *Grassland Remaining Grassland* are reported in *Cropland Remaining Cropland*, because it was not possible to disaggregate liming application among land use/land-use change categories.

Uncertainty

Uncertainty associated with the *Grassland Remaining Grassland* category includes the uncertainty associated with changes in mineral and organic soil C stocks. Uncertainty

Table 7-25: Quantitative Uncertainty Estimates for C Stock Changes occurring within *Grassland Remaining Grassland* (Tg CO_2 Eq. and Percent)

Source	2005 Stock Change Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Stock Change Estimate (Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: *Grassland Remaining Grassland*, Tier 3 Inventory Methodology	13.9	12.4	15.3	-10%	+10%
Mineral Soil C Stocks: *Grassland Remaining Grassland*, Tier 2 Inventory Methodology	(0.2)	(0.3)	0.04	-89%	+127%
Mineral Soil C Stocks: *Grassland Remaining Grassland* (Change in Soil C due to Sewage Sludge Amendments)	(1.3)	(1.9)	(0.6)	-50%	+50%
Organic Soil C Stocks: *Grassland Remaining Grassland*, Tier 2 Inventory Methodology	3.7	1.2	5.5	-66%	+49%
Combined Uncertainty for Agricultural Soil Carbon Stocks in *Grassland Remaining Grassland*	**16.1**	**13.2**	**18.5**	**-18%**	**+15%**

estimates are presented in Table 7-25 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). A combined uncertainty estimate for changes in agricultural soil C stocks occurring within *Grassland Remaining Grassland* 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 appear later in this section. The combined uncertainty for soil C stocks in *Grassland Remaining Grassland* was estimated to be 18 percent below and 15 percent above the inventory estimate of 16.1 Tg CO_2 Eq.

Uncertainties in Mineral Soil Carbon Stock Changes

Tier 3 Approach

The uncertainty analysis for *Grassland Remaining Grassland* using the Tier 3 approach and Tier 2 approach 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. See the Tier 3 approach for mineral soils under the *Cropland Remaining Cropland* section for additional discussion.

Additional Mineral Carbon Stock Change Calculations

A ±50 percent uncertainty was assumed for additional adjustments to the soil C stocks between 1990 and 2005 to account for additional C stock changes associated with amending grassland soils with sewage sludge.

Uncertainties in Organic Soil Carbon Stock Changes

Uncertainty in C emissions from organic soils was estimated using country-specific factors and a Monte Carlo analysis. PDFs for emission factors were derived from a synthesis of 10 studies, and combined with uncertainties in the NRI land use and management data for organic soils in the Monte Carlo analysis. See the Tier 2 section under minerals soils of *Cropland Remaining Cropland* for additional discussion.

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. An error was found in these steps and a corrective action was taken. Specifically, the error involved improved estimation of root production in irrigated systems. Root production had been parameterized based on rainfed forages; the parameters were adjusted to approximate C allocation to belowground growth in irrigated lands.

Recalculations Discussion

The specific changes in reporting in the current Inventory for *Grassland Remaining Grassland* are the same as those described in the *Cropland Remaining Cropland* section, except that the uncertainty is not addressed in the current Inventory for the random variation associated with Century model estimates at the site scale. The structural uncertainty requires further development before it can be used to address uncertainty inherent in the structure of the Century model for *Grassland Remaining Grassland*. Overall, the recalculations resulted in an average annual increase in emissions of 7.4 Tg CO_2 Eq. (46.2 percent) for soil C stock changes in *Grassland Remaining Grassland* over the period from 1990 through 2004.

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 in Century model results for *Grassland Remaining Grassland*, but this is a planned improvement for the Inventory. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.6. Land Converted to Grassland (IPCC Source Category 5C2)

Land Converted to Grassland includes all areas designated as grassland that had been in another land use in a prior time period according to the USDA NRI land use survey (USDA-NRCS 2000). Consequently, the area of *Land Converted to Grassland* changes through time with land-use change. Lands are retained in this category for 20 years as recommended by the IPCC guidelines (IPCC 2006) unless there is another land use change. 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/UNEP/OECD/IEA (1997) recommends reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, (2) agricultural land-use and management activities on organic soils, and (3) CO_2 emissions that result from liming of soils with dolomite and limestone. Mineral soil C stock changes and C emissions from organic soils are reported here for *Land Converted to Grassland*, but emissions from liming are reported in *Cropland Remaining Cropland*, because it was not possible to subdivide those estimates by land use and land-use change categories (see the Methodology section below for additional discussion).

Land-use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil C stocks over the entire time series, which was largely caused by annual cropland converted into pasture (see Table 7-26 and Table 7-27). Stock change rates over the time series varied from 14.6 to 16.3 Tg CO_2 Eq./yr (4.0 to 4.5 Tg C). Drainage of organic soils for grazing management led to annual losses of 0.9 Tg CO_2 Eq. in 2005.

The spatial variability in annual CO_2 flux associated with C stock changes in mineral soils is displayed in Figure 7-10 and Figure 7-11. Soil C stock increased in most MLRAs for *Land Converted to Grassland*. The largest gains were in the southeast and northwest, and the amount of sequestration increased through the 1990s. The patterns were driven by conversion of annual cropland into continuous pasture. Emissions from organic soils were largest in California, Florida and the upper Midwest, which coincides with largest concentrations of organic soils in the United States that are used for agricultural production.

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 soils for *Land Converted to Grassland*.

Soil C stock changes were estimated for *Land Converted to Grassland* according to land-use histories recorded in

Table 7-26: Net Soil C Stock Changes for *Land Converted to Grassland* (Tg CO_2 Eq.)

Soil Type	1990	1995	2000	2001	2002	2003	2004	2005
Mineral Soils[a]	(15.0)	(17.2)	(17.2)	(17.2)	(17.2)	(17.2)	(17.2)	(17.2)
Organic Soils	0.5	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Liming of Soils[b]	-	-	-	-	-	-	-	-
Total Net Flux	**(14.6)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

[a] Stock changes due to application of sewage sludge is reported in *Grassland Remaining Grassland*.

[b] Emissions from liming in *Land Converted to Grassland* are reported in *Cropland Remaining Cropland*.

Table 7-27: Net Soil C Stock Changes for *Land Converted to Grassland* (Tg C)

Soil Type	1990	1995	2000	2001	2002	2003	2004	2005
Mineral Soils[a]	(4.1)	(4.7)	(4.7)	(4.7)	(4.7)	(4.7)	(4.7)	(4.7)
Organic Soils	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Liming of Soils[b]	-	-	-	-	-	-	-	
Total Net Flux	**(4.0)**	**(4.5)**	**(4.5)**	**(4.5)**	**(4.5)**	**(4.5)**	**(4.5)**	**(4.5)**

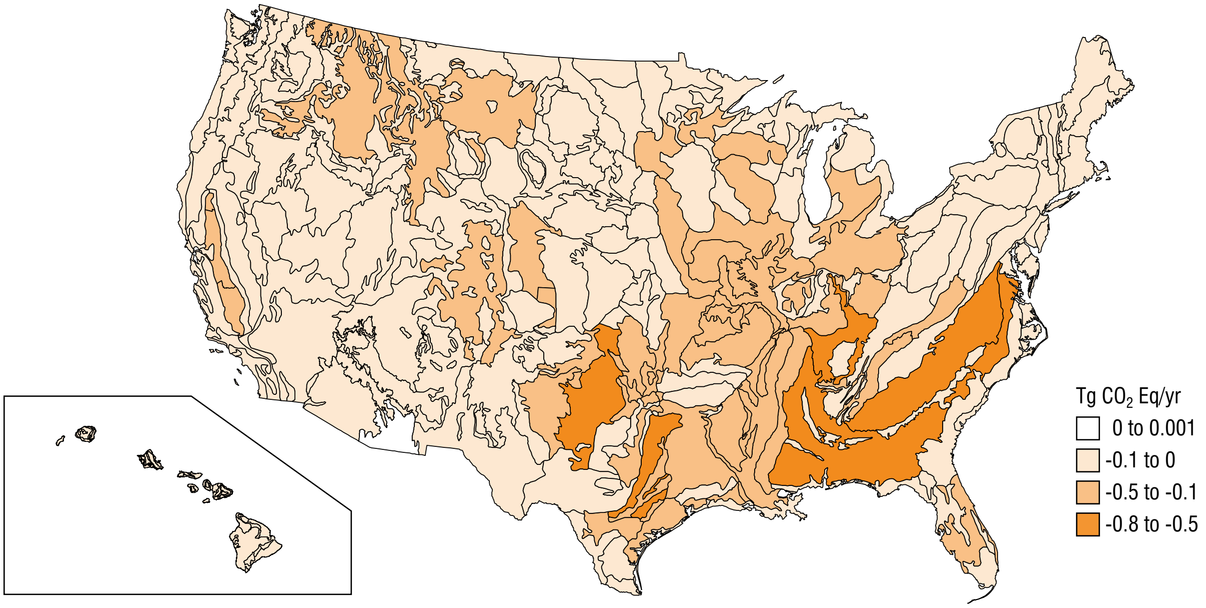
Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

[a] Stock changes due to application of sewage sludge is reported in *Grassland Remaining Grassland*.

[b] Emissions from liming in *Land Converted to Grassland* are reported in *Cropland Remaining Cropland*.

Figure 7-10

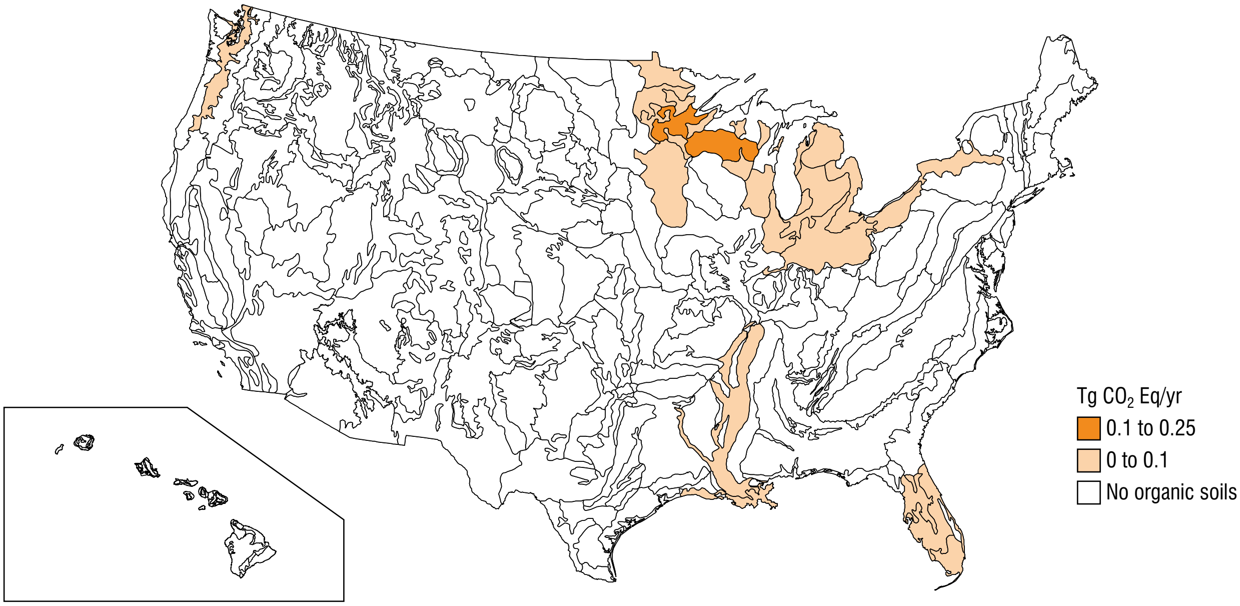
Net Soil C Stock Change for Mineral Soils in *Land Converted to Grassland*, 2005



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 Inventory computations. See Methodology for additional details.

Figure 7-11

Net Soil C Stock Change for Organic Soils in *Land Converted to Grassland*, 2005



Note: Values greater than zero represent emissions.

the USDA NRI survey (USDA-NRCS 2000).[12] Land use and some management information (e.g., legume pastures, crop type, soil attributes, and irrigation) were collected for each NRI point on a 5-year cycle beginning in 1982, and were subdivided into four inventory time periods, 1980–84, 1985–1989, 1990–94 and 1995–2000. NRI points were classified as *Land Converted to Grassland* for an inventory time period (e.g., 1990–1994 and 1995–2000) if the land use was grassland at the end of the respective inventory time period but had been another use in a prior inventory time period. Grassland includes pasture and rangeland used for grass forage production, where the primary use is livestock grazing. Rangeland 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. 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.

Mineral Soil Carbon Stock Changes

A Tier 3 model-based approach was used to estimate C stock changes for *Land Converted to Grassland* on mineral soils, with the exception of prior cropland used to produce vegetables, tobacco, perennial/horticultural crops, and rice, in addition to land areas with very gravelly, cobbly or shaley soils (greater than 35 by volume). An IPCC Tier 2 approach was used to estimate C stock changes for portions of the land base for *Land Converted to Grassland* that were not addressed with the Tier 3 approach (Ogle et al. 2003). 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 Century biogeochemical model as described for *Grassland Remaining Grassland*. 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 USDA Economic Research Service Cropping Practices Survey (ERS 1997) and National Agricultural Statistics Service (NASS 1992, 1999, 2004) (see *Grassland Remaining Grassland* Tier 3 methods section 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 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/UNEP/OECD/IEA (1997) and IPCC (2003), which utilizes 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 a Monte Carlo simulation with 50,000 iterations. Emissions were based on the 1992 and 1997 *Land Converted to Grassland* areas from the *1997 National Resources Inventory* (USDA-NRCS 2000). The annual flux estimated for 1992 was applied to 1990 through 1992, and the annual flux estimated for 1997 was applied to 1993 through 2005.

CO_2 Emissions from Agricultural Liming

Carbon dioxide emissions from degradation of limestone and dolomite applied to *Land Converted to Grassland* are reported in *Cropland Remaining Cropland*, because it was not possible to disaggregate liming application among land use and land-use change categories.

Uncertainty

Uncertainty associated with the *Land Converted to Grassland* category includes the uncertainty associated with changes in mineral soil C stocks. Uncertainty estimates are presented in Table 7-28 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). A combined uncertainty estimate for changes in agricultural soil C stocks occurring within *Land Converted to Grassland* 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

---

[12] NRI points were classified as agricultural if under grassland or cropland management in 1992 and/or 1997.

Table 7-28: Quantitative Uncertainty Estimates for C Stock Changes occurring within *Land Converted to Grassland* (Tg CO_2 Eq. and Percent)

Source	2005 Stock Change Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Stock Change 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	(12.2)	(12.5)	(11.9)	-2%	+2%
Mineral Soil C Stocks: *Land Converted to Grassland*, Tier 2 Inventory Methodology	(5.0)	(7.0)	(2.8)	-39%	+43%
Organic Soil C Stocks: *Land Converted to Grassland*, Tier 2 Inventory Methodology	0.9	0.2	1.8	-76%	+104%
Combined Uncertainty for Agricultural Soil Carbon Stocks in *Land Converted to Grassland*	**(16.3)**	**(18.4)**	**(14.0)**	**-13%**	**+14%**

quantities. More details on how the individual uncertainties were developed appear later in this section. The combined uncertainty for soil C stocks in *Land Converted to Grassland* ranged from 13 percent below and 14 percent above the 2005 estimate of 16.3 Tg CO_2 Eq.

Uncertainties in Mineral Soil Carbon Stock Changes

Tier 3 Approach

The uncertainty analysis for *Land Converted to Grassland* 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.

Uncertainties in Organic Soil Carbon Stock Changes

Annual C emission estimates from drained organic soils in *Land Converted to Grassland* were estimated using the Tier 2 approach, as described in the *Cropland Remaining Cropland* section.

QA/QC and Verification

See the QA/QC and Verification section under *Grassland Remaining Grassland*.

Recalculations Discussion

The specific changes in reporting in the current Inventory for *Land Converted to Grassland* are the same as those described in the *Cropland Remaining Cropland* section, except that the uncertainty is not addressed in the current Inventory for the random variation associated with Century model estimates at the site scale. The structural uncertainty requires further development before it can be used to address uncertainty inherent in the structure of the Century model for other uses besides cropland. Overall, the recalculations resulted in an average annual decrease in sinks of 4.3 Tg CO_2 Eq. (21.1 percent) for soil C stock changes in *Land Converted to Grassland* for the time series from 1990 through 2004.

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 in Century model results for *Land Converted to Grassland*, but this is a planned improvement for the inventory. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.7. 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 4.4 percent of the United States (Nowak et al. 2005). With an average tree canopy cover of 27.1 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

Table 7-29: Net C Flux from Urban Trees (Tg CO_2 Eq. and Tg C)

Year	Tg CO_2 Eq.	Tg C
1990	(57.5)	(15.7)
1995	(67.8)	(18.5)
2000	(78.2)	(21.3)
2001	(80.2)	(21.9)
2002	(82.3)	(22.4)
2003	(84.4)	(23.0)
2004	(86.4)	(23.6)
2005	(88.5)	(24.1)

Note: Parentheses indicate net sequestration.

for an average annual net sequestration of 73.0 Tg CO_2 Eq. (19.9 Tg C) over the period from 1990 through 2005. Total sequestration increased by 54 percent between 1990 and 2005 due to increases in urban land area. Data on C storage and urban tree coverage were collected throughout the 1990s, and have been applied to the entire time series in this report. Annual estimates of CO_2 flux were developed based on periodic U.S. Census data on urban area (Table 7-29).

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). Also, 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 per unit tree cover basis (tree canopy area), rather than total land area. Urban trees, therefore, appear to have a greater C density than forested areas (Nowak and Crane 2002).

Methodology

The methodology used by Nowak and Crane (2002) is based on average annual estimates of urban tree growth and decomposition, which were derived from field measurements and data from the scientific literature, urban area estimates from U.S. Census data, and urban tree cover estimates from remote sensing data. This approach is consistent with the default IPCC methodology in IPCC (2003), although sufficient data are not yet available to determine interannual changes 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.

Nowak and Crane (2002) developed estimates of annual gross C sequestration from tree growth and annual gross C emissions from decomposition for ten U.S. cities: Atlanta, GA; Baltimore, MD; Boston, MA; Chicago, IL; Jersey City, NJ; New York, NY; Oakland, CA; Philadelphia, PA; Sacramento, CA; and Syracuse, NY. The gross C sequestration estimates were derived from field data that were collected in these ten cities during the period from 1989 through 1999, including tree measurements of stem diameter, tree height, crown height, and crown width, and information on location, species, and canopy condition. The field data were converted to annual gross C sequestration rates for each species (or genus), diameter class, and land-use condition (forested, park-like, and open growth) by applying allometric equations, a root-to-shoot ratio, moisture contents, a C content of 50 percent (dry weight basis), an adjustment factor to account for smaller aboveground biomass volumes (given a particular diameter) in urban conditions compared to forests, an adjustment factor to account for tree condition (fair to excellent, poor, critical, dying, or dead), and annual diameter and height growth rates. The annual gross C sequestration rates for each species (or genus), diameter class, and land-use condition were then scaled up to city estimates using tree population information. The field data from the 10 cities, some of which are unpublished, are described in Nowak and Crane (2002) and references cited therein. The allometric equations were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), and the adjustments to account for smaller volumes in urban conditions were 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). Adjustment factors to account for tree condition were based on percent crown dieback (Nowak and Crane 2002). Tree growth rates were also 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.

Annual gross C emission estimates were derived by applying estimates of annual mortality and condition, and assumptions about whether dead trees were removed from the site, to C stock estimates. These values were derived as intermediate steps in the sequestration calculations, and different decomposition rates were applied to dead trees left standing compared with those removed from the site. The 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. Estimates of annual mortality rates by diameter class and condition class were derived from a study of street-tree mortality (Nowak 1986). Assumptions about whether dead trees would be removed from the site were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak and Crane 2002).

National annual net C sequestration by urban trees was estimated from estimates of gross and net sequestration from seven of the ten cities, and urban area and urban tree cover data for the United States. Annual net C sequestration estimates were derived for seven cities by subtracting the annual gross emission estimates from the annual gross sequestration estimates.[13] The urban areas are 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 has increased by approximately 36 percent from 1990 to 2000; Nowak et al. (2005) estimate that the changes in the definition of urban land have resulted in approximately 20 percent of the total reported increase in urban land area from 1990 to 2000. Under both 1990 and 2000 definitions, urban encompasses most cities, towns, and villages (i.e., it includes both urban and suburban areas). The gross and net 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 (0.30 kg C/m^2-year) was then multiplied by the estimate of national urban tree cover area to estimate national annual gross sequestration. 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 for those cities that had both estimates (0.70). The urban tree cover estimates for each of the 10 cities and the United States were obtained from Dwyer et al. (2000) and Nowak et al. (2002). The urban area estimates were taken from Nowak et al. (2005).

Uncertainty

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 the ten U.S. cities. A 10 percent uncertainty was associated with urban area estimates, based

Table 7-30: Carbon Stocks (Metric Tons C), Annual Carbon Sequestration (Metric Tons C/yr), Tree Cover (Percent), and Annual Carbon Sequestration per Area of Tree Cover (kg C/m^2 cover-yr) for Ten 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
New York, NY	1,225,200	38,400	20,800	20.9	0.23	0.12
Atlanta, GA	1,220,200	42,100	32,200	36.7	0.34	0.26
Sacramento, CA	1,107,300	20,200	NA	13.0	0.66	NA
Chicago, IL	854,800	40,100	NA	11.0	0.61	NA
Baltimore, MD	528,700	14,800	10,800	25.2	0.28	0.20
Philadelphia, PA	481,000	14,600	10,700	15.7	0.27	0.20
Boston, MA	289,800	9,500	6,900	22.3	0.30	0.22
Syracuse, NY	148,300	4,700	3,500	24.4	0.30	0.22
Oakland, CA	145,800	NA	NA	21.0	NA	NA
Jersey City, NJ	19,300	800	600	11.5	0.18	0.13

NA = not analyzed.

---

[13] Three cities did not have net estimates.

Table 7-31: 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	2005 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
Changes in C Stocks in Urban Trees	CO_2	(88.5)	(108.5)	(71.3)	-23%	+19%

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.

on expert judgment. A 5 percent uncertainty was associated with national urban tree covered area. Uncertainty associated with estimates of gross and net C sequestration for the ten U.S. cities was based on standard error estimates for each of the city-level sequestration estimates as reported in Nowak et al. (2002). These estimates are based on field data collected in ten 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. However, both the omission of urban soil C flux and the potential overlap with forest C are believed to be relatively minor (Nowak 2002a). Because these factors are currently inestimable due to data limitations, they are not quantified as part of this analysis.

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 7-31. The net C flux from changes in C stocks in urban trees was estimated to be between -108.5 and -71.3 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 23 percent below and 19 percent above the 2005 flux estimate of -88.5 Tg CO_2 Eq.

QA/QC and Verification

The net C flux resulting from urban trees was calculated using estimates of gross and net C sequestration estimates for urban trees and urban tree coverage area found in 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 the 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).

Recalculations Discussion

In previous Inventories, estimates of Tg C had been rounded to 2 significant figures based on Nowak (2002b). Since a Tier 2 uncertainty analysis was run for this source starting from the current Inventory, this rounding step was removed. This change resulted in a change in emission estimates for 1990 through 2004. On average, estimates of net C flux from urban trees decreased by less than one percent over the period from 1990 to 2004 relative to the previous report.

Planned Improvements

New estimates of C in urban trees based on new satellite and field data are being developed. Once those data become available, they will be incorporated into estimates of net C flux resulting from urban trees.

A consistent representation of the managed land base in the United States is also being developed. A component of this project will involve reconciling the overlap between urban forest and non-urban forest GHG inventories. It is highly likely that urban forest inventories are including areas considered non-urban 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 the U.S. Inventory. One goal of the plan to develop the consistent representation of the United States land base is to eliminate this overlap.

Direct N_2O Fluxes from Settlement Soils (IPCC Source Category 5E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 10 percent are applied to

Table 7-32: N_2O Fluxes from Soils in Settlements Remaining Settlements (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	5.1	17
1995	5.5	18
2000	5.6	18
2001	5.5	18
2002	5.6	18
2003	5.8	19
2004	6.0	19
2005	5.8	19

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*.

lawns, golf courses, and other landscaping occurring within settlement areas. Application rates are less 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 2005, N_2O emissions from this source were 5.8 Tg CO_2 Eq. (19 Gg). There was an overall increase of 13 percent over the period from 1990 through 2005 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 7-32.

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 in surface disposal of sewage sludge.

Nitrogen applications to settlement soils are assumed to be 10 percent of the total synthetic fertilizer used in the United States (Qian 2004). Total synthetic fertilizer applications were derived from fertilizer statistics (TVA 1991, 1992, 1993, 1994; AAPFCO 1995, 1996, 1997, 1998, 1999, 2000b, 2002, 2003, 2004, 2005, 2006) and a recent AAPFCO database (AAPFCO 2000a). Sewage sludge applications were derived from national data on sewage sludge generation, disposition, and nitrogen 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 proportions, 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 the total N contributions to indirect emissions, as reported in the Agricultural Soil Management source category of the Agriculture chapter.

Uncertainty

The amount of N_2O emitted from settlements depends not only on N inputs, but also on a large number of variables, including organic C availability, O_2 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 used here does not incorporate any of these variables and only accounts for variations in national 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 and the emission factors used to derive emission estimates.

The uncertainty in the amounts of sewage sludge applied to non-agricultural lands and used in surface disposal was based on the uncertainty of the following data points, which were used to determine the amounts applied in 2005: (1) N content of sewage sludge; (2) total sludge applied in 2000; (3) wastewater existing flow in 1996 and 2000; and (4) the sewage sludge disposal practice distributions to non-agricultural land application and surface disposal.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-33. N_2O emissions from soils in *Settlements Remaining Settlements* in 2005 were estimated to be between 3.0 and 15.3 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 49 percent below to 163 percent above the 2005 emission estimate of 5.8 Tg CO_2 Eq.

Table 7-33: Tier 2 Quantitative Uncertainty Estimates of N_2O Emissions from Soils in *Settlements Remaining Settlements* (Tg CO_2 Eq. and Percent)

Source	Gas	2005 Emissions (Tg CO_2 Eq.)	Uncertainty Range Relative to 2005 Emission Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Settlements Remaining Settlements: N_2O Fluxes from Soils	N_2O	5.8	3.0	15.3	-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*.

Recalculations Discussion

There were several recalculations for the current Inventory. The 2003 and 2004 total fertilizer application data were updated from the APPFCO *Commercial Fertilizers* 2003 Report (2004) and 2004 Report (2005). An error in unit conversion used in the sewage sludge calculations was corrected. Changes were made to the data used to calculate the amount of sewage sludge applied from 2001 to 2005, as discussed in Annex 3.11. In the previous Inventory, sewage sludge applied as commercial fertilizer was included in total synthetic fertilizer applied, as well as added to the total synthetic fertilizer applied, effectually double counting the amounts of sewage sludge applied to settlements. This error was corrected by not including sewage sludge in total synthetic fertilizer applied. The IPCC default emission factor of 1.25 percent for direct emissions from applied N was updated to 1 percent based on IPCC (2006). Additionally, because the direct emission factor was developed based on total N inputs, the new method has been revised to estimate direct N_2O emissions based on total N input. Previously, a portion of the N inputs were removed from the calculation of direct N_2O emissions, because it was assumed to be lost through volatilization before direct emissions occurred. All of these changes resulted in a 7.6 percent decrease in the emissions estimates for 2004 and an average decrease of about 7.5 percent over the period from 1990 to 2004.

Planned Improvements

The process-based DAYCENT model, which was used to estimate N_2O emissions from cropped soils, could also be used to simulate direct and indirect emissions from settlement soils using state-level settlement area data from the National Resource Inventory.

7.8. 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.

7.9. Other (IPCC Source Category 5G)

Changes in Yard Trimming and Food Scrap Stocks in Landfills

In the United States, a significant change in C stocks results from the removal of yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps from settlements to be disposed in landfills. Yard trimmings 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.

C storage is associated with particular land uses. For example, harvested wood products are accounted for under *Forest Land Remaining Forest Land* because these products are a component of this ecosystem. C stock changes in yard trimmings and food scraps are associated with settlements, but removals do not occur within settlements. Yard trimming and food scrap C storage is therefore reported under "Other."

Both the amount of yard trimmings and food scraps collected annually and the fraction that is landfilled have declined over the last decade. In 1990, nearly 51 million metric tons (wet weight) of yard trimmings and food scraps were generated (i.e., put at the curb for collection or taken to disposal or composting facilities) (EPA 2005). Since then, programs banning or discouraging disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent 18 percent decrease in the amount of yard trimmings collected. At the same time, a dramatic 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 2003 (the most recent year for which data are available; 2004 and 2005 values are assumed to equal 2003). There is considerably less centralized composting of food scraps; generation has grown by 32 percent since 1990, though the proportion of food scraps discarded in landfills has decreased slightly from 81 percent in 1990 to 78 percent in 2003. Overall, there has been a decrease in the yard trimmings and food scrap landfill disposal rate, which has resulted in a decrease in the rate of landfill C storage to 8.8 Tg CO_2 Eq. in 2005 from 22.8 Tg CO_2 Eq. in 1990 (Table 7-34 and Table 7-35).

Methodology

As empirical evidence shows, the removal of C from the natural cycling of C between the atmosphere and biogenic materials, which occurs when wastes of biogenic origin are deposited in landfills, sequesters C (Barlaz 1998, 2005). When wastes of sustainable, biogenic origin (such as yard trimming and food scraps) are landfilled and do not completely decompose, the C that remains is effectively removed from the global C cycle. 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) and IPCC (2006). 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 portion 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 adjusted by mass balance; 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

Table 7-34: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg CO_2 Eq.)

Carbon Pool	1990	1995	2000	2001	2002	2003	2004	2005
Yard Trimmings	**(20.3)**	**(11.8)**	**(7.5)**	**(7.7)**	**(7.9)**	**(6.4)**	**(5.5)**	**(5.8)**
Grass	(2.4)	(1.2)	(0.8)	(0.9)	(0.9)	(0.7)	(0.6)	(0.7)
Leaves	(8.2)	(4.7)	(2.9)	(3.0)	(3.1)	(2.5)	(2.1)	(2.2)
Branches	(9.7)	(5.8)	(3.7)	(3.8)	(3.9)	(3.2)	(2.8)	(2.9)
Food Scraps	**(2.5)**	**(1.6)**	**(3.0)**	**(2.9)**	**(2.9)**	**(3.0)**	**(3.2)**	**(3.0)**
Total Net Flux	**(22.8)**	**(13.3)**	**(10.5)**	**(10.6)**	**(10.8)**	**(9.3)**	**(8.7)**	**(8.8)**

Note: Totals may not sum due to independent rounding.

Table 7-35: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg C)

Carbon Pool	1990	1995	2000	2001	2002	2003	2004	2005
Yard Trimmings	**(5.5)**	**(3.2)**	**(2.0)**	**(2.1)**	**(2.2)**	**(1.7)**	**(1.5)**	**(1.6)**
Grass	(0.6)	(0.3)	(0.2)	(0.2)	(0.3)	(0.2)	(0.2)	(0.2)
Leaves	(2.2)	(1.3)	(0.8)	(0.8)	(0.8)	(0.7)	(0.6)	(0.6)
Branches	(2.6)	(1.6)	(1.0)	(1.0)	(1.1)	(0.9)	(0.8)	(0.8)
Food Scraps	**(0.7)**	**(0.4)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.9)**	**(0.8)**
Total Net Flux	**(6.2)**	**(3.6)**	**(2.9)**	**(2.9)**	**(3.0)**	**(2.5)**	**(2.4)**	**(2.4)**

Note: Totals may not sum due to independent rounding.

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: 2003 Facts and Figures* (EPA 2005), which provides data for 1960, 1970, 1980, 1990, 1995, and 2000 through 2003. To provide data for some of the missing years in the 1990 through 1999 period, two earlier reports were used (*Characterization of Municipal Solid Waste in the United States: 1998 Update* (EPA 1999), and *Municipal Solid Waste in the United States: 2001 Facts and Figures* [EPA 2003]). Remaining years in the time series for which data were not provided were estimated using linear interpolation. Values for 2004 and 2005 are assumed to be equal to values for 2003. The reports do not subdivide discards of individual materials into volumes landfilled and combusted, although they provide an estimate of the proportion of overall wastestream discards managed in landfills and combustors (i.e., ranging from 90 percent and 10 percent respectively in 1980, to 67 percent and 33 percent in 1960).

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 were determined by Barlaz (1998, 2005) (Table 7-36).

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), a portion of the initial C resists decomposition and is essentially persistent in the landfill environment; the modeling approach applied here builds on his findings. Barlaz (1998, 2005) 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 7-36).

For purposes of simulating U.S. landfill C flows, the proportion of C stored is assumed to persist in landfills; the remaining portion is assumed to degrade (and results 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. Grass and food scraps are assumed to have a half-life of 5 years; leaves and branches are assumed to have a half-life of 20 years.

For each of the four materials (grass, leaves, branches, food scraps), the stock of C in landfills for any given year is calculated according to the following formula:

$$LFC_{i,t} = \sum_{n} W_{i,n} \times (1 - MC_i) \times ICC_i \times \{[CS_i \times ICC_i] + [(1 - (CS_i \times ICC_i)) \times e^{-k\,(t-n)}]\}$$

where,

t = Year for which C stocks are being estimated

$LFC_{i,t}$ = Stock of C in landfills in year *t*, for waste *i* (grass, leaves, branches, food scraps)

$W_{i,n}$ = Mass of waste *i* disposed in landfills in year *n*, in units of wet weight

n = Year in which the waste was disposed, where $1960 \leq n \leq t$

MC_i = Moisture content of waste *i*

CS_i = Proportion of initial C that is stored for waste *i*

ICC_i = Initial C content of waste *i*

e = Natural logarithm, and

k = First order rate constant for waste *i*, which is equal to 0.693 divided by the half-life for decomposition

For a given year *t*, the total stock of C in landfills ($TLFC_t$) is the sum of stocks across all four materials. 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 (2005). For example, disposal of food scraps in 1960 resulted in depositing about 1,140,000 metric tons of C. Of this amount, 16 percent (180,000 metric tons) is persistent; the remaining

Table 7-36: Moisture Content (%), C Storage Factor, Proportion of Initial C Sequestered (%), Initial C Content (%), and Half-Life (years) for Yard Trimmings and Food Scrap Stocks in Landfills

	Yard Trimmings			Food Scraps
Variable	**Grass**	**Leaves**	**Branches**	
Moisture Content (% H_2O)	70	30	10	70
CS, proportion of initial C stored (%)	68	72	77	16
Initial C Content (%)	45	42	49	51
Half-life (years)	5	20	20	5

84 percent (960,000 metric tons) is degradable. By 1965, half of the degradable portion (480,000 metric tons) decomposes, leaving a total of 660,000 metric tons (the persistent portion, plus the remaining half of the degradable portion).

Continuing the example, by 2005, the total food scraps C originally disposed in 1960 had declined to 181,000 metric tons (i.e., virtually all of the degradable C had decomposed). By summing the C remaining from 1960 with the C remaining from food scraps disposed in subsequent years (1961 through 2005), the total landfill C from food scraps in 2005 was 31.3 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 2005, yielding a value of 220.6 million metric tons (as shown in Table 7-37). 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 7-35) is the difference in the landfill C stock for a given year and the stock in the preceding year. For example, the net change in 2005 shown in Table 7-35 (2.4 Tg C) is equal to the stock in 2005 (220.6 Tg C) minus the stock in 2004 (218.2 Tg C).

When applying the C storage data reported by Barlaz (1998), an adjustment was made to the reported values so that a perfect mass balance on total C could be attained for each of the materials. There are four principal elements in the mass balance:

- Initial C content (ICC, measured),
- C output as CH_4 (CH_4-C, measured),
- C output as CO_2 (CO_2-C, not measured), and
- Residual stored C (CS, measured).

In a simple system where the only C fates are CH_4, CO_2, and C storage, the following equation is used to attain a mass balance:

$$CH_4\text{-C} + CO_2\text{-C} + CS = ICC$$

The experiments by Barlaz and his colleagues (Barlaz 1998, Eleazer et al. 1997) did not measure CO_2 outputs in experiments. However, if the only decomposition is anaerobic, then $CH_4\text{-C} = CO_2\text{-C}$.[14] Thus, the system should be defined by:

$$2 \times CH_4\text{-C} + CS = ICC$$

The C outputs (= $2 \times CH_4\text{-C} + CS$) were less than 100 percent of the initial C mass for food scraps, leaves, and branches (75, 86, and 90 percent, respectively). For these materials, it was assumed that the unaccounted for C had exited the experiment as CH_4 and CO_2, and no adjustment was made to the measured value of CS.

Table 7-37: Carbon Stocks in Yard Trimmings and Food Scraps in Landfills (Tg C)

Carbon Pool	1990	1995	2000	2001	2002	2003	2004	2005
Yard Trimmings	**149.8**	**171.5**	**181.4**	**182.9**	**184.4**	**186.0**	**187.7**	**189.3**
Grass	18.2	20.7	21.7	21.8	22.0	22.2	22.4	22.6
Leaves	61.3	70.1	74.1	74.7	75.3	75.9	76.6	77.2
Branches	70.3	80.7	85.6	86.4	87.1	87.9	88.7	89.5
Food Scraps	**20.3**	**23.4**	**27.2**	**28.1**	**28.9**	**29.8**	**30.5**	**31.3**
Total Carbon Stocks	**170.1**	**195.0**	**208.6**	**210.9**	**213.3**	**215.8**	**218.2**	**220.6**

Note: Totals may not sum due to independent rounding.

---

[14] The molar ratio of CH_4 to CO_2 is 1:1 for carbohydrates (e.g., cellulose, hemicellulose). For proteins as $C_{3.2}H_5ON_{0.86}$, the molar ratio is 1.65 CH_4 per 1.55 CO_2 (Barlaz et al. 1989). Given the predominance of carbohydrates, for all practical purposes, the overall ratio is 1:1.

In the case of grass, the outputs were slightly more (103 percent) than initial C mass. To resolve the mass balance discrepancy, it was assumed that the measurements of initial C content and CH_4 mass were accurate. Thus, the value of CS was calculated as the residual of ICC (initial C content) minus ($2 \times CH_4$-C). This adjustment reduced the C storage value from the 71 percent reported by Barlaz (1998) to 68 percent (as shown in Table 7-36).

Uncertainty

The estimation of C storage in landfills is directly related to the following yard trimming and food scrap data and factors: disposal in landfills per year (tons of C), initial C content, moisture content, decomposition rate (half-life), 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 uncertainties associated with each of these factors.

A Monte Carlo (Tier 2) uncertainty analysis was then applied to estimate the overall uncertainty of the sequestration estimate. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-38. Total yard trimmings and food scraps CO_2 flux in 2005 was estimated to be between -17.1 and -5.3 Tg CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo stochastic simulations). This indicates a range of 94 percent below to 40 percent above the 2005 flux estimate of -8.8 Tg CO_2 Eq.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. The QA/QC check revealed the need to update one of the input values, addressed in the recalculations discussion below.

Recalculations Discussion

The only recalculation performed for the current Inventory was a correction. The value for the initial C content (ICC) of leaves was updated for the current Inventory (41.6 percent) based on updated experimental results provided by Barlaz (2005). Although the previous Inventory used an updated value for the carbon stored (CS) for leaves, the initial C content had not been updated (i.e., the earlier experimental value of 49.4 percent was used). This recalculation fixed that problem, and has the effect of reducing the stocks of C from leaves, and also reducing (by about 5 percent) the annual flux for yard trimmings and food scraps.

In the previous Inventory, Changes in Yard Trimming and Food Scrap C Stocks in Landfills was included in the *Settlements Remaining Settlements* section of this chapter. However, although C stock changes in yard trimmings and food scraps are associated with settlements, removals do not occur within settlements. Therefore, yard trimming and food scrap C storage is now reported under "Other."

Planned Improvements

Future work may evaluate the potential contribution of inorganic C to landfill sequestration, as well as 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.

Table 7-38: Tier 2 Quantitative Uncertainty Estimates for CO_2 Flux from Yard Trimmings and Food Scrap Stocks in Landfills (Tg CO_2 Eq. and Percent)

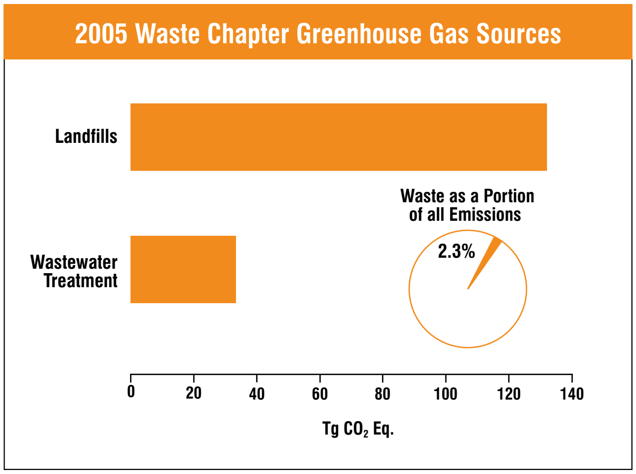
Source	Gas	2005 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Yard Trimmings and Food Scraps	CO_2	(8.8)	(17.1)	(5.3)	-94%	+40%

[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.

8. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 8-1). Landfills accounted for approximately 24 percent of total U.S. anthropogenic methane (CH_4) emissions in 2005,[1] the largest contribution of any CH_4 source in the United States. Additionally, wastewater treatment accounts for just under 5 percent of U.S. CH_4 emissions. 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. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are emitted by waste activities, and are addressed separately at

Figure 8-1



2005 Waste Chapter Greenhouse Gas Sources

Table 8-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**185.8**	**182.2**	**158.3**	**153.5**	**156.2**	**160.5**	**157.8**	**157.4**
Landfills	161.0	157.1	131.9	127.6	130.4	134.9	132.1	132.0
Wastewater Treatment	24.8	25.1	26.4	25.9	25.8	25.6	25.7	25.4
N_2O	**6.4**	**6.9**	**7.6**	**7.6**	**7.7**	**7.8**	**7.9**	**8.0**
Domestic Wastewater Treatment	6.4	6.9	7.6	7.6	7.7	7.8	7.9	8.0
Total	**192.2**	**189.1**	**165.9**	**161.1**	**163.9**	**168.4**	**165.7**	**165.4**

Note: Totals may not sum due to independent rounding.

Table 8-2: Emissions from Waste (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**8,848**	**8,674**	**7,537**	**7,310**	**7,439**	**7,645**	**7,514**	**7,496**
Landfills	7,668	7,479	6,280	6,078	6,210	6,425	6,292	6,286
Wastewater Treatment	1,180	1,195	1,257	1,232	1,229	1,220	1,222	1,210
N_2O	**21**	**22**	**24**	**25**	**25**	**25**	**26**	**26**
Domestic Wastewater Treatment	21	22	24	25	25	25	26	26
NO_x	**+**	**1**	**2**	**2**	**2**	**2**	**2**	**2**
CO	**1**	**2**	**8**	**8**	**7**	**7**	**7**	**7**
NMVOCs	**673**	**731**	**119**	**122**	**116**	**116**	**116**	**116**

Note: Totals may not sum due to independent rounding.

---

[1] 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.

the end of this chapter. A summary of greenhouse gas and indirect greenhouse gas emissions from the Waste chapter is presented in Table 8-1 and Table 8-2.

Overall, in 2005, waste activities generated emissions of 165.4 Tg CO_2 Eq., or just over 2 percent of total U.S. greenhouse gas emissions.

8.1. Landfills (IPCC Source Category 6A1)

In 2005, landfill CH_4 emissions were approximately 132 Tg CO_2 Eq. (6,286 Gg), representing the largest source of CH_4 emissions in the United States. Emissions from municipal solid waste (MSW) landfills, which received about 64 percent of the total solid waste generated in the United States, accounted for about 89 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 1,800 operational landfills exist in the United States, with the largest landfills receiving most of the waste and generating the majority of the CH_4 (BioCycle 2006, adjusted to include missing data from five states).

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 carbon dioxide (CO_2) and 50 percent CH_4, by volume.[2] Significant CH_4 production typically begins one or two years after waste disposal in a landfill and continues for 10 to 60 years.

From 1990 to 2005, net CH_4 emissions from landfills decreased by approximately 18 percent (see Table 8-3 and Table 8-4), 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,[3] which has more than offset the additional

Table 8-3: CH_4 Emissions from Landfills (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
MSW Landfills	188.7	204.7	217.3	221.4	227.2	234.9	242.4	249.6
Industrial Landfills	12.9	13.9	15.4	15.6	15.7	15.9	16.0	16.1
Recovered								
Gas-to-Energy	(17.6)	(22.3)	(49.0)	(54.3)	(54.4)	(54.9)	(57.1)	(58.6)
Flared	(5.0)	(21.8)	(37.1)	(40.8)	(43.7)	(46.0)	(54.4)	(60.4)
Oxidized[a]	(17.9)	(17.5)	(14.7)	(14.2)	(14.5)	(15.0)	(14.7)	(14.7)
Total	**161.0**	**157.1**	**131.9**	**127.6**	**130.4**	**134.9**	**132.1**	**132.0**

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	1995	2000	2001	2002	2003	2004	2005
MSW Landfills	8,985	9,745	10,348	10,541	10,820	11,188	11,543	11,885
Industrial Landfills	614	664	731	744	749	757	761	767
Recovered								
Gas-to-Energy	(840)	(1,061)	(2,335)	(2,588)	(2,590)	(2,614)	(2,720)	(2,790)
Flared	(239)	(1,039)	(1,766)	(1,943)	(2,080)	(2,192)	(2,593)	(2,877)
Oxidized[a]	(852)	(831)	(698)	(675)	(690)	(714)	(699)	(698)
Total	**7,668**	**7,479**	**6,280**	**6,078**	**6,210**	**6,425**	**6,292**	**6,286**

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

[a] Includes oxidation at both municipal and industrial landfills.

---

[2] The percentage of CO_2 in biogas released from a landfill may be smaller because some CO_2 dissolves in landfill water (Bingemer and Crutzen 1987). Additionally, less than 1 percent of landfill gas is typically composed of non-CH_4 volatile organic compounds (NMVOCs).

[3] 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.

CH_4 emissions resulting from an increase in the amount of municipal solid waste landfilled.

Methane emissions from landfills are a function of several factors, including: (1) the total amount of municipal solid waste in landfills, which is related to total municipal solid 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. The estimated annual quantity of waste placed in landfills increased from about 209 Tg in 1990 to 304 Tg in 2005, an increase of 45 percent (see Annex 3.14). During this period, the estimated CH_4 recovered and combusted from landfills increased as well. In 1990, for example, approximately 1,079 Gg of CH_4 were recovered and combusted (i.e., used for energy or flared) from landfills. In 2005, the estimated quantity of CH_4 recovered and combusted increased to 5,668 Gg, a 7 percent increase from 2004 levels.

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 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 encouraging CH_4 recovery and use such as EPA's Landfill Methane Outreach Program (LMOP), and federal and state economic incentives.

Methodology

CH_4 emissions from landfills were estimated to equal 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:

$$CH_{4,\text{ Solid Waste}} = [CH_{4,MSW} + CH_{4,ind} - R] - Ox$$

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. For further information, see Annex 3.14.

National landfill waste generation and disposal data for 1989 through 2005 were obtained from *BioCycle* (2006). 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 (2006) and national per capita solid waste generation from *BioCycle* (2006). 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.

The estimated landfill gas recovered per year was based on updated data collected from vendors of flaring equipment, a database of landfill gas-to-energy (LFGTE) projects compiled by LMOP (EPA 2006), and a database maintained by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2006). 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 2005 was estimated. 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 emissions reductions associated with LFGTE projects for which a flare had not been identified from the emissions reductions associated with flares.

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 (98 to 100 percent) recommended for flares in EPA's *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 in LMOP.

Emissions from industrial landfills were estimated from activity data for industrial production, waste disposal factors, and the first order decay model. 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

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 methane 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 methane estimated to be recovered). For flaring without metered recovery data (approximately 34 percent of the methane 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. The total nitrogen (N) in sewage sludge increased from 189 to 268 Gg total N between 1990 and 2005, however; the quantity of sewage sludge applied to landfills decreased from 28 to 10 percent from 1990 to 2005.[4]

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 8-5. Landfill CH_4 emissions in 2005 were estimated to be between 80.5 and 174.2 Tg CO_2 Eq.,

---

[4] The methodology for estimating the quantity of N in sewage sludge disposed via incineration, land application, surface disposal, landfill, ocean dumping, and other is described in Annex 3.11 Methodology for Estimating N_2O Emissions From Agricultural Soil Management.

Table 8-5: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (Tg CO_2 Eq. and Percent)

Source	Gas	2005 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	132.0	80.5	174.2	-39%	+32%

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

which indicates a range of 39 percent below to 32 percent above the actual 2005 emission estimate of 132 Tg CO_2 Eq.

Recalculations Discussion

Two recalculations affected the estimates of CH_4 generation from landfills. As recommended in IPCC (2006) for MSW landfills, the more accurate integrated form of the first order decay model was applied (see Annex 3A.1 of IPCC 2006), and a delay time of 6 months was incorporated. The integrated form of the FOD model captures a constantly changing rate of reaction, whereas the previously used method, which was not integrated, instead assumed that the rate of reaction remained constant throughout each year. The 6-month delay represents the time before substantial methane generation begins at a landfill. By recalculating previous emissions estimates using this method, estimates of CH_4 generation from MSW landfills were reduced by 4 percent over the time series. The second change was an improvement in the estimate of CH_4 generation from industrial landfills, which was based on industrial production, waste disposal factors, and the first order decay model. For previous Inventories, the generation rate was estimated as simply 7 percent of CH_4 generation from MSW landfills. This change resulted in a decrease of 2 percent in the estimated CH_4 generation at industrial landfills relative to the previous Inventory.

Another recalculation affecting estimates of CH_4 recovery was associated with updating the EIA, LMOP, and flare vendor databases. The estimates of gas recovery by LFGTE projects and flares from 1990 to 2004 increased by 0.7 percent based on changes to the current Inventory. This change is due in part to updating the EIA database and identifying additional flares installed in 2004 that were not included in the previous Inventory. The EIA database for 2004 did not become available until late in 2005; consequently, the gas recovery rate for 2004 was estimated from the 2003 data. The 2004 update showed that LFGTE projects in the EIA 2003 database reported more gas recovery in 2004 than 2003, and additional landfills were included in the 2004 database, both of which increased the estimate of CH_4 recovery. A recalculation that had a minor effect was the application of a destruction efficiency of 99 percent to CH_4 recovered to estimate CH_4 emissions avoided.

The overall effect of these recalculations was an average decrease of 5 percent in the estimated CH_4 emissions from landfills over the 1990 to 2004 time series.

Planned Improvements

For future Inventories, additional efforts will be made to improve the estimates of CH_4 generation at industrial landfills. Improvements to the flare database will be investigated, and an effort will be made to identify additional landfills that have flares.

Box 8-1: Biogenic Emissions and Sinks of Carbon

CO_2 emissions from the combustion or decomposition of biogenic materials (e.g., paper, wood products, and yard trimmings) grown on a sustainable basis are considered to mimic the closed loop of the natural carbon cycle—that is, they return to the atmosphere CO_2 that was originally removed by photosynthesis. In contrast, CH_4 emissions from landfilled waste occur due to the man-made anaerobic conditions conducive to CH_4 formation that exist in landfills, and are consequently included in this Inventory.

Depositing wastes of biogenic origin in landfills causes the removal of carbon from its natural cycle between the atmosphere and biogenic materials. As empirical evidence shows, some of these wastes degrade very slowly in landfills, and the carbon they contain is effectively sequestered in landfills over a period of time (Barlaz 1998, 2005). Estimates of carbon 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).

8.2. Wastewater Treatment (IPCC Source Category 6B)

Wastewater treatment processes can produce anthropogenic CH_4 and N_2O emissions. Wastewater from domestic (municipal sewage) 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,[5] 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 21 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 2006b).

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 nitrogen 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 is more often associated with denitrification.

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.

In 2005, CH_4 emissions from domestic wastewater treatment were estimated to be 17.0 Tg CO_2 Eq. (809 Gg). Emissions fluctuated from 1990 through 1996, and have decreased since 1997 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 2005, CH_4 emissions from industrial wastewater treatment were estimated to be 8.4 Tg CO_2 Eq. (400 Gg). Industrial emission sources have increased across the time series through 1999 and then slightly decreased in keeping with production changes associated with the treatment of wastewater from the pulp and paper; meat and poultry; and vegetables, fruits, and juices processing industries.[6] 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 systems that has been discharged into aquatic environments. The 2005 emissions of N_2O from centralized wastewater treatment processes and from effluent were estimated to be 0.2 Tg CO_2 Eq. (1 Gg) and 7.8 Tg CO_2 Eq. (25 Gg), respectively. Total N_2O emissions from domestic wastewater were estimated to be 8.0 Tg CO_2 Eq. (26 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.

---

[5] Package plants are treatment plants assembled in a factory, skid mounted, and transported to the treatment site.

[6] Emissions associated with refinery wastewater are estimated in Annex 2.3 Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels. Other industrial sectors include organic chemicals, starch production, alcohol refining, creameries, and textiles; however, emissions from these sectors are considered to be insignificant.

Table 8-6: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**24.8**	**25.1**	**26.4**	**25.9**	**25.8**	**25.6**	**25.7**	**25.4**
Domestic	17.4	16.7	17.7	17.5	17.3	17.2	17.1	17.0
Industrial*	7.4	8.4	8.7	8.4	8.5	8.4	8.5	8.4
N_2O	**6.4**	**6.9**	**7.6**	**7.6**	**7.7**	**7.8**	**7.9**	**8.0**
Domestic	6.4	6.9	7.6	7.6	7.7	7.8	7.9	8.0
Total	**31.2**	**32.0**	**34.0**	**33.5**	**33.5**	**33.4**	**33.6**	**33.4**

* Industrial activity includes the pulp and paper; meat and poultry; and vegetables, fruits, and juices processing 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	1995	2000	2001	2002	2003	2004	2005
CH_4	**1,180**	**1,195**	**1,257**	**1,232**	**1,229**	**1,220**	**1,222**	**1,210**
Domestic	826	797	842	832	826	820	815	809
Industrial*	354	398	415	400	402	400	407	400
N_2O	**21**	**22**	**24**	**25**	**25**	**25**	**26**	**26**
Domestic	21	22	24	25	25	25	26	26

* Industrial activity includes the pulp and paper; meat and poultry; and vegetables, fruits, and juices processing industries.
Note: Totals may not sum due to independent rounding.

Methodology

Domestic and Industrial 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, 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 total BOD_5 produced in the United States by the percent of wastewater treated in septic systems (21 percent), the maximum CH_4-producing capacity for domestic wastewater (0.60 kg CH_4/kg BOD), and the CH_4 correction factor (MCF) for septic systems (0.5). CH_4 emissions from POTWs were estimated by multiplying the total BOD_5 produced in the United States by the percent of wastewater treated centrally (79 percent), the relative percentage of wastewater treated by aerobic and anaerobic systems, the maximum CH_4-producing capacity of domestic wastewater, and the relative MCFs for aerobic (zero or 0.3) and anaerobic (0.8) systems. CH_4 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, the density of CH_4, and the destruction efficiency associated with burning the biogas in an energy/thermal device.[7] The methodological equations are:

Emissions from Septic Systems = A
= (% onsite) × (total BOD_5 produced) × (B_o) ×
(MCF-septic) × 1/10^6

Emissions from Centrally Treated Aerobic Systems = B
= (% collected) × (total BOD_5 produced) × (% aerobic) ×
(% 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) ×
(B_o) × (MCF-anaerobic) × 1/10^6

Emissions from Anaerobic Digesters = D
= [(POTW_flow_AD) × (digester gas)/(per capita flow)] ×
0.0283 × (FRAC_CH_4) × (365.25) × (density of CH_4) ×
(1-DE) × 1/10^9

Total CH_4 Emissions (Gg) = A + B + C + D

where,

% onsite = Flow to septic systems/total flow
% collected = Flow to POTWs/total flow

---

[7] Anaerobic digesters at wastewater treatment plants generated 799 Gg CH_4 in 2005, 791 Gg of which was combusted in flares or energy devices (assuming a 99% destruction efficiency).

% aerobic = Flow to aerobic systems/total flow to POTWs

% anaerobic = Flow to anaerobic systems/total flow to POTWs

% operations not well managed = Percent of aerobic systems that are not well managed and in which Some anaerobic degradation occurs

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)

MCF-septic = CH_4 correction factor for septic systems (0.5)

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)

0.0283 = Conversion factor, ft^3 to m^3

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 2006a) 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 2005. The proportions of domestic wastewater treated onsite versus at centralized treatment plants were based on data from the 1993, 1995, 1997, 1999, 2001, 2003, and 2005 American Housing Surveys conducted by the U.S. Census Bureau (U.S. Census 2006b), with data for intervening years obtained by linear interpolation. The wastewater flow to aerobic systems and anaerobic systems, and the wastewater flow to POTWs that have anaerobic digesters were obtained from the 1992, 1996, 2000, and 2004 Clean Watershed Needs Survey, collected by EPA (EPA 1992, 1996, 2000, and 2004a).[8] Data for intervening years were obtained by linear interpolation. The BOD_5 production rate per capita (0.09 kg/capita/day) for domestic wastewater was obtained from Metcalf and Eddy (1991and 2003). The CH_4 emission factor (0.6 kg CH_4/kg BOD_5) and the MCF data were taken from IPCC (2006a). The CH_4 destruction efficiency, 99 percent, was selected based on the range of efficiencies (98–100 percent) recommended for flares in EPA's "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 in the LMOP. The

Table 8-8: U.S. Population (Millions) and Domestic Wastewater BOD_5 Produced (Gg)

Year	Population	BOD_5
1990	254	8,350
1995	271	8,895
2000	287	9,419
2001	289	9,509
2002	292	9,597
2003	295	9,685
2004	297	9,774
2005	300	9,864

Source: U.S. Census Bureau (2006a); Metcalf & Eddy 1991 and 2003.

---

[8] Aerobic and anaerobic treatment were determined based on unit processes in use at the facilities. Because the list of unit processes became more extensive in the 2000 and 2004 surveys, the criteria used to identify aerobic and anaerobic treatment differ slightly across the time series. Once facilities were identified as aerobic or anaerobic, they were separated by whether or not they had anaerobic digestion in place. Once these classifications were determined, the flows associated with facilities in each category were summed.

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 per person per day (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).

CH_4 emissions estimates from industrial wastewater were developed according to the methodology described in IPCC (2006a). 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 three industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; and vegetables, fruits, and juices processing. Table 8-9 contains production data for these industries.

CH_4 emissions from these categories were estimated by multiplying the annual product output by the average outflow, the organics loading (in COD) in the outflow, the percentage of organic loading assumed to degrade anaerobically, and the emission factor. Ratios of BOD:COD in various industrial wastewaters were obtained from the World Bank (1999) 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 2006a). The methodological equation is:

$$CH_4\text{ (industrial wastewater)} = P \times W \times (COD) \times TA \times B_o \times MCF$$

where,

CH_4 (industrial wastewater) = Total$C$ H_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 = Percent of wastewater treated anaerobically on site
MCF = CH_4 correction factor, indicating the extent to which the organic content (measured as COD) degrades anaerobically
B_o = Maximum$C$ H_4-producing potential of industrial wastewater (default value of 0.25 kg CH_4/kg COD)

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. Primary treatment lagoons are aerated to reduce anaerobic activity. However, the lagoons are large and zones of anaerobic activity may occur and, consequently, the primary lagoons are assumed to be 1.4 percent anaerobic (based on expert judgment). Approximately 42 percent of the BOD passes on to secondary treatment, which is less likely to be aerated (EPA 1993a,b). Twenty-five percent of the BOD in secondary treatment lagoons was assumed to degrade anaerobically, while 10 percent passes through to be discharged with the effluent (EPA 1997a). Consequently, the overall percentage of wastewater organics that degrade anaerobically was determined to be 10.3 percent (i.e., 58 percent × 1.4 percent + 42 percent × 90 percent × 25 percent). A time series of CH_4 emissions for 1990 through 2001 was developed based on

Table 8-9: U.S. Pulp and Paper; Meat and Poultry; and Vegetables, Fruits, and Juices Production (Tg)

Year	Pulp and Paper	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices
1990	128.9	27.3	14.6	40.5
1995	140.9	30.8	18.9	49.0
2000	142.8	32.1	22.2	52.7
2001	134.3	31.6	22.8	46.7
2002	132.7	32.7	23.5	49.1
2003	131.9	32.3	23.7	46.2
2004	136.4	31.2	24.4	49.1
2005	131.4	31.4	25.1	43.6

production figures reported in the Lockwood-Post Directory (Lockwood-Post 2002). Published data from the American Forest and Paper Association (AF&PA) and data published by Paper Loop were used to estimate production for 2002 through 2005 (Pulp and Paper 2005, 2006 and monthly reports from 2003–2006). The overall wastewater outflow was estimated to be 85 m^3/metric ton, and the average BOD loading entering the secondary treatment lagoons was estimated to be 0.4 gram BOD/liter (EPA 1997b, EPA 1993a,b, World Bank 1999).

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 COD/kg CH_4 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 2006). 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.

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, 5 percent of these wastewater organics are assumed to degrade anaerobically. EPA used the IPCC default B_o of 0.25 kg COD/kg CH_4 and default MCF of 0.8 for anaerobic treatment to estimate the CH_4 produced from these on-site treatment systems. The USDA National Agricultural Statistics Service (USDA 2006) provided production data for potatoes, other vegetables, citrus fruit, non-citrus fruit, and grapes processed for wine. Outflow and BOD data, presented in Table 8-10, were obtained from EPA (1974) for potato, citrus fruit, and apple processing, and from the World Bank (1999) for all other sectors.

Table 8-10: 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	8.64	0.817
Fruit		
Apples	3.66	1.317
Citrus	10.11	0.317
Non-citrus	11.7	0.982
Grapes (for wine)	1.53	2.346

Domestic Wastewater N_2O Emission Estimates

N_2O emissions from domestic wastewater (wastewater treatment) were estimated using the updated IPCC (2006) methodology, including calculations that take into account N removal with sewage sludge, non-consumption and industrial 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.[9]
- The IPCC methodology uses annual, per capita protein consumption (kg protein/[person-year]). This number is likely to underestimate the amount of protein entering the sewer or septic system. Food (waste) that is not consumed is often washed down the drain, as a result of the use of garbage disposals. Also, bath and laundry water can be expected to contribute to N loadings. As a result, a factor of 1.4 for non-consumption N is introduced for each year in the Inventory.[10] Furthermore, a significant quantity of industrial wastewater (N) is

---

[9] The methodology for estimating the quantity of sewage sludge N not entering aquatic environments is described in Annex 3.11

[10] Metcalf & Eddy (1991) provide a typical influent nitrogen concentration of 40 mg/L Total Kjeldahl Nitrogen (TKN) for average wastewater from residences, which includes bathwater, laundry, and the use of garbage disposals. The factor for non-consumptive protein was estimated based on wastewater treated in 1990, the percent of population serviced by centralized treatment systems, and the per capita TKN loading, resulting in a factor of 1.4.

co-discharged with domestic wastewater. To account for this, a factor of 1.25 is used.[11]

- Small amounts of gaseous nitrogen oxides are formed as by-products in the conversion of nitrate to N gas in anoxic biological treatment systems. Approximately 7 grams N_2O is generated per capita per year if wastewater treatment includes nitrification and denitrification (Scheehle and Doorn 2001). Analysis of the 2000 CWNS shows 88 treatment plants in the United States, serving a population of 2,636,668 persons, with denitrification as one of their unit operations. Based on an emission factor of 7 grams/capita/year, approximately 17.5 metric tons of additional N_2O may have been emitted via denitrification in 2000. Similar analysis was done for each year in the Inventory using data from CWNS on the amount of wastewater in centralized systems treated in denitrification units.

With the modifications described above, N_2O emissions from domestic wastewater were estimated using the following methodology:

$$N_2O_{TOTAL} = N_2O_{PLANT} + N_2O_{EFFLUENT}$$

$$N_2O_{PLANT} = N_2O_{NIT/DENIT} + N_2O_{WOUT\ NIT/DENIT}$$

$$N_2O_{NIT/DENIT} = [(US_{POPND}) \times EF_2] \times 1/10\text{^}9$$

$$N_2O_{WOUT\ NIT/DENIT} = \{[(US_{POP} \times WWTP) - US_{POPND}] \times EF_1\} \times 1/10\text{^}9$$

$$N_2O_{EFFLUENT} = \{[(US_{POP} \times Protein \times F_{NPR} \times F_{NON\text{-}CON} \times F_{IND\text{-}COM}) - N_{SLUDGE}] \times EF_3 \times 44/28\} \times 1/10\text{^}6$$

where,

N_2O_{TOTAL} = Annual emissions of N_2O

N_2O_{PLANT} = N_2O emissions from centralized wastewater treatment plants

$N_2O_{NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants with nitrification/denitrification

$N_2O_{WOUT\ NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants without nitrification/denitrification

$N_2O_{EFFLUENT}$ = N_2O emissions from wastewater effluent discharged to aquatic environments

US_{POP} = U.S.popul ation

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)

EF_2 = Emission factor (7 g N_2O/person-year)

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

$F_{IND\text{-}COM}$ = Factor for industrial and commercial co-discharged protein into the sewer system

N_{SLUDGE} = N removed with sludge, kg N/yr

EF_3 = Emission factor (0.005 kg N_2O-N/kg sewage-N produced)

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 2006a) 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 1993, 1995, 1997, 1999, 2001, and 2003 American Housing Survey (U.S. Census 2006b). Data for intervening years were obtained by linear interpolation. The emission factor (EF_1) to estimate emissions from wastewater treatment was taken from IPCC (2006a). Data on annual per capita protein intake were provided by the United Nations Food and Agriculture Organization for the 1990 to 2003 time frame (FAO 2006). Protein consumption data for 2004 and

---

[11] The type, composition, and quantity of this co-discharged wastewater vary greatly between municipalities. Metcalf & Eddy (1991) provide a range of influent nitrogen concentrations of 20 to 85 mg/L TKN (average 55) for combined residential and industrial wastewater, while residential wastewater loading was roughly estimated at 40 mg TKN/liter (see previous footnote). Until better data become available, the amount of N in wastewater is increased by 10 mg/L to account for industrial co-discharge (factor of 1.25).

Table 8-11: U.S. Population (Millions) and Average Protein Intake [kg/(person-year)]

Year	Population	Protein
1990	254	39.2
1995	271	40.0
2000	287	41.6
2001	289	41.3
2002	292	41.3
2003	295	41.7
2004	297	41.9
2005	300	42.1

Source: U.S. Census Bureau (2006a), FAO (2006).

2005 were extrapolated from data for 1990 through 2003. Table 8-11 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 newly-revised 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). An estimate for the nitrogen 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.

Uncertainty

The overall uncertainty associated with both the 2005 CH_4 and N_2O emissions 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 included that of numerous input variables used to model emissions from domestic wastewater, and wastewater from the pulp and paper industry, meat and poultry processing, as well as from fruits, vegetables and juices processing. Uncertainty associated with the parameters used to estimate N_2O emissions included 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 8-12. CH_4 emissions from wastewater treatment were estimated to be between 15.8 and 37.3 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 38 percent below to 47 percent above the 2005 emissions estimate of 25.4 Tg CO_2 Eq. N_2O emissions from wastewater treatment were estimated to be between 1.7 and 15.4 Tg CO_2 Eq., which indicates a range of approximately 79 percent below to 93 percent above the actual 2005 emissions estimate of 8.0 Tg CO_2 Eq.

Recalculations Discussion

The 2005 estimates for CH_4 emissions from domestic wastewater include two major methodological refinements and one major data change. First, CH_4 emissions were estimated from four distinct source categories (septic systems, centrally treated aerobic systems, centrally treated anaerobic systems, and anaerobic digesters) rather than calculating an overall percentage of wastewater treated anaerobically from which to calculate emissions. Calculating emissions from anaerobic digesters constitutes the second methodological refinement to the Inventory. Emissions from anaerobic digesters were included to account for the increasing number of facilities that produce and use digester

Table 8-12: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Wastewater Treatment ($Tg CO_2$ Eq. and Percent)

Source	Gas	2005 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
Wastewater Treatment	CH_4	25.4	15.8	37.3	-38%	+47%
Domestic	CH_4	17.0	8.6	28.2	-49%	+66%
Industrial	CH_4	8.4	4.6	13.5	-45%	+60%
Domestic Wastewater Treatment	N_2O	8.0	1.7	15.4	-79%	+93%

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

biogas. The major data adjustment for the current inventory estimates involves the BOD per capita rate. In previous inventories, the BOD per capita rate varied across the time series. However, the 2005 estimates employ a standard value for the BOD per capita rate (0.09 kg/capita/day). This change resulted in varying differences in emissions estimates over time, ranging from an increase of 52 percent (1990) to a decrease of 15 percent (2004).

For industrial wastewater, production data for the entire time series were updated and other factors, such as wastewater outflow, BOD, and percent of waste treated anaerobically, were revised. Production data for potato processing, which accounts for about 45 percent of all vegetable processing in the United States, and about 25 percent of all fruit and vegetable processing, had not been included in previous inventories. However, the increase in industrial wastewater emissions due to the inclusion of potatoes was offset by other changes made to the Inventory. Flow and BOD data for fruits and vegetable processing wastewater were updated to reflect commodity-specific data, which resulted in a decrease in emissions. In addition, the amount of meat and poultry processing wastewater treated on site anaerobically was substantially revised. Previously, it was assumed that all wastewater from meat and poultry processing was treated anaerobically. However, data from EPA's Office of Water and from U.S. Poultry and Egg Association became available to show that indirect dischargers do not treat wastewater anaerobically. Therefore, the percent of waste treated anaerobically was reduced (to 33 percent for meat processors and 25 percent for poultry processors), which resulted in a significant decrease in emission estimates. These changes resulted in overall decreases of industrial wastewater emissions between 45 and 50 percent across the time series.

Overall, the CH_4 emission estimates for wastewater treatment are on average 17 percent lower than the previous Inventory.

For N_2O emissions from domestic wastewater, minor changes were made to the time series to include more specific estimates of the percent of U.S. population using centralized wastewater treatment, and a factor was introduced to account for the amount of biological denitrification occurring at centralized treatment plants. The calculation estimates for protein consumed were updated for the entire time series. These improvements resulted in minor decreases to the emission estimates across the time series, from 3 to 4 percent.

Finally, the default factor for N_2O emissions from N in effluent discharged to aquatic environments was updated from 0.01 to 0.005 kg N_2O -N/kg sewage-N, which resulted in a decrease of approximately 50 percent in emission estimates over the time series compared to the previous Inventory. The effect of all changes was an overall decrease in emission estimates from 50.1 to 51.4 percent across the time series.

Overall, emissions from wastewater treatment and discharge (CH_4 and N_2O) decreased by an average of 28 percent from the previous Inventory.

Planned Improvements Discussion

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 designation of systems as aerobic or anaerobic could be further refined to 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. Currently it is assumed that all aerobic 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 are currently being pursued.

Currently, BOD removal is not explicitly included in inventory calculations. The appropriateness of including a factor to account for BOD that is not removed through treatment and therefore does not contribute to CH_4 emissions is being investigated.

The methodology to estimate emissions for industrial wastewater currently accounts for pulp and paper, meat and poultry processing, and fruits and vegetables processing wastewater treatment. Information is currently being collected on ethanol production in the United States to determine if this should be included in future Inventories.

With respect to estimating N_2O emissions, the default emission factor for N_2O from wastewater effluent has a high uncertainty. The IPCC recently updated this factor; however, future research may identify new studies that include updated data. The factor that accounts for non-sewage nitrogen in wastewater (bath, laundry, kitchen, industrial components) also has a high uncertainty. Obtaining data on the changes in average influent nitrogen 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. In addition, more research may be conducted to update the protein consumption data.

8.3. Waste Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of indirect greenhouse gas emissions. Total emissions of NO_x, CO, and NMVOCs from waste sources for the years 1990 through 2005 are provided in Table 8-13.

Methodology

These emission estimates were obtained from preliminary data (EPA 2006), 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 basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data 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.

Activity data were used in conjunction with emission factors, which 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

No quantitative estimates of uncertainty were calculated for this source category. Uncertainties in these estimates, however, are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.

Table 8-13: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
NO_x	**+**	**1**	**2**	**2**	**2**	**2**	**2**	**2**
Landfills	+	1	2	2	2	2	2	2
Wastewater Treatment	+	+	+	+	+	+	+	+
Miscellaneous[a]	+	1	+	+	+	+	+	+
CO	**1**	**2**	**8**	**8**	**7**	**7**	**7**	**7**
Landfills	1	2	7	7	6	6	6	7
Wastewater Treatment	+	+	1	1	+	+	+	+
Miscellaneous[a]	+	1	+	+	+	+	+	+
NMVOCs	**673**	**731**	**119**	**122**	**116**	**116**	**116**	**116**
Wastewater Treatment	57	61	51	53	50	50	50	50
Miscellaneous[a]	558	602	46	46	44	44	44	44
Landfills	58	68	23	23	22	22	22	22

[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.

9. Other

The United States does not report any greenhouse gas emissions under the “other” Intergovernmental Panel on Climate Change (IPCC) 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 Intergovernmental Panel on Climate Change (IPCC) *Good Practice Guidance* (IPCC 2000), which states, "It is good practice to recalculate historic emissions when methods are changed or refined, when new source categories are included in the national inventory, or when errors in the estimates are identified and corrected."

The results of all methodology changes and historical data updates are presented in this section; detailed descriptions of each recalculation are contained within each source's description contained in this report, if applicable. Table 10-1 summarizes the quantitative effect of these changes on U.S. greenhouse gas emissions and Table 10-2 summarizes the quantitative effect on U.S. sinks, both relative to the previously published U.S. Inventory (i.e., the 1990 through 2004 report). These tables present the magnitude of these changes in units of teragrams of carbon dioxide equivalent (Tg CO_2 Eq.). In addition to the changes summarized by the tables below, the following sources and gases were added to the current Inventory:

- methane (CH_4) emissions from Ferroalloy Production;
- CH_4 and nitrous oxide (N_2O) emissions from Forest Land Remaining Forest Land to account for emissions from forest fires;
- CO_2 emissions from Silicon Carbide Production; and
- CH_4 emissions from Silicon Carbide Consumption.

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 2004) has been recalculated to reflect the change, per IPCC (2000). Changes in historical data are generally the result of changes in statistical data supplied by other agencies.

The following emission sources, which are listed in descending order of absolute average annual change in emissions between 1990 and 2004, underwent some of the most important methodological and historical data changes. A brief summary of the recalculation and/or improvement undertaken is provided for each emission source.

- *Agricultural Soil Management*. Changes occurred as a result of (1) modifying nitrogen (N) inputs to be consistent with the agricultural soil carbon (C) inventory, (2) modeling within-county variation in soil characteristics and weather, and (3) incorporating revised methods and emission factors from IPCC (2006). Overall, changes resulted in an average annual increase in N_2O emissions from agricultural soil management of 90.4 Tg CO_2 Eq. (33 percent) for the period 1990 through 2004.

Table 10-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2001	2002	2003	2004
CO_2	**56.4**	**59.3**	**75.5**	**47.8**	**76.9**	**74.9**	**76.3**
Fossil Fuel Combustion	27.6	33.3	51.2	24.8	55.5	53.4	56.5
Non-Energy Uses of Fossil Fuels	0.1	0.4	0.3	0.3	(1.1)	(2.2)	(3.2)
Natural Gas Systems	27.9	24.8	23.6	22.7	23.4	22.4	22.2
Cement Manufacture	NC	NC	NC	NC	NC	NC	+
Lime Manufacture	+	+	+	+	+	+	+
Limestone and Dolomite Use	+	NC	NC	NC	NC	NC	NC
Soda Ash Manufacture and Consumption	NC	NC	NC	NC	NC	NC	NC
CO_2 Consumption	0.6	0.6	0.5	+	+	+	+
Municipal Solid Waste Combustion	+	+	+	(0.3)	(0.3)	0.1	0.8
Titanium Dioxide Production	NC	NC	NC	NC	NC	NC	NC
Aluminum Production	(0.2)	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)
Iron and Steel Production	+	+	(0.2)	0.1	+	+	+
Ferroalloy Production	0.2	0.2	0.2	0.1	0.1	0.1	0.1
Ammonia Production and Urea Application	NC	NC	+	+	(0.7)	0.9	+
Phosphoric Acid Production	NC	NC	NC	NC	NC	NC	NC
Petrochemical Production	NC	NC	NC	NC	NC	NC	NC
Silicon Carbide Production and Consumption	0.3	0.2	0.1	0.1	0.1	0.1	0.1
Lead Production	NC	NC	NC	NC	NC	NC	NC
Zinc Production	+	+	+	+	+	+	+
Net CO_2 Flux from Land Use, Land-Use Change, and Forestry	*197.4*	*(213.6)*	*2.8*	*0.5*	*(43.3)*	*(37.1)*	*(44.7)*
International Bunker Fuels[a]	*0.2*	+	*(0.2)*	*(0.3)*	*(0.4)*	*(0.4)*	*2.7*
Wood Biomass and Ethanol Consumption[a]	*2.6*	*(5.1)*	*1.5*	*2.7*	*10.0*	*7.5*	*13.6*
CH_4	**(9.0)**	**(10.3)**	**(3.3)**	**(12.6)**	**(10.1)**	**(15.1)**	**(16.5)**
Stationary Combustion	0.2	(0.3)	0.1	0.2	0.6	0.5	0.7
Mobile Combustion	+	+	+	(0.1)	(0.1)	(0.2)	(0.2)
Coal Mining	+	0.7	(0.4)	+	(0.5)	(2.8)	(1.8)
Abandoned Underground Coal Mines	NC	NC	0.1	0.1	0.1	0.1	0.1
Natural Gas Systems	(2.3)	+	(0.1)	(0.2)	(0.4)	(1.0)	0.2
Petroleum Systems	+	+	+	+	+	(0.1)	(0.3)
Petrochemical Production	(0.3)	(0.4)	(0.5)	(0.4)	(0.4)	(0.4)	(0.5)
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production	NC	NC	NC	NC	NC	NC	NC
Ferroalloy Production[b]	+	+	+	+	+	+	+
Enteric Fermentation	(2.2)	(2.4)	(2.2)	(2.2)	(2.1)	(2.1)	(2.1)
Manure Management	(0.3)	(1.0)	0.7	1.3	1.8	1.3	0.3
Rice Cultivation	NC	NC	NC	NC	NC	+	+
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Forest Land Remaining Forest Land[b]	7.1	4.0	14.0	6.0	10.4	8.1	6.9
Landfills	(11.3)	(6.2)	(7.1)	(8.5)	(9.4)	(7.5)	(8.8)
Wastewater Treatment	+	(4.8)	(7.9)	(8.8)	(10.0)	(11.0)	(11.3)
International Bunker Fuels[a]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	+
N_2O	**87.1**	**30.0**	**83.6**	**89.7**	**71.8**	**73.7**	**58.5**
Stationary Combustion	+	(0.1)	+	+	0.2	0.1	0.2
Mobile Combustion	0.3	0.3	0.1	(0.2)	(0.4)	(1.0)	(1.6)
Adipic Acid Production	NC	NC	NC	NC	NC	NC	NC
Nitric Acid Production	NC	NC	NC	NC	+	NC	(0.6)
Manure Management	(7.6)	(8.1)	(8.3)	(8.3)	(8.3)	(8.2)	(8.3)
Agricultural Soil Management	100.8	45.3	98.6	106.0	88.3	91.0	77.3
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Wastewater Treatment	(6.5)	(7.3)	(7.9)	(8.0)	(8.0)	(8.0)	(8.1)
N_2O Product Usage	NC	NC	NC	NC	(0.5)	(0.5)	(0.5)
Municipal Solid Waste Combustion	NC	NC	NC	(0.1)	(0.1)	(0.1)	(0.1)
Settlements Remaining Settlements	(0.5)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.5)
Forest Land Remaining Forest Land	0.7	0.4	1.4	0.6	1.0	0.8	0.7

Table 10-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.) (continued)

Gas/Source	1990	1995	2000	2001	2002	2003	2004
International Bunker Fuels[a]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	+
HFCs, PFCs, and SF_6	**(1.4)**	**8.6**	**9.1**	**8.9**	**10.3**	**11.6**	**10.9**
Substitution of Ozone Depleting Substances	(0.1)	8.1	9.7	9.9	10.7	12.0	11.2
Aluminum Production	0.1	(0.1)	(0.4)	(0.5)	+	+	+
HCFC-22 Production	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC	NC
Electrical Transmission and Distribution	(1.5)	0.6	(0.1)	(0.3)	(0.2)	(0.2)	(0.2)
Magnesium Production and Processing	NC	NC	(0.2)	(0.2)	(0.2)	(0.1)	(0.1)
Net Change in Total Emissions[a]	**133.1**	**87.7**	**164.9**	**133.8**	**148.8**	**145.1**	**129.2**
Percent Change	**6.4%**	**-2.1%**	**2.7%**	**2.2%**	**1.7%**	**1.7%**	**1.3%**

+ Absolute value does not exceed 0.05 Tg CO_2 Eq. or 0.05 percent.

NC (No Change)

[a] Totals exclude net CO_2 flux from Land Use, Land-Use Change, and Forestry, and emissions from International Bunker Fuels and Wood Biomass and Ethanol Consumption.

[b] New source category relative to previous Inventory.

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

Table 10-2: Revisions to Net Flux of CO_2 to the Atmosphere 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	1995	2000	2001	2002	2003	2004
Forest Land Remaining Forest Land	174.9	(228.9)	(7.7)	(11.7)	(53.5)	(51.2)	(60.1)
Cropland Remaining Cropland	5.0	(11.0)	(10.4)	(10.3)	(10.3)	(9.6)	(10.4)
Land Converted to Cropland	7.2	10.0	10.0	10.0	10.0	10.0	10.0
Grassland Remaining Grassland	4.6	8.8	8.8	8.9	8.9	8.9	8.9
Land Converted to Grassland	3.1	4.8	4.8	4.8	4.8	4.8	4.8
Settlements Remaining Settlements	25.7	15.7	7.7	9.5	7.6	9.4	10.9
Other	(22.8)	(13.3)	(10.5)	(10.6)	(10.8)	(9.3)	(8.7)
Net Change in Total Flux	**197.6**	**(213.9)**	**2.8**	**0.5**	**(43.3)**	**(37.1)**	**(44.7)**
Percent Change	**21.7%**	**-34.8%**	**0.4%**	**0.1%**	**-5.6%**	**-4.8%**	**-5.7%**

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.

- *Net CO_2 Flux from Land Use, Land-Use Change, and Forestry.* Influential changes in the Land Use, Land-Use Change, and Forestry sector occurred in calculations for forest C stock and flux estimates. Changes for the period 1990 through 2004, as compared to the estimates presented in the previous Inventory, are based on the cumulative effects of (1) incorporating additional state and sub-state inventory data, and (2) adjusting total stock estimates used in earlier years to account for inclusion or removal of different ecological community types in subsequent state and sub-state inventory years. Overall, these changes, in combination with adjustments in the other sources/sinks within the sector, resulted in an average annual decrease in net flux of CO_2 to the atmosphere from the Land Use, Land-Use Change, and Forestry sector of 38.3 Tg CO_2 Eq. (7 percent) for the period 1990 through 2004. However, the most consequential changes from these recalculations occurred in 1990, which saw a 197.6 Tg CO_2 Eq. (21.7 percent) decrease in estimated sequestration.
- *CO_2 from Fossil Fuel Combustion.* The most important update that affected the historical estimates for CO_2 emissions from fossil fuel combustion was the change to the C oxidation factor for all fuel types to 100 percent. This change was made according to IPCC (2006) and impacted emission estimates for all fuel types. Additionally, silicon carbide used for petroleum coke manufacturing was reallocated to the Industrial Processes chapter. Overall, changes resulted in an average annual increase of 36.9 Tg CO_2 Eq. (0.7 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2004.

- *Natural Gas Systems*. The Inventory now contains estimates for non-combustion-related (vented, fugitive, flared) CO_2 emissions from the natural gas industry. The estimation uses the same activity and emission factors from the CH_4 emission estimates but adjusts the emission factors for the ratio of CO_2/CH_4 content of the natural gas. Efforts were made to ensure that there was no double-accounting of CO_2 emissions from other system inventories in the overall Inventory. Overall, changes resulted in an average annual increase in CO_2 emissions from natural gas systems of 24.4 Tg CO_2 Eq. (376 percent) for the period 1990 through 2004.
- *Manure Management*. A few changes have been incorporated into the overall methodology for the manure management emission estimates. State temperatures are now calculated using data from every county in the state. Another major change in methodology was using climate-specific CH_4 conversion factors for dry manure management systems. The percentage of dairy cattle, swine, and sheep on each type of manure management system was also updated for the current Inventory, based on farm size data from the 2002 USDA Census of Agriculture (USDA 2005e). Changes were also made to the current calculations involving animal population data. N_2O emission estimates from manure management systems have decreased for all years of the current Inventory compared to the previous Inventory due to the use of updated emission factors from IPCC (2006). Overall, the changes resulted in an average annual decrease in N_2O emissions from manure management of 8.1 Tg CO_2 Eq. (47 percent) for the period 1990 through 2004.
- *Substitution of Ozone Depleting Substances*. An extensive review of chemical substitution trends, market sizes, growth rates, and charge sizes, together with input from industry representatives, resulted in updated assumptions for the Vintaging Model, which is used to calculate emissions from this category. These changes resulted in an average annual increase in hydrofluorocabon (HFC) and perfluorocarbon (PFC) emissions from the substitution of ozone depleting substances of 7.6 Tg CO_2 Eq. (21 percent) for the period 1990 through 2004.
- *N_2O Emissions from Wastewater Treatment*. For N_2O emissions from domestic wastewater, a minor change made to the time series was to include more specific estimates of the percent of U.S. population that uses centralized wastewater treatment. Also, a factor was introduced to account for the amount of biological denitrification used at centralized treatment plants. The calculation estimates for protein consumed were updated for the entire time series. Additionally, the default factor for N_2O emissions from N in effluent discharged to aquatic environments was updated from 0.01 to 0.005 kg N_2O-N/kg sewage-N. Overall, the changes resulted in an average annual decrease in N_2O emissions from wastewater treatment of 7.5 Tg CO_2 Eq. (51 percent) for the period 1990 through 2004.
- *Landfills*. For municipal solid waste landfills, changes to historical data resulted from the application of a more accurate integrated form of the first order decay model, and incorporating a delay time of 6 months. Another improvement was made in the estimate of CH_4 generation from industrial landfills, which was based on industrial production, waste disposal factors, and the first order decay model. Additionally, EIA, LMOP, and flare vendor databases were updated, affecting estimates of CH_4 recovery. Overall, changes resulted in an average annual decrease in CH_4 emissions from landfills of 7.5 Tg CO_2 Eq. (4.9 percent) for the period 1990 through 2004.
- *CH_4 Emissions from Wastewater Treatment*. Two methodological refinements and one major data change resulted in a decrease in CH_4 emissions from wastewater treatment for the period 1990 through 2004 relative to the previous Inventory. First, the current estimates are based on four distinct source categories (septic systems, centrally treated aerobic systems, centrally treated anaerobic systems, and anaerobic digesters), whereas in previous inventories, emissions were calculated based on an overall percentage of anaerobically treated wastewater. Calculating emissions from anaerobic digesters constitutes the second methodological refinement to this category. The major data adjustment involves the Biochemical Oxygen Demand (BOD) per capita rate. The current estimates employ a standard value for the BOD per capita rate across the time series (0.09 kg/capita/day). For industrial wastewater, production data for the entire time series were updated and other factors such as wastewater outflow, BOD, and percent of waste treated anaerobically, were revised. Overall, changes resulted in an average

annual decrease in CH_4 emissions from wastewater treatment of 5.6 Tg CO_2 Eq. (16.7 percent) for the period 1990 through 2004.

- *Wood Biomass and Ethanol Consumption*. Commercial wood consumption values were revised for the full timeseries, based on updated information from EIA's Commercial Building Energy Consumption Survey (EIA 2006). EIA (2006) also reported minor changes in wood consumption by the residential and industrial sectors for the full timeseries, and in ethanol consumption for 2001 through 2004. Overall, changes resulted in an average annual increase in emissions from wood biomass and ethanol consumption of 2.9 Tg CO_2 Eq. (1 percent) from 1990 through 2004.

11. References

Executive Summary

BEA (2006) *2005 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2005*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, DC. July 29, 2006. Available online at <http://www.bea.doc.gov/bea/dn1.htm>.

EIA (2006a) *Monthly Energy Review, September 2006* and Unpublished Supplemental Tables on Petroleum Product detail. Energy Information Administration (EIA), U.S. Department of Energy, Washington, DC, DOE/EIA-0035(2006/09).

EIA (2006b) *International Energy Annual 2004*. Energy Information Administration (EIA), U.S. Department of Energy, Washington, DC. Updated May–July 2006. Available online at <http://www.eia.doe.gov/iea/carbon.html>.

EPA (2006) *Air Emissions Trends—Continued Progress Through 2005*. U.S. Environmental Protection Agency (EPA), Washington, DC. December 19, 2006. Available online at <http://www.epa.gov/air/airtrends/index.html>.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data between the Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency (EPA). December 22, 2003.

Hofmann, D. (2004) *Long-lived Greenhouse Gas Annual Averages for 1979–2004*. NOAA/ESRL Global Monitoring Division, Boulder, CO.

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.

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 (2001) *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change (IPCC), 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, U.K.

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.

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, U.K.

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 (2006) U.S. Census Bureau International Database (IDB). Available online at <http://www.census.gov/ipc/www/idbnew.html>. Accessed August 15, 2006.

Introduction

Blasing and Jones (2004) *Current Greenhouse Gas Concentrations*. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. Oak Ridge, TN.

EPA (2005) *Air Emissions Trends—Continued Progress Through 2003*. U.S. Environmental Protection Agency, Washington, DC. Available online at <http://www.epa.gov/airtrends/econ-emissions.html>.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data between the Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency (EPA). December 22, 2003.

IPCC (2001) *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change (IPCC), 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, U.K.

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.

IPCC (1999) *Aviation and the Global Atmosphere*. Intergovernmental Panel on Climate Change; Penner, J.E., et al., eds.; Cambridge University Press. Cambridge, U.K.

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, U.K.

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.

NRC (2001) *Climate Change Science: An Analysis of Some Key Questions*. Committee of the Science of Climate Change, National Research Council (NRC). Available online at <http://books.nap.edu/html/climatechange>.

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. Subsidiary Body for Scientific and Technical Advice. (FCCC/SBSTA/2006/9) 18 August 2006.

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.

WMO (1999) *Scientific Assessment of Ozone Depletion, Global Ozone Research and Monitoring Project–Report No. 44*, World Meteorological Organization, Geneva, Switzerland.

Trends in Greenhouse Gas Emissions

BEA (2006) 2005 *Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2005*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, DC. July 29, 2006. Available online at <http://www.bea.doc.gov/bea/dn1.htm>.

Duffield, J. (2005) Telephone and email conversations between Lauren Flinn of ICF International and Jim Duffield, Office of Energy Policy and New Uses, USDA. April and December.

EIA (2006a) *Monthly Energy Review*, September 2006 and Unpublished Supplemental Tables on Petroleum Product detail. Energy Information Administration, U.S. Department of Energy, Washington, DC, DOE/EIA-0035(2006/09).

EIA (2006b) *Short-Term Energy Outlook*. Energy Information Administration, U.S. Department of Energy, Washington, DC. December.

EIA. (2006c) *Annual Energy Review*. "Appendix A. Table A3: Approximate Heat Content of Petroleum Consumption." Energy Information Administration. Available online at <http://tonto.eia.doe.gov/bookshelf/SearchResults.asp?title=Annual+Energy+Review>

EIA (1991 through 2005) *Fuel Oil and Kerosene Sales*. "Table 22: Adjusted Sales for Farm Use: Distillate Fuel Oil and Kerosene; Sales for Electric Power and Oil Company Uses: Distillate Fuel Oil and Residual Fuel Oil, 2004." Energy Information Administration. U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov/pub/oil_gas/petroleum/data_publications/fuel_oil_and_kerosene_sales/historical/2004/foks_2004.html>.

EPA (2005) *Air Emissions Trends—Continued Progress Through 2003*. U.S. Environmental Protection Agency, Washington, DC. Available online at <http://www.epa.gov/airtrends/econ-emissions.html>.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data between the Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency (EPA). December 22, 2003.

Hoffman, D. (2004) *Long-lived Greenhouse Gas Annual Averages for 1979–2004*. NOAA/ESRL Global Monitoring Division, Boulder, CO.

IPCC (2001) *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change (IPCC), 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, U.K.

Keeling, C.D. and T.P. Whorf (2005) "Atmospheric CO_2 records from sites in the SIO air sampling network." In *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. U.S. Department of Energy, Oak Ridge, TN., U.S.A. Available online at <http://cdiac.esd.ornl.gov/trends/co2/sio-keel.htm>.

U.S. Census Bureau (2006) U.S. Census Bureau International Database (IDB). Available online at <http://www.census.gov/ipc/www/idbnew.html>. Accessed August 15, 2006.

Energy

EIA (2006) *International Energy Annual 2004*. Energy Information Administration, U.S. Department of Energy, Washington, DC. Updated May–July 2006. Available online at <http://www.eia.doe.gov/iea/carbon.html>.

Carbon Dioxide Emissions from Fossil Fuel Combustion

AAR (2005) *Railroad Facts*, 2002 Ed. Policy and Economics Department, Association of American Railroads, Washington, DC.

BEA (2006) *2005 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2005*. Bureau of Economic Analysis, U.S. Department of Commerce, Washington, DC. July 29, 2006. Available online at <http://www.bea.doc.gov/bea/dn1.htm>.

BEA (1991 through 2006) Unpublished BE-36 survey data. Bureau of Economic Analysis, U.S. Department of Commerce, Washington, DC.

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.

Corathers, L. (2006) Personal communication between Erin Fraser of ICF International and Lisa Corathers, Commodity Specialist, U.S. Geological Survey. October, 2006.

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 (2006) 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 2006) Unpublished *Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries*. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce, Washington, DC. Form-563.

DOE (1993 through 2004) *Transportation Energy Data Book*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. ORNL-6959.

DOT (1991 through 2006) *Fuel Cost and Consumption*. Federal Aviation Administration, U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, DC. DAI-10.

EFMA (1995) *Production of Ammonia*. European Fertilizer Manufacturers Association. March 1, 1995.

EIA (2006a) *Annual Energy Review 2005*. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0384(2005). July 2006.

EIA (2006b) *Monthly Energy Review, December 2006* and Unpublished Supplemental Tables on Petroleum Product detail. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2006/12).

EIA (2006c) *Emissions of Greenhouse Gases in the United States 2005, Draft Report*. Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE-EIA-0573(2005).

EIA (2006d) "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>. Table 3.1.

EIA (2006e) *Natural Gas Annual 2005*. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0131(04). December 2006.

EIA (2006f) *Short-Term Energy Outlook*. Energy Information Administration, U.S. Department of Energy, Washington, DC. December 2006.

EIA (2006g) Personal Communication between Joseph Aamidor of ICF International and Joel Lou, Energy Information Administration. Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island. September 19, 2006.

EIA (2005a) *Quarterly Coal Report*. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0121.

EIA (2005b) *Manufacturing Consumption of Energy 2002*. Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA (2004) *Natural Gas Annual*. 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 (2001a) *Historical Natural Gas Annual, 1930–2003*. Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA (2001b) *U.S. Coal, Domestic and International Issues*. Energy Information Administration, U.S. Department of Energy, Washington, DC. March 2001.

EIA (1991 through 2005) *Fuel Oil and Kerosene Sales*. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0535-annual.

EPA (2005) *Air Emissions Trends—Continued Progress Through 2004*. U.S. Environmental Protection Agency, Washington, DC. August 18, 2005. Available online at <http://www.epa.gov/airtrends/2005/econ-emissions.html>.

EPA (2004) NONROAD Model. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at <http://www.epa.gov/otaq/ngm.htm>.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data between the Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. December 22, 2003.

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 (2005) *FAA Aerospace Forecasts Fiscal Years 2005–2016*. Table 32 "General Aviation Aircraft Fuel Consumption," Federal Aviation Administration. Available online at <http://www.faa.gov/data_statistics/aviation/aerospace_forecasts/2005-2016/>.

FHWA (1996 through 2006) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, DC. Report FHWA-PL-96-023-annual.

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>.

FRB (2006) *Industrial Production and Capacity Utilization*. Federal Reserve Board, Federal Reserve Statistical Release, G.17. November 7, 2006 Annual Revision. Available online at <http://www.federalreserve.gov/releases/G17/table1_2.htm>.

Gambogi, J. (2006) Personal communication between Erin Fraser of ICF International and Joseph Gambogi, Commodity Specialist, U.S. Geological Survey. September 2006.

Grillot, M. (2006) Personal communication between Lauren Pederson of ICF International and Mike Grillot, Energy Information Administration. *U.S. Territories Fossil Fuel Consumption, 1990–2005*. Unpublished data developed by the U.S. Energy Information Administration, Washington, DC.

Johnson, G. L. (2006) Personal communication between Erin Fraser of ICF International and Greg Johnson, Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA). October, 2006.

Kass, N. (2005) Personal communication between Erin Fraser of ICF International and Nathaniel Kass, Energy Information Administration, U.S. Department of Energy. October 2005.

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.

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 A. Pippin (1990) "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity." *Energy Systems and Policy*, 14(4):323.

Onder, H. and E.A. Bagdoyan (1993) *Everything You've Always Wanted to Know about Petroleum Coke*. Allis Mineral Systems.

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 Energy Information Administration (EIA), Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, DC. June 22, 2001.

USAA (2006) *Primary Aluminum Statistics*. Aluminum Association, Washington, DC. January 2006.

USAF (1998) *Fuel Logistics Planning*. U.S. Air Force document AFPAM23-221. May 1, 1998.

U.S. Census Bureau (2006) *Current Industrial Reports Fertilizer and Related Chemicals Summary: 2005*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2005) *Current Industrial Reports Fertilizer Materials and Related Products: Fourth Quarter Report 2004 Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2004) *International Data Base (IDB): World Population Information*. Washington, DC. September 30, 2006. Available online at <http://www.census.gov/ipc/www/idbnew.html>.

U.S. Census Bureau (1991 through 1994) *Current Industrial Reports Fertilizer Materials Annual Report*. Report No. MQ28B.

USGS (1998 through 2002) *Mineral Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Mineral Industry Surveys: Aluminum Annual Review 1994*. U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines, Washington, DC. May 1995.

USGS (1991a through 2005a) *Silicon: Annual Report*. U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines, Washington, DC.

USGS (1991b through 2005b) *Mineral Yearbook: Titanium Annual Report*. U.S. Geological Survey, Reston, VA.

USITC (2006) USITC *Interactive Tariff and Trade DataWeb*. United States International Trade Commission, U.S. Department of Commerce, Washington, DC. Available online at <http://dataweb.usitc.gov>.

U.S. International Trade Commission (2006) *HTS-2707995010: Carbon Black Feedstock*. U.S. Domestic Exports. Available online at <http://dataweb.usitc.gov>.

U.S. International Trade Commission (2004) *HTS-2707: Oils and Other Products of the Distillation of High Temperature Coal Tar; Similar Products in which the Weight of Aromatic Constituents Predominate*. U.S. General Imports. Available online at <http://dataweb.usitc.gov>.

Carbon Emitted from Non-Energy Uses of Fossil Fuels

ACC (2006) *Guide to the Business of Chemistry, 2005*. American Chemistry Council.

ACC (2005) *Guide to the Business of Chemistry, 2003*. American Chemistry Council.

Adler, B. (2001) Personal communication between Robert Lanza of ICF International and Bob Adler, U.S. Energy Information Administration (EIA). September 14, 2001.

APC (2006) APC Year-End Statistics for 2005. American Plastics Council (APC) website. Available online at <http://www.americanplasticscouncil.org/benefits/economic/economic.html>. Accessed April 2006.

APC (2005) APC Year-End Statistics for 2004. American Plastics Council website. Available online at <http://www.americanplasticscouncil.org/benefits/economic/economic.html>. Accessed April 2005.

APC (2004) APC Year-End Statistics for 2003. American Plastics Council website. Available online at <http://www.americanplasticscouncil.org/benefits/economic/economic.html>. Accessed March 2004.

APC (2003) APC Year-End Statistics for 2002. American Plastics Council website. Available online at <http://www.americanplasticscouncil.org/benefits/economic/economic.html>. Accessed June 2003.

APC (2001) as reported in ACS (2001) "Production: slow gains in output of chemicals and products lagged behind U.S. economy as a whole." *Chemical & Engineering News*, 79(26). June 25, 2001. Available online at <http://pbus.acs.org/cen>.

APC (2000) as reported in "Facts & Figures for the Chemical Industry." *Chemical and Engineering News*, 78(26). June 26, 2000. American Plastics Council, Arlington, VA. Available online at <http://www.plasticsindustry.org/industry/stat3.htm>.

Bank of Canada (2006) Financial Markets Department Year Average of Exchange Rates. Available online at <http://www.bankofcanada.ca/en/rates/exchange_avg_pdf.html>.

CMA (1999) *U.S. Chemical Industry Statistical Handbook*. Chemical Manufacturer's Association, Washington, DC.

Connolly, U. (2000) Personal communication between Suzanne Bratis of ICF International and Una Connelly, National Asphalt Pavement Association. August 2000.

EIA (2006) *Monthly Energy Review*, December 2006 and Unpublished Supplemental Tables on Petroleum Product detail. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2006/12).

EIA (2005) *EIA Manufacturing Consumption of Energy (MECS) 2002*. U.S. Department of Energy, Energy Information Administration, Washington, DC.

EIA (2001) *Manufacturing Energy Consumption Survey (MECS) 1998*. U.S. Department of Energy, Energy Information Administration, Washington, DC. Available online at <http://www.eia.doe.gov/emeu/mecs/mecs98/datatables/contents.html>.

EIA (1997) *Manufacturing Energy Consumption Survey (MECS) 1994*. U.S. Department of Energy, Energy Information Administration, Washington, DC. December 1997. DOE/EIA-0512(94).

EIA (1994) *Manufacturing Energy Consumption Survey (MECS) 1991*. U.S. Department of Energy, Energy Information Administration, Washington, DC. December 1994. DOE/EIA-0512(91).

EIIP (1999) *Methods for Estimating Greenhouse Gas Emissions from Combustion of Fossil Fuels*. Emissions Inventory Improvement Program: State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officials and U.S. Environmental Protection Agency, EIIP Document Series Volume VIII, Chapter 1, STAPPA/ALAPCO/EPA, Washington, DC. August 2000. Available online at <http://www.epa.gov/ttn/chief/eiip/viii01.pdf>. Accessed August 28, 2000.

EIIP (1998) "Area Sources." In *Asphalt Paving*. Emissions Inventory Improvement Program: State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officials and U.S. Environmental Protection Agency, EIIP Document Series Volume III, Chapter 17, STAPPA/ALAPCO/EPA, Washington, DC. August 2000. Available online at <http://www.epa.gov/ttn/chief/eiip/iii17.pdf>. Accessed July 27, 2000.

Eldredge-Roebuck, B. (2000) Personal communication between Joe Casola of ICF International and Brandt Eldredge-Roebuck, American Plastics Council. July 11, 2000.

EPA (2006a) *Air Emissions Trends—Continued Progress Through 2005*. U.S. Environmental Protection Agency, Washington, DC. December 19, 2006. Available online at <http://www.epa.gov/air/airtrends/index.html>.

EPA (2006b) *Biennial Reporting System (BRS) Database*. U.S. Environmental Protection Agency, Envirofacts Warehouse, Washington, DC. Available online at <http://www.epa.gov/enviro/html/brs/>.

EPA (2004a) *Biennial Reporting System (BRS)*. U.S. Environmental Protection Agency, Envirofacts Warehouse, Washington, DC. Available online at <http://www.epa.gov/enviro/html/brs/>.

EPA (2004b) *Pesticides Industry Sales and Usage: 2000 and 2001 Market Estimates*. U.S. Environmental Protection Agency, Office of Prevention, Pesticides and Toxic Substances, Washington, DC. Available online at <http://www.epa.gov/oppbead1/pestsales/>.

EPA (2002) *Pesticides Industry Sales and Usage, 1998 and 1999 Market Estimates*. U.S. Environmental Protection Agency, Office of Prevention, Pesticides and Toxic Substances, Washington, DC. Available online at <http://www.epa.gov/oppbead1/pestsales/99pestsales/market_estimates1999.pdf>. Accessed July 2003.

EPA (2001) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–1999*. U.S. Environmental Protection Agency, Office of Atmospheric Programs, Washington, DC. EPA 236-R-01-001.

EPA (2000a) *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 (2000b) *Hot Mix Asphalt Plants Emission Assessment Report (Draft Report)*, AP-42. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC. June 2000. Available online at <http://www.epa.gov/ttn/emc/asphalt/ea-report.pdf>. Accessed July 25, 2000.

EPA (1999) *Pesticides Industry Sales and Usage: 1996 and 1997 Market Estimates*. U.S. Environmental Protection Agency, Office of Prevention, Pesticides and Toxic Substances, Washington, DC. Available online at <http://www.epa.gov/oppbead1/pestsales/97pestsales/market_estimates1997.pdf>.

EPA (1998) *Pesticides Industry Sales and Usage, 1994 and 1995 Market Estimates*. U.S. Environmental Protection Agency, Office of Prevention, Pesticides and Toxic Substances, Washington, DC. Available online at <http://www.epa.gov/oppbead1/pestsales/95pestsales/market_estimates1995.pdf>. Accessed July 2003.

EPA (1995) *Asphalt Paving Operations*, AP-42. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

FEB (2006) Fiber Economics Bureau, as cited in C&EN (2006) *Production: Growth in the Norm*. Chemical & Engineering News, American Chemical Society. July 10, 2006. 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. July 11, 2005. 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 July 7, 2003. Available online at <http://www.cen-online.org>.

FEB (2001) as reported in "Production: slow gains in output of chemicals and products lagged behind U.S. economy as a whole." *Chemical and Engineering News*, Vol. 79(26). Fiber Economics Bureau, Washington, DC. June 25, 2001. Available online at <http://pubs.acs.org/cen/coverstory/7926/7926facts&figures.html>.

The Financial Planning Association (2006) Canada/US Cross-Border Tools: US/Canada Exchange Rates. Available from: <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, MD.

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) as reported in ACS (2001) "Facts & Figures for the Chemical Industry. *Chemical and Engineering News*, Vol. 78(26). June 26, 2000. International Institute of Synthetic Rubber Producers, Houston, Texas. Available online in IISRP's February 18, 2000, News Release: <http://www.iisrp.com/Press%20Releases/2000%20Press%20Releases/ASPR2000-2004.PDF>.

INEGI (2006) Producción bruta total de las unidades económicas manufactureras por Subsector, Rama, Subrama y Clase de actividad. Available online at <http://www.inegi.gob.mx/est/contenidos/espanol/proyectos/censos/ce2004/tb_manufacturas.asp>. Accessed August 15, 2006.

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.

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(4), 232-261.

Miller, T. (1999) *Material Safety Data Sheet, Carbon Black*. Continental Carbon Company. September 1, 1999. Available online at <http://www.continentalcarbon.com/downloads/MSDS.pdf>. Accessed October 10, 2003.

NPRA (2001) *Selected Petrochemical Statistics—U.S. Trade, Production and Consumption*. National Petrochemical & Refiners Association, Washington, DC.

PAN (2002) Pesticides Database. Pesticide Action Network North America. Available online at <http://www.pesticideinfo.org>. Accessed summer–fall 2003.

RMA (2006) *Scrap Tire Markets in the United States 2005 Edition*. Rubber Manufacturers Association, Washington, DC. November 2006.

RMA (2002) *U.S. Scrap Tire Markets 2001*. Rubber Manufacturers Association, Washington, DC. December 2002.

Schneider, S. (2007) E-mail communication between Sarah Shapiro of ICF International and Shelly Schneider, Franklin Associates, A Division of ERG. January 10, 2007.

SPI (2000) The Society of the Plastics Industry Website. Available online at <http://www.plasticsindustry.org/industry/stat3.htm>. Accessed June 28, 2000.

Statistics Canada (2006) Canadian Trade by Industry—NAICS Codes: NAICS 3252 - Resin, Synthetic Rubber, and Artificial and Synthetic Fibres and Filaments Manufacturing (NAICS 3252). Available online at <http://strategis.ic.gc.ca/sc_mrkti/tdst/tdo/tdo.php?headFootDir=%2Fsc_mrkti%2Ftdst%2Fheadfoot&naArea=&lang=30&searchType=CS&toFromCountry=CDN&currency=US&hSelectedCodes=%7C3252&period=&timePeriod=%7CCustom+Years&periodString=1990%7C1991%7C1992%7C1993%7C1994%7C1995%7C1996%7C1997%7C1998%7C1999%7C2000%7C2001%7C2002%7C2003&productBreakDown=Custom+Years&reportType=DS&productType=NAICS&areaCodeStrg=%7CAll&runReport_x=32&javaChart_x=&runGraph_x=&outputType=RPT&chartType=columnApp&grouped=GROUPED#tag>.

STMC (2003) *Scrap Tire Facts and Figures*. Scrap Tire Management Council of the Rubber Manufacturers Association, Washington, DC. Available online at <http://www.rma.org/scrap_tires/scrap_tire_markets/facts_and_figures/> and <http://www.rma.org/scrap_tires/scrap_tire_markets/scrap_tire_characteristics/>. Accessed July 7, 2003.

Tooly, L. (2001) Personal communication between Robert Lanza of ICF International and Lee Tooly, EPA’s Office of Air Quality Planning and Standards. Microsoft Access file sent in an email. August 20, 2001.

U.S. Census Bureau (2004) Soap and Other Detergent Manufacturing: 2002. Issued December 2004, document number EC02-31I-325611 (RV). Available online at <http://www.census.gov/prod/ec02/ec0231i325611.pdf>.

U.S. Census Bureau (2003) U.S International Trade Commission (USITC) Trade Dataweb. Available online at <http://dataweb.usitc.gov/>. Accessed fall 2002–spring 2003.

U.S. Census Bureau (1999) 1997 Economic Census, Manufacturing—Industry Series, Petroleum Lubricating Oil and Grease Manufacturing and Petroleum Refining. Document numbers EC97M-3241D and EC97M-3241A (2 reports).

U.S. International Trade Commission (2006) Available online at <http://dataweb.usitc.gov/>. Accessed September 27, 2006.

Wood, A. (2003) Compendium of Pesticide Common Names. Alan Wood’s Web Site. Available online at <http://www.alanwood.net/pesticides/index.html>. Accessed summer-fall 2003.

Stationary Combustion (excluding CO_2)

EIA (2006a) *Monthly Energy Review, September 2006* and Unpublished Supplemental Tables on Petroleum Product detail. Energy Information Administration, U.S. Department of Energy, Washington, DC, DOE/EIA-0035(2006/09).

EIA (2006b) *Annual Energy Review 2005*. Energy Information Administration, U.S. Department of Energy, Washington, DC, DOE/EIA-0384(2005). July.

EPA (2005) *Air Emissions Trends—Continued Progress Through 2004*. U.S. Environmental Protection Agency, Washington DC. August 18, 2005. Available online at <http://www.epa.gov/airtrends/2005/econ-emissions.html>.

EPA (2004) NONROAD Model. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at <http://www.epa.gov/otaq/ngm.htm>.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data between EPA OAP and EPA OAQPS. December 22, 2003.

Grillot, M. (2006) Personal communication. *U.S. Territories Fossil Fuel Consumption, 1990–2005*. Unpublished data developed by the U.S. Energy Information Administration, Washington, DC.

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.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

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 Energy Information Administration (EIA), Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, DC. 22 June.

Mobile Combustion (excluding CO_2)

AAR (2006) *Railroad Facts, 2006 Ed*. Policy and Economics Department, Association of American Railroads, Washington, DC.

ANL (2006) Argonne National Laboratory (2006) GREET model Version 1.7. June 2006.

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 (1991 through 2005) Unpublished BE-36 survey data. Bureau of Economic Analysis (BEA), U.S. Department of Commerce.

Benson, D. (2002 through 2004) Personal communication. Unpublished data developed by the Upper Great Plains Transportation Institute, North Dakota State University and American Short Line & Regional Railroad Association.

Browning, 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.

DESC (2006) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense.

DOC (1991 through 2006) 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.

DOE (1993 through 2006) *Transportation Energy Data Book*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. ORNL-6959.

DOT (1991 through 2006) *Fuel Cost and Consumption*. Federal Aviation Administration, U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, DC. DAI-10.

EIA (2006a) *Monthly Energy Review*, December 2006 and Unpublished Supplemental Tables on Petroleum Product detail. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2005/12).

EIA (2006b) *International Energy Annual*. World Petroleum Supply and Disposition, Table 3.1. Available online at <http://www.eia.doe.gov/iea/pet.html>.

EIA (2006c) Annual Energy Review 2005. Energy Information Administration, U.S. Department of Energy, Washington, DC. July 2006. DOE/EIA-0384(2005).

EIA (2004) Natural Gas Annual 2004. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0131(04).

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 2006) *Fuel Oil and Kerosene Sales*. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0535-annual.

EPA (2006a) 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 (2006b) Confidential engine family sales data submitted to EPA by manufacturers. Office of Transportation and Air Quality, U.S. Environmental Protection Agency.

EPA (2006c) Air Emissions Trends—Continued Progress Through 2005. U.S. Environmental Protection Agency, Washington, DC. December 19, 2006. Available online at <http://www.epa.gov/air/airtrends/index.html>.

EPA (2006d) NONROAD Model. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at <http://www.epa.gov/otaq/nonrdmdl.htm>.

EPA (2006e) 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 (2005) National Emissions Inventory Air Pollutant Emissions Trends Data. Available online at <http://www.epa.gov/ttn/chief/trends/index.html#tables>.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data between the Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency (EPA). December 22, 2003.

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 (2006a). *FAA Aerospace Forecasts Fiscal Years 2006–2017*. Table 30 "General Aviation Aircraft Fuel Consumption," Federal Aviation Administration. Available online at <http://www.faa.gov/data_statistics/aviation/aerospace_forecasts/2006-2017/media/FAA%20Aerospace%20Forecast.pdf/>.

FAA (2006b) Email correspondence containing aviation emissions estimates from the System for Assessing Aviation's Global Emissions (SAGE). August 2006.

FHWA (1996 through 2006) *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>.

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. Available online at <http://ist-socrates.berkeley.edu/~rael/Climatic_Change.pdf>.

Lou, J. (2002) Personal Communication with Joel Lou, Residual and Distillate Fuel Oil Consumption for Vessel (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island.

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) Personal communication, Class II and III Rail energy consumption, American Short Line and Regional Railroad Association.

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 (2006) *Annual Coal Report 1991–2005* (Formerly called *Coal Industry Annual*). Table 3, U.S. Department of Energy, Energy Information Administration, 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 Yanebi 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*. Pennsylvania State University, Department of Energy and Geo-Environmental Engineering, University Park, PA.

U.S. Department of Labor, Mine Health & Safety Administration (2006) 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.

Alabama (2006) Alabama State Oil and Gas Board. Available online at <http://www.ogb.state.al.us>.

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.

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 (2006a) "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 (2006b) Number of Producing Gas and Gas Condensate Wells, 1989–2004, Natural Gas Navigator. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://tonto.eia.doe.gov/dnav/ng/ng_prod_wells_s1_a.htm>.

EIA (2006c) "Table 2—Supply and Disposition of Dry Natural Gas in the United States 1999–2005." Natural Gas Monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov>.

EIA (2006d) "Table 3—Natural Gas Consumption in the United States." Natural Gas Monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov>.

EIA (2006e) 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 (2006f) "Table 7—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 (2006g) U.S. Imports by Country. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://tonto.eia.doe.gov/dnav/ng/ng_move_top.asp>.

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>.

EPA (2006) Natural Gas STAR Reductions 1990–2005. Natural Gas STAR Program.

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.

GRI (2001) Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. GRI-01/0136.

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 (2006) 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.

MMS (2006a) Gulf of Mexico Region Offshore Information. Minerals Management Service, U.S. Department of Interior. Available online at <http://www.gomr.mms.gov/homepg/offshore/fldresv/resvmenu.html>.

MMS (2006b) Gulf of Mexico Region Products/Free Data. Minerals Management Service, U.S. Department of Interior. Available online at <http://www.gomr.mms.gov/homepg/pubinfo/freeasci/platform/freeplat.html>.

MMS (2006c) *Gulfwide Emission Inventory Study for the Regional Haze and Ozone Modeling Effort*. OCS Study MMS 2004-072.

MMS (2006d) OCS Platform Activity. Minerals Management Service, U.S. Department of Interior. Available online at <http://www.mms.gov/stats>.

MMS (2006e) Pacific OCS Region. Minerals Management Service, U.S. Department of Interior. Available online at <http://www.gomr.mms.gov/homepg/pubinfo/pacificfreeasci/platform/pacificfreeplat.html>.

Montana (2006) 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 (2006a) Annual Gas Well Counts by State District. Available online at <http://www.emnrd.state.nm.us/emnrd/ocd/>.

New Mexico (2006b) Districts. Available online at <http://www.emnrd.state.nm.us/ocd/districts.htm>.

OGJ (1997–2006) “Worldwide Gas Processing.” *Oil & Gas Journal*, PennWell Corporation, Tulsa, OK.

Oklahoma (2006) Oklahoma Petroleum Information Center—Coalbed-Methane Completions database. Oklahoma Geological Survey. Available online at <http://www.ogs.ou.edu/OPIC/>.

OPS (2006a) 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 (2006b) Distribution Annuals Data. Office of Pipeline Safety, U.S. Department of Transportation, Washington, DC. Available online at <http://ops.dot.gov/stats/DT98.htm>.

Texas (2006a) Gas Well Counts by County. Texas Railroad Commission. Available online at <http://www.rrc.state.tx.us/divisions/og/statistics/wells/oggwlct.pdf>.

Texas (2006b) Oil Well Counts by County. Texas Railroad Commission. Available online at <http://www.rrc.state.tx.us/divisions/og/statistics/wells/ogowlct.pdf>.

Texas (2006c) *The Barnett Shale Regional Report*. Foster, Brad, Devon Energy, Texas Railroad Commission. Available online at <http://www.findarticles.com/p/articles/mi_qn4182/is_20050620/ai_n14675582>.

Texas (2006d) Oil and Gas District Boundaries. Texas Railroad Commission. Available online at <http://www.rrc.state.tx.us/divisions/og/ogmap.html>.

Utah (2006) 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>.

World Oil Magazine (2006a) “Outlook 2006: United States Producing gas wells.” 227(2). February 2006. Available online at <http://www.worldoil.com/magazine/MAGAZINE_DETAIL.asp?ART_ID=2800& MONTH_YEAR=Feb-2006>.

World Oil Magazine (2006b) “Outlook 2006: United States Producing oil wells.” 227(2). February 2006. Available online at <http://www.worldoil.com/magazine/magazine_detail.asp?ART_ID=2799>.

Wyoming (2006) Wyoming Oil and Gas Conservation Commission. Available online at <http://wogcc.state.wy.us/coalbedchart.cfm>.

Petroleum Systems

EIA (1995 through 2005) *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 2006) *Monthly Energy Review*. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov/emeu/mer>.

EIA (1990 through 2005) *Petroleum Supply Annual 1990–2005 Volume 1*. Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA (1990 through 2006) *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>.

EPA (2005) I*ncorporating the Mineral Management Service Gulfwide Offshore Activities Data System (GOADS) 2000 data into the methane emissions inventories*. U.S. Environmental Protection Agency, Prepared by ICF International. 2005.

EPA (1999) *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report)*. Office of Air and Radiation, U.S. Environmental Protection Agency, Prepared by ICF International. October 1999.

EPA (1996) *Methane Emissions from the U.S. Petroleum Industry (Draft)*. U.S. Environmental Protection Agency, Prepared by Radian. 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*. U.S. Environmental Protection Agency, Prepared by Radian. April 1996.

EPA & GRI (1996b) *Methane Emissions from the Natural Gas Industry, V11: Compressor Driver Exhaust*. U.S. Environmental Protection Agency, Prepared by Radian. April 1996.

EPA & GRI (1996c) *Methane Emissions from the Natural Gas Industry, V12: Pneumatic Devices*. U.S. Environmental Protection Agency, Prepared by Radian. April 1996.

EPA & GRI (1996d) *Methane Emissions from the Natural Gas Industry, V13: Chemical Injection Pumps*. U.S. Environmental Protection Agency, Prepared by Radian. April 1996.

MMS (2005a) *OCS Platform Activity*. Minerals Management Service, U.S. Department of Interior. Available online at <http://www.mms.gov/stats>.

MMS (2005b) *Platform Information and Data*. Minerals Management Service, U.S. Department of Interior. Available online at <http://www.gomr.mms.gov/homepg/pubinfo/freeasci/platform/freeplat.html>.

MMS (2005c). *Gulfwide Emission Inventory Study for the Regional Haze and Ozone Modeling Effort*. OCS Study MMS 2004-072.

MMS (2005d) Pacific OCS Region. Minerals Management Service, U.S. Department of Interior. Available online at <http://www.gomr.mms.gov/homepg/pubinfo/pacificfreeasci/platform/pacificfreeplat.html>.

MMS (2001) *Field and Reserve Information*. Minerals Management Service, U.S. Department of Interior. Available online at <http://www.gomr.mms.gov/homepg/offshore/fldresv/resvmenu.html>.

OGJ (2006) *Oil and Gas Journal 1990–2005*. Worldwide Refining Issue, January 1, 2006.

OGJ (2005) *Oil and Gas Journal 1990–2006*. Pipeline Economics Issue, August or September 2005.

United States Army Corps of Engineers (1995–2004) *Waterborne Commerce of the United States, Part 5: National Summaries*. U.S. Army Corps of Engineers, Washington, DC.

Municipal Solid Waste Combustion

De Soete, G.G. (1993) "Nitrous Oxide from Combustion and Industry: Chemistry, Emissions and Control." In Van Amstel, A. R. (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.

DeZan, D. (2000) Personal communication between Joe Casola of ICF International and Diane DeZan, Fiber Economics Bureau. August 4, 2000.

EPA (2006a) *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 (2006b) *Municipal Solid Waste in the United States: Facts and Figures for 2005*. 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 (2005a) *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2003*. 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/pubs/msw05rpt.pdf>.

EPA (2003) *Characterization of Municipal Solid Waste in the United States: 2001 Update (Draft)*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, DC.

EPA (2002) *Characterization of Municipal Solid Waste in the United States: 2000 Update*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, DC. EPA530-R-02-001.

EPA (2000a) *Characterization of Municipal Solid Waste in the United States: 1999 Update Fact Sheet (and Data Tables)*. Office of Solid Waste, U.S. Environmental Protection Agency, Washington, DC. EPA530-F-00-024.

EPA (2000b) *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.

EPA (1999) *Characterization of Municipal Solid Waste in the United States: 1998 Update*. Report No. EPA530-R-99-021. Office of Solid Waste, U.S. Environmental Protection Agency, Washington, DC.

EPA (1998) *Characterization of Municipal Solid Waste in the United States: 1997 Update*. Office of Solid Waste, U.S. Environmental Protection Agency, Washington, DC. EPA530-R-98-007.

EPA (1997) *Characterization of Municipal Solid Waste in the United States: 1996 Update*. Office of Solid Waste, U.S. Environmental Protection Agency, Washington, DC. EPA530-R-97-015.

EPA (1996) *Characterization of Municipal Solid Waste in the United States: 1995 Update*. Office of Solid Waste, U.S. Environmental Protection Agency, Washington, DC.

EPA (1995) *Compilation of Air Pollutant Emission Factors, AP-42*. Fifth Edition, Volume I: Stationary Point and Area Sources, Introduction, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC. October 1995.

FEB (2006) Fiber Economics Bureau, as cited in C&EN (2006) "Production: Growth in Most Regions," Chemical & Engineering News, American Chemical Society, July 11, 2006. Available online at <http://www.cen-online.org>.

Glenn, Jim (1999) "11th Annual BioCycle Nationwide Survey: The State of Garbage in America." *BioCycle*, JG Press, Emmaus, PA. April 1999.

Goldstein, N. and C. Madtes (2001) "13th Annual BioCycle Nationwide Survey: The State of Garbage in America." *BioCycle*, JG Press, Emmaus, PA. December 2001.

Goldstein, N. and C. Madtes (2000) "12th Annual BioCycle Nationwide Survey: The State of Garbage in America, Part I." *BioCycle*, JG Press, Emmaus, PA. November 2000.

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.

Johnke (1999) as cited in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, 2000.

Kaufman, et al. (2004a) "14th Annual BioCycle Nationwide Survey: The State of Garbage in America 2004" *BioCycle*, JG Press, Emmaus, PA. January, 2004.

Kaufman, et al. (2004b) "Corrections to State of Garbage 2004" *BioCycle*, JG Press, Emmaus, PA. April, 2004.

Miller, T. (1999) *Material Safety Data Sheet, Carbon Black*. Continental Carbon Company. September 1, 1999. Available online at <http://www.continentalcarbon.com/downloads/MSDS.pdf>. Accessed October 10, 2003.

RMA (2006) *U.S. Scrap Tire Markets in the United States 2005 Edition*. Rubber Manufacturers Association, Washington, DC. November 2006.

Schneider, S. (2007) E-mail communication between Sarah Shapiro of ICF International and Shelly Schneider, Franklin Associates, A Division of ERG. 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.

STMC (2006) *Scrap Tire Facts and Figures*. Scrap Tire Management Council of the Rubber Manufacturers Association, Washington, DC. Available online at <http://www.rma.org/scrap_tires/scrap_tire_markets/facts_and_figures/> and <http://www.rma.org/scrap_tires/scrap_tire_markets/scrap_tire_characteristics/>. Accessed January 3, 2007.

STMC (2003) *Scrap Tire Facts and Figures*. Scrap Tire Management Council of the Rubber Manufacturers Association, Washington, DC. Available online at <http://www.rma.org/scrap_tires/scrap_tire_markets/facts_and_figures/> and <http://www.rma.org/scrap_tires/scrap_tire_markets/scrap_tire_characteristics/>. Accessed July 7, 2003.

STMC (2002) *Scrap Tire Facts and Figures*. Scrap Tire Management Council of the Rubber Manufacturers Association, Washington, DC. Available online at <http://www.rma.org/scraptires/facts_figures.html>. Accessed October 22, 2002.

STMC (2001) *Scrap Tire Facts and Figures*. Scrap Tire Management Council of the Rubber Manufacturers Association, Washington, DC. Available online at <http://www.rma.org/scraptires/facts_figures.html>. Accessed September 5, 2001.

STMC (2000) *Scrap Tire Facts and Figures*. Scrap Tire Management Council of the Rubber Manufacturers Association, Washington, DC. Available online at <http://www.rma.org/scrapfctn.html>. Accessed July 26, 2000.

UK: Environment Agency (1999) as cited in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, 2000.

Yasuda (1993) as cited in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, 2000.

Energy Sources of Indirect Greenhouse Gas Emissions

EPA (2006) Air Emissions Trends—Continued Progress Through 2005. U.S. Environmental Protection Agency, Washington, DC. December 19, 2006. Available online at <http://www.epa.gov/air/airtrends/index.html>.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data between the Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency (EPA). December 22, 2003.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, 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>.

BEA (1991 through 2006) Unpublished BE-36 survey data. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, DC.

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 (2006) 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 2006) Unpublished *Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries*. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce, Washington, DC. Form-563.

DOT (1991 through 2006) *Fuel Cost and Consumption*. Airline Information, Bureau of Transportation Statistics, U.S. Department of Transportation, Washington, DC.

EIA (2006) *Monthly Energy Review*, December 2006 and Unpublished Supplemental Tables on Petroleum Product detail. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2006/12).

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.

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 (2006) *Annual Energy Review 2005*. Energy Information Administration, U.S. Department of Energy. Washington, DC, Tables 10.2a and 10.2b. July 2006. DOE/EIA-0384(2005).

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.

Lindstrom, P. (2006) Personal communication between Jean Kim of ICF International and Perry Lindstrom, Energy Information Administration.

Industrial Processes

Cement Manufacture

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 (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, U.K.

USGS (2005) *Minerals Yearbook: Cement Annual Report 2004*. U.S. Geological Survey, Reston, VA.

USGS (2004) *Minerals Yearbook: Cement Annual Report 2003*. U.S. Geological Survey, Reston, VA.

USGS (2003) *Minerals Yearbook: Cement Annual Report 2002*. U.S. Geological Survey, Reston, VA.

USGS (2002) *Minerals Yearbook: Cement Annual Report 2001*. U.S. Geological Survey, Reston, VA.

USGS (2001) *Minerals Yearbook: Cement Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Cement Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Cement Annual Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Mineral Industrial Survey: Cement 1997*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Mineral Industrial Survey: Cement 1996*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Cement Annual Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Cement Annual Report 1994*. U.S. Geological Survey, Reston, VA.

USGS (1994) *Minerals Yearbook: Cement Annual Report 1993*. U.S. Geological Survey, Reston, VA.

USGS (1993) *Minerals Yearbook: Cement Annual Report 1992*. U.S. Geological Survey, Reston, VA.

Van Oss (2006) Personal communication between Hendrik Van Oss, Commodity Specialist of the U.S. Geological Survey and Erin Fraser of ICF International. September 20, 2006.

Iron and Steel Production

AISI (2006) *2005 Annual Statistical Report*, American Iron and Steel Institute, Washington, DC.

AISI (2005) *2004 Annual Statistical Report*, American Iron and Steel Institute, Washington, DC.

AISI (2004) *2003 Annual Statistical Report*, American Iron and Steel Institute, Washington, DC.

AISI (2003) *2002 Annual Statistical Report*, American Iron and Steel Institute, Washington, DC.

AISI (2002) *2001 Annual Statistical Report*, American Iron and Steel Institute, Washington, DC.

AISI (2001) *2000 Annual Statistical Report*, American Iron and Steel Institute, Washington, DC.

AISI (1996) *1995 Annual Statistical Report*, American Iron and Steel Institute, Washington, DC.

AISI (1995) *1994 Annual Statistical Report*, American Iron and Steel Institute, Washington, DC.

DOE (1997) *Energy and Environmental Profile of the U.S. Aluminum Industry*. Office of Industrial Technologies, U.S. Department of Energy. July 1997.

EIA (2006a) *Annual Energy Review 2005*. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/ EIA-0384.

EIA (2006b) Emissions of Greenhouse Gases in the United States 2005. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0573 (2005).

EIA (2006c) *Quarterly Coal Report* January–March 2006, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0121.

EIA (2004a) *Quarterly Coal Report* October–December 2003, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0121.

EIA (2004b) Emissions of Greenhouse Gases in the United States 2003. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0573.

EIA (2003) *Quarterly Coal Report* October–December 2002, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0121.

EIA (2002) *Quarterly Coal Report* October–December 2001, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0121.

EIA (2001) *Quarterly Coal Report* October–December 2000, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0121.

EIA (2000) *Quarterly Coal Report* October–December 1999, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0121 (2000/4Q).

EIA (1999) *Quarterly Coal Report* October–December 1998, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0121.

EIA (1998) *Quarterly Coal Report* October–December 1997, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0121.

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.

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.

IPCC/UNEP/OECD/IEA (1995) *IPCC Guidelines for National Greenhouse Gas Inventories, Volume 3, Greenhouse Gas Inventory Reference Manual*. Table 2-2. Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. IPCC WG1 Technical Support Unit, UK.

Jorgenson, J. (2006) Telephone conversation between Chris Steuer of ICF International and John Jorgenson, Commodity Specialist, USGS. 20 September 2006.

USAA (2006) *Primary Aluminum Statistics*. U.S. Aluminum Association, Washington, DC. January 2006.

USAA (2005) *Primary Aluminum Statistics*. U.S. Aluminum Association, Washington, DC. January 2005.

USAA (2004) *Primary Aluminum Statistics*. U.S. Aluminum Association, Washington, DC. January 2004.

U.S. Census Bureau (2006) U.S International Trade Commission (USITC) Trade Dataweb. Available online at <http://dataweb.usitc.gov/>. Accessed Fall 2006.

USGS (2006) *Minerals Yearbook: Iron Ore Report 2005*. U.S. Geological Survey, Reston, VA.

USGS (2005) *Minerals Yearbook: Iron Ore Report 2004*. U.S. Geological Survey, Reston, VA.

USGS (2004) *Minerals Yearbook: Iron Ore Report 2003*. U.S. Geological Survey, Reston, VA.

USGS (2003) *Minerals Yearbook: Iron Ore Report 2002*. U.S. Geological Survey, Reston, VA.

USGS (2002) *Minerals Yearbook: Iron Ore Report 2001*. U.S. Geological Survey, Reston, VA.

USGS (2001) *Minerals Yearbook: Iron Ore Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Iron Ore Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Iron Ore Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Iron Ore Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Iron Ore Report 1996*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Iron Ore Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Iron Ore Report 1994*. U.S. Geological Survey, Reston, VA.

USGS (1994) *Minerals Yearbook: Iron Ore Report 1993*. U.S. Geological Survey, Reston, VA.

Ammonia Manufacture and Urea Application

Bark (2004) *Coffeyville Nitrogen Plant*. Available online at <http://www.gasification.org/Docs/2003_Papers/07BARK.pdf> Accessed: December 15, 2004.

Coffeyville Resources Nitrogen Fertilizers, LLC (2006) *Business Data*. Available online at <http://www.coffeyvillegroup.com/businessSnapshot.asp> Accessed September 7, 2006.

Coffeyville Resources Nitrogen Fertilizers, LLC (2005) *Business Data*. Available online at <http://www.coffeyvillegroup.com/businessSnapshot.asp> Accessed September 12, 2005.

EFMA (1995) *Production of Ammonia*. European Fertilizer Manufacturers Association. March 1, 1995.

EIA (1998) *Manufacturing Energy Consumption Survey* (MECS) U.S. Department of Energy, Energy Information Administration, Washington, DC. Available online at <http://www.eia.doe.gov/emeu/mecs/mecs98/datatables/contents.html>.

EIA (1994) *Manufacturing Energy Consumption Survey* (MECS) U.S. Department of Energy, Energy Information Administration, Washington, DC.

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.

TFI (2002) U.S. Nitrogen Imports/Exports Table. The Fertilizer Institute. Available online at <http://www.tfi.org/statistics/usnexim.asp>. Accessed August 2002.

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 (2005) *Current Industrial Reports Fertilizer Materials and Related Products: Fourth Quarter Report 2004 Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2004) *Current Industrial Reports Fertilizer Materials and Related Products: Fourth Quarter Report 2003 Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2003) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Reports 2002 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 (2002b) *Current Industrial Reports Fertilizer Materials and Related Products: Fourth Quarter 2001*. March 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 (2001b) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Report 2000*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2000) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Report 1999*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (1999) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Report 1998*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (1998) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Report 1997*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (1994) *Current Industrial Reports Fertilizer Materials Annual Report 1993*. Report No. MQ28B. U.S. Census Bureau, Washington, DC.

U.S. Census Bureau (1993) *Current Industrial Reports Fertilizer Materials Annual Report 1992*. Report No. MQ28B. U.S. Census Bureau, Washington, DC.

U.S. Census Bureau (1992) *Current Industrial Reports Fertilizer Materials Annual Report 1991*. Report No. MQ28B. U.S. Census Bureau, Washington, DC.

U.S. Census Bureau (1991) *Current Industrial Reports Fertilizer Materials Annual Report 1990*. Report No. MQ28B. U.S. Census Bureau, Washington, DC.

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>. Accessed August 2002.

Lime Manufacture

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.

Males, E. (2003) Public review comments received in a memorandum from Eric Males, National Lime Association to Mr. William N. Irving & Mr. Leif Hockstad, Environmental Protection Agency. March 6, 2003.

USGS (2006) *Minerals Yearbook: Lime Annual Report 2005*. U.S. Geological Survey, Reston, VA.

USGS (2005) *Minerals Yearbook: Lime Annual Report 2004*. U.S. Geological Survey, Reston, VA.

USGS (2004) *Minerals Yearbook: Lime Annual Report 2003*. U.S. Geological Survey, Reston, VA.

USGS (2003) *Minerals Yearbook: Lime Annual Report 2002*. U.S. Geological Survey, Reston, VA.

USGS (2002) *Minerals Yearbook: Lime Annual Report 2001*. U.S. Geological Survey, Reston, VA.

USGS (2001) *Minerals Yearbook: Lime Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Lime Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Lime Annual Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Lime Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Lime Annual Report 1996*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Lime Annual Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Lime Annual Report 1994*. U.S. Geological Survey, Reston, VA.

USGS (1994) *Minerals Yearbook: Lime Annual Report 1993*. U.S. Geological Survey, Reston, VA.

USGS (1992) *Minerals Yearbook: Lime Annual Report 1991*. U.S. Geological Survey, Reston, VA.

Limestone and Dolomite Use

USGS (2006) *Minerals Yearbook: Magnesium Annual Report 2005*. U.S. Geological Survey, Reston, VA.

USGS (2005a) *Minerals Yearbook: Magnesium Annual Report 2004*. U.S. Geological Survey, Reston, VA.

USGS (2005b) *Minerals Yearbook: Magnesium Annual Report 2004*. U.S. Geological Survey, Reston, VA.

USGS (2004a) *Minerals Yearbook: Crushed Stone Annual Report 2003*. U.S. Geological Survey, Reston, VA.

USGS (2004b) *Minerals Yearbook: Magnesium Annual Report 2003*. U.S. Geological Survey, Reston, VA.

USGS (2003a) *Minerals Yearbook: Crushed Stone Annual Report 2002*. U.S. Geological Survey, Reston, VA.

USGS (2003b) *Minerals Yearbook: Magnesium Annual Report 2002*. U.S. Geological Survey, Reston, VA.

USGS (2002a) *Minerals Yearbook: Crushed Stone Annual Report 2001*. U.S. Geological Survey, Reston, VA.

USGS (2002b) *Minerals Yearbook: Magnesium Annual Report 2001*. U.S. Geological Survey, Reston, VA.

USGS (2001a) *Minerals Yearbook: Crushed Stone Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2001b) *Minerals Yearbook: Magnesium Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2000a) *Minerals Yearbook: Crushed Stone Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (2000b) *Minerals Yearbook: Magnesium Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1999a) *Minerals Yearbook: Crushed Stone Annual Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1999b) *Minerals Yearbook: Magnesium Annual Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1998a) *Minerals Yearbook: Crushed Stone Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1998b) *Minerals Yearbook: Magnesium Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1997a) *Minerals Yearbook: Crushed Stone Annual Report 1996*. U.S. Geological Survey, Reston, VA.

USGS (1997b) *Minerals Yearbook: Magnesium Annual Report 1996*. U.S. Geological Survey, Reston, VA.

USGS (1996a) *Minerals Yearbook: Crushed Stone Annual Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1996b) *Minerals Yearbook: Magnesium Annual Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1995a) *Minerals Yearbook: Crushed Stone Annual Report 1993*. U.S. Geological Survey, Reston, VA.

USGS (1995b) *Minerals Yearbook: Crushed Stone Annual Report 1994*. U.S. Geological Survey, Reston, VA.

USGS (1995c) *Minerals Yearbook: Magnesium Annual Report 1994*. U.S. Geological Survey, Reston, VA.

USGS (1993) *Minerals Yearbook: Crushed Stone Annual Report 1991*. U.S. Geological Survey, Reston, VA.

Weaver, S. (2006) Electronic mail from Susan Weaver, Commodity Specialist, U.S. Geological Survey, to Erin Fraser of ICF International. September 14, 2006.

Soda Ash Manufacture and Consumption

USGS (2006) *Minerals Yearbook: Soda Ash Annual Report 2005*. U.S. Geological Survey, Reston, VA.

USGS (2005) *Minerals Yearbook: Soda Ash Annual Report 2004*. U.S. Geological Survey, Reston, VA.

USGS (2004) *Minerals Yearbook: Soda Ash Annual Report 2003*. U.S. Geological Survey, Reston, VA.

USGS (2003) *Minerals Yearbook: Soda Ash Annual Report 2002*. U.S. Geological Survey, Reston, VA.

USGS (2002) *Minerals Yearbook: Soda Ash Annual Report 2001*. U.S. Geological Survey, Reston, VA.

USGS (2001) *Minerals Yearbook: Soda Ash Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Soda Ash Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Soda Ash Annual Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Soda Ash Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Soda Ash Annual Report 1996*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Soda Ash Annual Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Soda Ash Annual Report 1994*. U.S. Geological Survey, Reston, VA.

USGS (1994) *Minerals Yearbook: Soda Ash Annual Report 1993*. U.S. Geological Survey, Reston, VA.

Titanium Dioxide Production

Gambogi, J. (2002) Telephone conversation between Philip Groth of ICF International and Joseph Gambogi, Commodity Specialist, U.S. Geological Survey. November 2002.

Kramer, D. (2006) Telephone conversation between Erin Fraser of ICF International and Deborah Kramer, Commodity Specialist, U.S. Geological Survey. September 2006.

Onder, H, and E.A. Bagdoyan (1993) *Everything You've Always Wanted to Know about Petroleum Coke*. Allis Mineral Systems.

USGS (2006) *Minerals Commodity Summaries: Titanium Mineral Concentrates 2005*. U.S. Geological Survey, Reston, VA.

USGS (2005) *Mineral Yearbook: Titanium Annual Report 2004*. U.S. Geological Survey, Reston, VA.

USGS (2004) *Mineral Yearbook: Titanium Annual Report 2003*. U.S. Geological Survey, Reston, VA.

USGS (2003) *Mineral Yearbook: Titanium Annual Report 2002*. U.S. Geological Survey, Reston, VA.

USGS (2002) *Mineral Yearbook: Titanium Annual Report 2001*. U.S. Geological Survey, Reston, VA.

USGS (2001) *Mineral Yearbook: Titanium Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Mineral Yearbook: Titanium Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Mineral Yearbook: Titanium Annual Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Mineral Yearbook: Titanium Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Mineral Yearbook: Titanium Annual Report 1996*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Mineral Yearbook: Titanium Annual Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Mineral Yearbook: Titanium Annual Report 1994*. U.S. Geological Survey, Reston, VA.

USGS (1994) *Mineral Yearbook: Titanium Annual Report 1993*. U.S. Geological Survey, Reston, VA.

USGS (1993) *Mineral Yearbook: Titanium Annual Report 1992*. U.S. Geological Survey, Reston, VA.

USGS (1992) *Mineral Yearbook: Titanium Annual Report 1991*. U.S. Geological Survey, Reston, VA.

USGS (1991) *Mineral Yearbook: Titanium Annual Report 1990*. U.S. Geological Survey, Reston, VA.

Ferroalloy Production

Corathers, L. (2006) Personal communication between Lisa Corathers, Commodity Specialist, U.S. Geological Survey and Erin Fraser of ICF International. October 2006.

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.

Onder, H., and E.A. Bagdoyan (1993) *Everything You've Always Wanted to Know about Petroleum Coke*. Allis Mineral Systems.

USGS (2005) *Minerals Yearbook: Silicon Annual Report 2004*. U.S. Geological Survey, Reston, VA.

USGS (2004) *Minerals Yearbook: Silicon Annual Report 2003*. U.S. Geological Survey, Reston, VA.

USGS (2003) *Minerals Yearbook: Silicon Annual Report 2002*. U.S. Geological Survey, Reston, VA.

USGS (2002) *Minerals Yearbook: Silicon Annual Report 2001*. U.S. Geological Survey, Reston, VA.

USGS (2001) *Minerals Yearbook: Silicon Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Silicon Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Silicon Annual Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Silicon Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Silicon Annual Report 1996*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Silicon Annual Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Silicon Annual Report 1994*. U.S. Geological Survey, Reston, VA.

USGS (1994) *Minerals Yearbook: Silicon Annual Report 1993*. U.S. Geological Survey, Reston, VA.

USGS (1993) *Minerals Yearbook: Silicon Annual Report 1992*. U.S. Geological Survey, Reston, VA.

USGS (1992) *Minerals Yearbook: Silicon Annual Report 1991*. U.S. Geological Survey, Reston, VA.

USGS (1991) *Minerals Yearbook: Silicon Annual Report 1990*. U.S. Geological Survey, Reston, VA.

Phosphoric Acid Production

EFMA (2000) *Production of Phosphoric Acid*. Booklet No. 4 of 8 in the series "Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry," 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 from Gary Albarelli of the Florida Institute of Phosphate Research, Bartow, Florida, to Robert Lanza of ICF International, July 29, 2003.

FIPR (2003a) Florida Institute of Phosphate Research, personal communication between Mr. Michael Lloyd, Laboratory Manager, FIPR, Bartow, Florida, and Mr. Robert Lanza, ICF International, August 2003.

USGS (2006) *Minerals Yearbook. Phosphate Rock Annual Report 2005*. U.S. Geological Survey, Reston, VA.

USGS (2005) *Minerals Yearbook. Phosphate Rock Annual Report 2004*. U.S. Geological Survey, Reston, VA.

USGS (2004) *Minerals Yearbook. Phosphate Rock Annual Report 2003*. U.S. Geological Survey, Reston, VA.

USGS (2003) Electronic mails from Mr. Stephen M Jasinski, USGS Commodity Specialist, Phosphate Rock to Mr. Robert Lanza, ICF International, July-August, 2003.

USGS (2002) *Minerals Yearbook. Phosphate Rock Annual Report 2001*. U.S. Geological Survey, Reston, VA.

USGS (2001) *Minerals Yearbook. Phosphate Rock Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook. Phosphate Rock Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook. Phosphate Rock Annual Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook. Phosphate Rock Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook. Phosphate Rock Annual Report 1996*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook. Phosphate Rock Annual Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook. Phosphate Rock Annual Report 1994*. U.S. Geological Survey, Reston, VA.

USGS (1994) *Minerals Yearbook. Phosphate Rock Annual Report 1993*. 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 (2006) *CO_2-EOR: An Enabling Bridge for the Oil Transition*. Presented to: 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, R. (2006) Electronic mail from Mr. Ron Broadhead, New Mexico Bureau of Geology and Mineral Resources to Mr. Erin Fraser, ICF International, September 2006.

Denbury Resources Inc. (2006) *Annual Report, 2004*, 34.

Denbury Resources Inc. (2005) *Annual Report, 2004*, 32.

Denbury Resources Inc. (2004) *Annual Report, 2003*, 41.

Denbury Resources Inc. (2003) *Annual Report, 2002*, 14.

Denbury Resources Inc. (2002) *Annual Report, 2001*, 22.

Zinc Production

Gabby, P. (2006) Telephone conversation between Erin Fraser of ICF International and Peter Gabby, Commodity Specialist, U.S. Geological Survey. 29 September 2006.

Queneau P.B., James S.E., Downey J.P., Livelli G.M. (1998) *Recycling Lead and Zinc in the United States*. Zinc and Lead Processing. The Metallurgical Society of CIM.

Recycling Today (2005) *Horsehead Sales Complete*. Available at <http://www.recyclingtoday.com/news/news.asp?ID=5137&SubCatID=74&CatID=23>. January 5, 2005.

Sjardin (2003) *CO_2 Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry*. Copernicus Institute, Utrecht, the Netherlands.

Stuart (2005) Telephone conversation between Christopher Steuer of ICF International and Eric Stuart of the Steel Manufacturers Association. October 31, 2005.

USGS (2005) *Minerals Yearbook: Zinc Annual Report 2004*. U.S. Geological Survey, Reston, VA.

USGS (2004) *Minerals Yearbook: Zinc Annual Report 2003*. U.S. Geological Survey, Reston, VA.

USGS (2003) *Minerals Yearbook: Zinc Annual Report 2002*. U.S. Geological Survey, Reston, VA.

USGS (2002) *Minerals Yearbook: Zinc Annual Report 2001*. U.S. Geological Survey, Reston, VA.

USGS (2001) *Minerals Yearbook: Zinc Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Zinc Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Zinc Annual Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Zinc Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Zinc Annual Report 1996*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Zinc Annual Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Zinc Annual Report 1994*. 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.

Gabby, P. (2006) Telephone conversation between Erin Fraser of ICF International and Peter Gabby, Commodity Specialist, USGS, 29 September 2006.

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's Encyclopedia of Industrial Chemistry: Fifth Edition (1997) Volume A5. John Wiley and Sons.

USGS (2005) *Minerals Yearbook: Lead Annual Report 2004*. U.S. Geological Survey, Reston, VA.

USGS (2004) *Minerals Yearbook: Lead Annual Report 2003*. U.S. Geological Survey, Reston, VA.

USGS (2003) *Minerals Yearbook: Lead Annual Report 2002*. U.S. Geological Survey, Reston, VA.

USGS (2002) *Minerals Yearbook: Lead Annual Report 2001*. U.S. Geological Survey, Reston, VA.

USGS (2001) *Minerals Yearbook: Lead Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Lead Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Lead Annual Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Lead Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Lead Annual Report 1996*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Lead Annual Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Lead Annual Report 1994*. U.S. Geological Survey, Reston, VA.

Petrochemical Production

ACC (2006) *Guide to the Business of Chemistry 2005*. American Chemistry Council, Arlington, VA.

ACC (2005) *Guide to the Business of Chemistry 2005*. American Chemistry Council, Arlington, VA.

ACC (2003) *Guide to the Business of Chemistry 2003*. American Chemistry Council, Arlington, VA.

ACC (2002) *Guide to the Business of Chemistry 2002*. American Chemistry Council, Arlington, VA.

CMA (1999) *U.S. Chemical Industry Statistical Handbook*. Chemical Manufacturer's Association. Washington, DC.

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 Volumen Inorganic Chemicals—Solid and Others Industry*, Table 4.21. European Commission, 224. August 2004.

The Innovation Group (2004) *Carbon Black Plant Capacity*. Available online at <http://www.the-innovation-group.com/ChemProfiles/Carbon%20Black.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.

Johnson, G. L. (2006) Personal communication between Erin Fraser of ICF International and Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA). October 2006.

Johnson, G. L. (2005) Personal communication between Erin Fraser of ICF International and Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA). October 2005.

Johnson, G. L. (2003) Personal communication between Caren Mintz of ICF International and Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA). 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.

U.S. Census Bureau (2006) U.S International Trade Commission (USITC) Trade DataWeb. Available online at <http://dataweb.usitc.gov/>. Accessed Fall 2006.

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.

Silicon Carbide Production

Corathers, L. (2006) Personal communication between Lisa Corathers, Commodity Specialist, U.S. Geological Survey and Erin Fraser of ICF International. October 2006.

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.

U.S. Census Bureau (2006) U.S International Trade Commission (USITC) Trade DataWeb. Available online at <http://dataweb.usitc.gov/>. Accessed Fall 2006.

U.S. Census Bureau (2005) U.S International Trade Commission (USITC) Trade DataWeb. Available online at <http://dataweb.usitc.gov/>. Accessed Fall 2005.

USGS (2006) *Minerals Yearbook: Manufactured Abrasives Annual Report 2004*. U.S. Geological Survey, Reston, VA.

USGS (2005a) *Minerals Yearbook: Manufactured Abrasives Annual Report 2004*. U.S. Geological Survey, Reston, VA.

USGS (2005b) *Minerals Yearbook: Silicon Annual Report* 2004. U.S. Geological Survey, Reston, VA.

USGS (2004a) *Minerals Yearbook: Manufactured Abrasives Annual Report 2003*. U.S. Geological Survey, Reston, VA.

USGS (2004b) *Minerals Yearbook: Silicon Annual Report* 2003. U.S. Geological Survey, Reston, VA.

USGS (2003a) *Minerals Yearbook: Manufactured Abrasives Annual Report 2002*. U.S. Geological Survey, Reston, VA.

USGS (2003b) *Minerals Yearbook: Silicon Annual Report* 2002. U.S. Geological Survey, Reston, VA.

USGS (2002a) *Minerals Yearbook: Manufactured Abrasives Annual Report 2001*. U.S. Geological Survey, Reston, VA.

USGS (2002b) *Minerals Yearbook: Silicon Annual Report* 2001. U.S. Geological Survey, Reston, VA.

USGS (2001a) *Minerals Yearbook: Manufactured Abrasives Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2001b) *Minerals Yearbook: Silicon Annual Report* 2000. U.S. Geological Survey, Reston, VA.

USGS (2000a) *Minerals Yearbook: Manufactured Abrasives Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (2000b) *Minerals Yearbook: Silicon Annual Report* 1999. U.S. Geological Survey, Reston, VA.

USGS (1999a) *Minerals Yearbook: Manufactured Abrasives Annual Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1999b) *Minerals Yearbook: Silicon Annual Report* 1998. U.S. Geological Survey, Reston, VA.

USGS (1998a) *Minerals Yearbook: Manufactured Abrasives Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1998b) *Minerals Yearbook: Silicon Annual Report* 1997. U.S. Geological Survey, Reston, VA.

USGS (1997a) *Minerals Yearbook: Manufactured Abrasives Annual Report 1996*. U.S. Geological Survey, Reston, VA.

USGS (1997b) *Minerals Yearbook: Silicon Annual Report* 1996. U.S. Geological Survey, Reston, VA.

USGS (1996a) *Minerals Yearbook: Manufactured Abrasives Annual Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1996b) *Minerals Yearbook: Silicon Annual Report* 1995. U.S. Geological Survey, Reston, VA.

USGS (1995a) *Minerals Yearbook: Manufactured Abrasives Annual Report 1994*. U.S. Geological Survey, Reston, VA.

USGS (1995b) *Minerals Yearbook: Silicon Annual Report* 1994. U.S. Geological Survey, Reston, VA.

USGS (1994a) *Minerals Yearbook: Manufactured Abrasives Annual Report 1993*. U.S. Geological Survey, Reston, VA.

USGS (1994b) *Minerals Yearbook: Silicon Annual Report* 1993. U.S. Geological Survey, Reston, VA.

USGS (1993a) *Minerals Yearbook: Manufactured Abrasives Annual Report 1992*. U.S. Geological Survey, Reston, VA.

USGS (1993b) *Minerals Yearbook: Silicon Annual Report* 1992. U.S. Geological Survey, Reston, VA.

USGS (1992a) *Minerals Yearbook: Manufactured Abrasives Annual Report 1991*. U.S. Geological Survey, Reston, VA.

USGS (1992b) *Minerals Yearbook: Silicon Annual Report* 1991. U.S. Geological Survey, Reston, VA.

USGS (1991a) *Minerals Yearbook: Manufactured Abrasives Annual Report 1990*. U.S. Geological Survey, Reston, VA.

USGS (1991b) *Minerals Yearbook: Silicon Annual Report* 1990. U.S. Geological Survey, Reston, VA.

Nitric Acid Production

C&EN (2006) "Facts and Figures in the Chemical Industry." *Chemical & Engineering News*, 84(28):64. July 10, 2006.

C&EN (2005) "Facts and Figures in the Chemical Industry." *Chemical & Engineering News*, 83(28):72. July 11, 2005.

C&EN (2004) "Facts and Figures in the Chemical Industry." *Chemical & Engineering News*, 82(27):54. July 5, 2004.

C&EN (2003) "Facts and Figures in the Chemical Industry." *Chemical & Engineering News*, 81(30):56. July 28, 2003.

C&EN (2002) "Facts and Figures in the Chemical Industry." *Chemical & Engineering News*, 80(25):62. June 24, 2002.

C&EN (2001) "Facts and Figures in the Chemical Industry." *Chemical & Engineering News*, 79(26):46. June 25, 2001.

Choe, J.S., P.J. Cook, and F.P. Petrocelli (1993) "Developing N_2O Abatement Technology for the Nitric Acid Industry." Prepared for presentation at the 1993 ANPSG Conference. Air Products and Chemicals, Inc., Allentown, PA.

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), 3.35. May 2000.

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.

Adipic Acid Production

ACC (2003) "Adipic Acid Production." Table 3.12—Production of the Top 100 Chemicals. American Chemistry Council *Guide to the Business of Chemistry*. August 2003.

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.

Childs, D. (2003) Personal communication between Dave Childs of DuPont, USA and Duncan Rotherham of ICF International. August 7, 2003.

Childs, D. (2002) Personal communication between Dave Childs of DuPont, USA and Laxmi Palreddy of ICF, Consulting, USA. August 8, 2002.

CMR (2001) "Chemical Profile: Adipic Acid." *Chemical Market Reporter*. July 16, 2001.

CMR (1998) "Chemical Profile: Adipic Acid." *Chemical Market Reporter*. June 15, 1998.

CW (2005) "Product Focus: Adipic Acid." *Chemical Week*. May 4, 2005.

CW (1999) "Product Focus: Adipic Acid/Adiponitrile." *Chemical Week*, p. 31. March 10, 1999.

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. Pg 3.34.

Reimer, R. (1999) Personal communication between Ron Reimer of DuPont, USA and Heike Mainhardt of ICF International. May 19, 1999.

Thiemens, M.H., and W.C. Trogler (1991) "Nylon production; an unknown source of atmospheric nitrous oxide." Science 251:932–934.

Subsitution of Ozone Depleting Substances

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.

HCFC-22 Production

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.

Rand, S., M. Branscome, and D. Ottinger (1999) “Opportunities for the Reduction of HFC-23 Emissions from the Production of HCFC-22.” In: *Proceedings from the Joint IPCC/TEAP Expert Meeting On Options for the Limitation of Emissions of HFCs and PFCs*. Petten, the Netherlands, 26–28 May 1999.

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.

Electrical Transmission and Distribution

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.

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.

Maiss, M. and C.A.M. Brenninkmeijer (2000) “A reversed trend in emissions of SF_6 to the atmosphere?” *Non-CO_2 Greenhouse Gases: Scientific Understanding, Control, and Implementation, Proceedings of the Second International Symposium*, Noordwijkerhout, the Netherlands, September 8–10, 1999, Kluwer Academic Publishers, 2000, 199.

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) Katie D. Smythe, RAND Environmental Science and Policy Center, “Trends in SF_6 Sales and End-Use Applications: 1961–2003,” *International Conference on SF_6 and the Environment: Emission Reduction Strategies*, Scottsdale, AZ, December 1–3, 2004.

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.

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. 20001 November 2001.

Burton, C.S., and H. Mallya (2005) “PFC Reduction/Climate Partnership for the Semiconductor Industry: Trends in Emissions and Documentation,” Draft Report, prepared for Office of Atmospheric Programs, U. S. Environmental Protection Agency, Washington, DC. 20001. August 2005.

Citigroup Smith Barney (2005) *Global Supply/Demand Model for Semiconductors*. March 2005.

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.

ITRS (2005) *International Technology Roadmap for Semiconductors: 2004 Update*. January 2005. This 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.

Semiconductor Equipment and Materials Industry (2006) *World Fab Watch, April 2006 Edition.*

Strategic Marketing Associates (2003) Personal communication between C. S. Burton and George Burns, President of Strategic Marketing Associates, Santa Cruz, CA. September 5, 2003.

VLSI Research, Inc. (2005) Document 327202, V5.061—Worldwide Silicon Demand by Wafer Size, by Linewidth and by Device Type. June 2005. Available online at <http://www.vlsiresearch.com>.

VSLI Research, Inc. (2003) Personal communication between C. S. Burton and Marta Hernandez, Analyst at VLSI Research Inc., San Jose, CA. September 5, 2003.

Aluminum Production

Gariepy, B. and G. Dube (1992) “Treating Aluminum with Chlorine.” U.S. Patent 5,145,514. Issued September 8, 1992.

IAI (2003) Aluminum Sector Greenhouse Gas Protocol: Greenhouse Gas Emissions Monitoring and Reporting by the Aluminum Industry, International Aluminum Institute, May 2003. Available at <http://www.world-aluminium.org/environment/climate/ghg_protocol.pdf>.

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.

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.

Kantamaneni R. and D. Pape (2001) “2000 Aluminum Inventory—Uncertainty Analysis”, Under EPA Contract No. 68-W6-0029, Task Order 408. Memorandum to EPA from ICF International. October, 18, 2001.

Ko, M.K.W., N.D. Sze, W.-C. Wang, G. Shia, A. Goldman, F.J. Murcray, D.G. Murcray, and C.P. Rinsland (1993) “Atmospheric Sulfur Hexafluoride: Sources, Sinks, and Greenhouse Warming.” *Journal of Geophysical Research*, 98:10499–10507.

MacNeal, J., T. Rack, and R. Corns (1990) “Process for Degassing Aluminum Melts with Sulfur Hexafluoride.” U.S. Patent 4,959,101. Issued September 25, 1990.

Ten Eyck, N. and M. Lukens (1996) “Process for Treating Molten Aluminum with Chlorine Gas and Sulfur Hexafluoride to Remove Impurities.” U.S. Patent 5,536,296. Issued July 16, 1996.

USAA (2006) *Primary Aluminum Statistics*. U.S. Aluminum Association, Washington, DC. January 2006.

USAA (2005) *Primary Aluminum Statistics*. U.S. Aluminum Association, Washington, DC. January 2005.

USAA (2004) *Primary Aluminum Statistics*. U.S. Aluminum Association, Washington, DC. January 2004.

USGS (2006) *Mineral Commodity Summaries*. U.S. Geological Survey, Reston, VA.

USGS (2002) *Minerals Yearbook: Aluminum Annual Report 2001*. U.S. Geological Survey, Reston, VA.

USGS (2001) *Minerals Yearbook: Aluminum Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Aluminum Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Aluminum Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Aluminum Annual Report 1994*. U.S. Geological Survey, Reston, VA.

Victor, D.G. and G.J. MacDonald (1998) “A Model for Estimating Future Emissions of Sulfur Hexafluoride and Perfluorcarbons.” Interim Report for the International Institute for Applied Systems Analysis (IIASA). July, 1998. Available online at <http://www.iiasa.ac.at/>. Accessed May 23, 2000.

Zurecki, Z. (1996) “Effect of Atmosphere Composition on Homogenizing Al-Mg and Al-Li Alloys.” *Gas Interactions in Nonferrous Metals Processing—Proceedings of the 1996 125th The Minerals, Metals & Materials Society (TMS) Annual Meeting*, Anaheim, CA, 77–93.

Magnesium Production and Processing

Bartos S., J. Marks, R. Kantamaneni, C. Laush (2003) “Measured SF_6 Emissions from Magnesium Die Casting Operations,” *Magnesium Technology 2003, Proceedings of The Minerals, Metals & Materials Society (TMS) Conference*. March 2003.

EPA (2004) *Characterization of Cover Gas Emissions from U.S. Magnesium Die Casting*, Office of Air and Radiation, U.S. Environmental Protection Agency. EPA430-R-04-004.

Gjestland, H. and D. Magers (1996) “Practical Usage of Sulphur Hexafluoride for Melt Protection in the Magnesium Die Casting Industry.” #13, *International Magnesium Association 1996 Annual Conference Proceedings*, Ube City, 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.

RAND (2002) Katie D. Smythe, RAND Environmental Science and Policy Center, "Production and Distribution of SF_6 by End-Use Application." *International Conference on SF_6 and the Environment: Emission Reduction Strategies*, San Diego, CA. November 21–22.

USGS (2006) *Minerals Yearbook: Magnesium Annual Report 2005*. U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/index.html#mis>.

USGS (2005a) *Minerals Yearbook: Magnesium Annual Report 2004*. U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/index.html#mis>.

USGS (2005b) Personal communication between Jeremy Scharfenberg of ICF International and Deborah A. Kramer of the U.S. Geological Survey, Reston, VA. September, 2005.

USGS (2003) *Minerals Yearbook: Magnesium Annual Report 2002*. U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/index.html#mis>.

USGS (2002) *Minerals Yearbook: Magnesium Annual Report 2001*. U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/index.html#mis>.

Industrial Sources of Indirect Greenhouse Gases

EPA (2006) Air Emissions Trends—Continued Progress Through 2005. U.S. Environmental Protection Agency, Washington, DC. December 19, 2006. Available online at <http://www.epa.gov/air/airtrends/index.html>.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data between the 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 Product Usage

CGA (2003) "CGA Nitrous Oxide Abuse Hotline." Compressed Gas Association. November 3, 2003. Available online at <http://www.cganet.com/N_2O/factsht.asp>.

CGA (2002) "CGA/NWSA Nitrous Oxide Fact Sheet." Compressed Gas Association. March 25, 2002.

Heydorn, B. (1997) "Nitrous Oxide—North America." *Chemical Economics Handbook*, SRI Consulting. May 1997.

IPCC (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.

Kirt-Otthmer (1990) "Anesthetics." *Kirk-Otthmer Encyclopedia of Chemical Technology*, Volume 2, 781–782.

Tupman, M. (2003) Personal communication between Martin Tupman of Airgas Nitrous Oxide and Daniel Lieberman of ICF International. August 8, 2003.

Tupman, M. (2002) Personal communication between Martin Tupman of Airgas Nitrous Oxide and Laxmi Palreddy of ICF International. July 3, 2002.

Indirect Greenhouse Gas Emissions from Solvent Use

EPA (2006) Air Emissions Trends—Continued Progress Through 2005. U.S. Environmental Protection Agency, Washington, DC. December 19, 2006. Available online at <http://www.epa.gov/air/airtrends/index.html>.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data between the 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

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 between Kacey Donovan of the University of California at Davis and staff at ICF International.

Donovan, K. and L. Baldwin (1999) Results of the AAMOLLY model runs for the Enteric Fermentation Model. University of California, Davis.

EPA (2000) Draft Enteric Fermentation Model Documentation. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC. June 13, 2000.

EPA (1993) *Anthropogenic Methane Emissions in the United States: Estimates for 1990*. Report to Congress, Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC.

FAO (2006) FAOSTAT Statistical Database. Food and Agriculture Organization of the United Nations. Available online at <http://apps.fao.org>.

Feedstuffs (1998) "Nutrient requirements for pregnant replacement heifers." *Feedstuffs*, Reference Issue, p. 50.

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.* Memo 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, H.S. Eggleston, L. Buenida, K. Miwa, T Ngara, and K. Tanabe, eds.; Institute for Global Environmental Strategies (IGES). 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.

Johnson, D. (2002) Personal Communication between Don Johnson of Colorado State University, Fort Collins, and ICF International.

Johnson, D. (2000) *Enteric Fermentation Model Progress and Changes*. Comments prepared by Don Johnson of Colorado State University, Fort Collins, for ICF International.

Johnson, D. (1999) Personal Communication between Don Johnson of Colorado State University, Fort Collins, and David Conneely of ICF International.

Lange, J. (2000) Telephone conversation between Lee-Ann Tracy of ERG and John Lange, Agricultural Statistician, U. S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. May 8, 2000.

NRC (2000) *Nutrient Requirements of Beef Cattle: Seventh Revised Edition: Update 2000*. Table 11-1, Appendix Table 1. National Research Council.

NRC (1999) 1996 Beef NRC, Appendix Table 22. National Research Council.

USDA (2006a) *Cattle*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. August 2, 2006. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2006b) *Livestock Slaughter*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. August 2, 2006. Available online at <http://www.nass.usda.gov/QuickStats/>

USDA (2006c) *Milk Production*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. August 2, 2006. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2006d) *Cattle on Feed*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. August 2, 2006. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2006e) *Sheep and Goats*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. August 2, 2006. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2006f) *Hogs and Pigs*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. August 2, 2006. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2005a) *Cattle*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. August 8, 2005. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2005b) *Livestock Slaughter*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. August 8, 2005. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2005c) *Milk Production*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. August 8, 2005. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2005d) *Cattle on Feed*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. August 8, 2005. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2005e) *Sheep and Goats*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. August 8, 2005. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2005f) *Hogs and Pigs*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. August 8, 2005. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2005i) *Census of Agriculture*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. Data for 1992, 1997, and 2002 accessed from <http://www.nass.usda.gov/QuickStats/> in June 2005.

USDA (2004a) *Cattle*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. July 1, 2004. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2004b) *Hogs and Pigs*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. June 27, 2003. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2004c) *Livestock Slaughter*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. July 6–7, 2004. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2004d) *Milk Production*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. July 1, 2004. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2004e) *Sheep and Goats*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 31, 2003. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2004f) *Cattle on Feed*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. July 1, 2004. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2004g) *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 (2004h) *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 (2003a) *Cattle*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 31, 2003. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2003b) *Hogs and Pigs*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. June 27, 2003. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2003c) *Livestock Slaughter*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 24–June 20, 2003. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2003d). *Milk Production*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 14, 2003. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2003e) *Sheep and Goats*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 31, 2003. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2003f) *Cattle on Feed*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 14, 2003. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2002a) *Cattle*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 1, 2002. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2002b) *Hogs and Pigs*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. June 28, 2002. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2002c) *Livestock Slaughter*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 25–June 21, 2002. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2002d) *Milk Production*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 15, 2002. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2002e) *Sheep and Goats*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 1, 2002. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2002f) *Cattle on Feed*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 15, 2002. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2001a) *Cattle*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 26, 2001. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2001b) *Hogs and Pigs*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. December 28, 2001. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2001c) *Livestock Slaughter*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 19–December 21, 2001. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2001d) *Milk Production*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 16, 2001. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2001e) *Sheep and Goats*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 26, 2001. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2001f) *Cattle on Feed*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 16, 2001. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2000a) *Cattle*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 28, 2000. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2000b) *Chicken and Eggs—Final Estimates 1988–1993*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/data-sets/livestock/95908/sb908.txt>. Accessed May 3, 2000.

USDA (2000c) *Livestock Slaughter*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 21–December 22, 2000. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2000d) *Milk Production*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 16, 2000. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2000e) *Cattle on Feed*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 18, 2000. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (2000f) *Chicken and Eggs—Final Estimates 1988–1993*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/data-sets/livestock/95908/sb908.txt>. Accessed May 3, 2000.

USDA (1999a) *Cattle, Final Estimates 1994–1998*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (1999b) *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 (1999c) *Livestock Slaughter*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 22–December 23, 1999. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (1999d) *Milk Cows and Milk Production—Final Estimates 1993–1997*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1999. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (1999e) *Sheep and Goats, Final Estimates 1994–98*. U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (1999f) *Cattle on Feed*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (1999g) *Miscellaneous Livestock and Animal Specialties Inventory and Sales: 1997 and 1992*, Table 25. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. <http://www.nass.usda.gov/census/census97/volume1/us-51/us2_25.pdf>. Accessed May 2000.

USDA (1998a) *Hogs and Pigs, Final Estimates 1993–97*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (1998b) *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 (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. March 1996. Available online at <http://www.aphis.usda.gov/vs/ceah/cahm>.

USDA (1995a) *Cattle, Final Estimates 1989–93*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1995. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (1995b) *Dairy Outlook*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 27, 1995. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (1995c) *Poultry Production and Value—Final Estimates 1988–1993*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1995. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1994a) *Hogs and Pigs, Final Estimates 1988–92*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. December 1994. Available online at <http://www.nass.usda.gov/QuickStats/>.

USDA (1994b) *Sheep and Goats, Final Estimates 1988–93*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 31, 1994. Available online at <http://www.nass.usda.gov/QuickStats/>.

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>.

Western Dairyman (1998) "How Big Should Heifers Be at Calving?" *The Western Dairyman*, p. 12. September 1998.

Manure Management

Anderson, S. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Steve Anderson, Agricultural Statistician, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. May 31, 2000.

ASAE (1999) *ASAE Standards 1999, 46th 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) Telephone conversation between Lee-Ann Tracy of ERG and Peter B. Deal, Rangeland Management Specialist, Florida Natural Resource Conservation Service. June 21, 2000.

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/2005digest.pdf> Accessed July 2006.

EPA (2004) National Emission Inventory—Ammonia Emissions from Animal Husbandry Operations. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC. Available online at <http://www.epa.gov/ttn/chief/ap42/ch09/related/nh3inventorydraft_jan2004.pdf>.

EPA (2003a) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2001*. EPA 430-R-03-004. U.S. Environmental Protection Agency, Washington, DC. April 15, 2003.

EPA (2003b) *AgSTAR Digest*. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC. Winter 2003. <http://www.epa.gov/agstar/pdf/2002digest.pdf> Accessed 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.

EPA (1992) *Global Methane Emissions from Livestock and Poultry Manure*, U.S. Environmental Protection Agency, Office of Air and Radiation. February 1992.

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 Bo Literature Review). ERG, Lexington, MA. June 2000.

FAO (2006) 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>. Accessed May 2006.

Garrett, W.N. and D.E. Johnson (1983) “Nutritional energetics of ruminants.” *Journal of Animal Science*, 57(suppl.2):478–497. July 1983.

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, H.S. Eggleston, L. Buenida, K. Miwa, T. Ngara, and K. Tanabe, eds.; Institute for Global Environmental Strategies (IGES). Hayama, Kanagawa, Japan.

Johnson, D. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Dan Johnson, State Water Management Engineer, California Natural Resource Conservation Service. June 23, 2000.

Lange, J. (2000) Telephone conversation between Lee-Ann Tracy of ERG and John Lange, Agricultural Statistician, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. May 8, 2000.

Miller, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Paul Miller, Iowa Natural Resource Conservation Service. June 12, 2000.

Milton, B. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Bob Milton, Chief of Livestock Branch, U.S. Department of Agriculture, National Agriculture Statistics Service. May 1, 2000.

Morris, G.R. (1976) Anaerobic Fermentation of Animal Wastes: A Kinetic and Empirical Design Fermentation. M.S. Thesis. Cornell University.

NOAA (2005) National Oceanic and Atmospheric Administration (NOAA), 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/globalsod/> (for Alaska and Hawaii). Accessed June 2005.

Pederson, L. and D. Pape. (2006) 1990–2005 Volatile Solids and Nitrogen Excretion Rates, Deliverable Under EPA Contract GS-10F-0124J, Task Order 056-01. Memorandum to EPA from ICF International. August 5, 2006.

Poe, G., N. Bills, B. Bellows, P. Crosscombe, R. Koelsch, M. Kreher, and P. Wright (1999) Staff Paper Documenting the Status of Dairy Manure Management in New York: Current Practices and Willingness to Participate in Voluntary Programs, Department of Agricultural, Resource, and Managerial Economics, Cornell University, Ithaca, New York, September.

Safley, L.M., Jr. (2000) Telephone conversation between Deb Bartram of ERG and L.M. Safley, President, Agri-Waste Technology. June and October 2000.

Safley, L.M., Jr. and P.W. Westerman (1990) “Psychrophilic Anaerobic Digestion of Animal Manure: Proposed Design Methodology.” *Biological Wastes.*, 34:133–148.

Stettler, D. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Don Stettler, Environmental Engineer, National Climate Center, Oregon Natural Resource Conservation Service. June 27, 2000.

Sweeten, J. (2000) Telephone conversation between Indra Mitra of ERG and John Sweeten, Texas A&M University. 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 (2006a) *Cattle*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 2006. Available online at <http://www.nass.usda.gov>.

USDA (2006b) *Cattle on Feed*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. April 2006. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2006c) *Chicken and Eggs 2005 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 2006. Available online at <http://www.nass.usda.gov>.

USDA (2006d) *Poultry—Production and Value 2005 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. April 2006. Available online at <http://www.nass.usda.gov>.

USDA (2006e) *Published Estimates Database*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://www.nass.usda.gov>. Accessed May 2006.

USDA (2005a) *Cattle on Feed*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 21, 2005. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2005b) *Poultry Production and Value Annual Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. April 28, 2005. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2005c) *Quarterly Hogs and Pigs*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. December 2005. Available online at <http://www.nass.usda.gov>.

USDA (2005d) *Sheep and Goats*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 28, 2005. Available online at <http://www.usda.gov/nass/pubs/reportname.htm>.

USDA (2005e) 1992, 1997, and 2002 *Census of Agriculture*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://www.nass.usda.gov/census/>. Accessed March 2006.

USDA (2004a) *Cattle—Final Estimates 1999–2003*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. April 2004. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (2004b) *Hogs and Pigs—Final Estimates 1998–2002*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. March 2004. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (2004c) *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 (2004d) *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 (2004e) *Sheep and Goats—Final Estimates 1999–2003*. 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 (2000a) *Chicken and Eggs—Final Estimates 1988–1993*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/data-sets/livestock/95908/sb908.txt>. May 3, 2000.

USDA (2000b) Re-aggregated data from the National Animal Health Monitoring System's (NAHMS) Dairy '96 study provided by Stephen L. Ott of the U.S. Department of Agriculture, Animal and Plant Health Inspection Service. June 19, 2000.

USDA (2000c) *Layers '99-Part II: References of 1999 Table Egg Layer Management in the U.S.* U.S. Department of Agriculture, Animal and Plant Health Inspection Service (APHIS), National Animal Health Monitoring System (NAHMS). January 2000.

USDA (1999a) *Cattle—Final Estimates 1994–98*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1999. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1999b) *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 (1999c) *Sheep and Goats—Final Estimates 1994–1998*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1999. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1998a) *Hogs and Pigs—Final Estimates 1993–97*. 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) *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 (1998c) Re-aggregated data from the National Animal Health Monitoring System's (NAHMS) Swine '95 study aggregated by Eric Bush of the 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) *Cattle—Final Estimates 1989–93*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1995. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1995b) *Poultry Production and Value—Final Estimates 1988–1993*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1995. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1994a) *Hogs and Pigs—Final Estimates 1988–92*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. December 1994. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1994b) *Sheep and Goats—Final Estimates 1989–1993*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 31, 1994. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

Wright, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Peter Wright, Cornell University, College of Agriculture and Life Sciences. June 23, 2000.

Rice Cultivation

Bollich, P. (2000) Telephone conversation between Payton Deeks of ICF International and Pat Bollich, Professor with Louisiana State University Agriculture Center. May 17, 2000.

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.

Cantens, G. (2005) Telephone conversation between Lauren Flinn of ICF International and Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company. August 4, 2005.

Cantens, G. (2004) Telephone conversation between Lauren Flinn of ICF International and Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company. July 30, 2004.

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) Telephone conversation between Caren Mintz and Dr. Chris Deren, Everglades Research and Education Centre at the University of Florida. August 15, 2002.

Guethle, D. (2006) Telephone conversation between Lauren Flinn of ICF International and David Guethle, Agronomy Specialist, Missouri Cooperative Extension Service. July 2005.

Guethle, D. (2005) Email correspondence between Lauren Flinn of ICF International and David Guethle, Agronomy Specialist, Missouri Cooperative Extension Service. July 2005.

Guethle, D. (2004) Telephone conversation between Lauren Flinn of ICF International and David Guethle, Agronomy Specialist, Missouri Cooperative Extension Service. June 23, 2004.

Guethle, D. (2003) Telephone conversation between Caren Mintz of ICF International and David Guethle, Agronomy Specialist, Missouri Cooperative Extension Service. June 19, 2003.

Guethle, D. (2002) Telephone conversation between Caren Mintz of ICF International and David Guethle, Agronomy Specialist, Missouri Cooperative Extension Service. August 19, 2002.

Guethle, D. (2001a) Telephone conversation between Caren Mintz of ICF International and David Guethle, Agronomy Specialist at Missouri Cooperative Extension Service. July 31, 2001.

Guethle, D. (2001b) Telephone conversation between Caren Mintz of ICF International and David Guethle, Agronomy Specialist at Missouri Cooperative Extension Service. September 4, 2001.

Guethle, D. (2000) Telephone conversation between Payton Deeks of ICF International and David Guethle, Agronomy Specialist, Missouri Cooperative Extension Service. May 17, 2000.

Guethle, D. (1999) Telephone conversation between Payton Deeks of ICF International and David Guethle, Agronomy Specialist, Missouri Cooperative Extension Service. August 6, 1999.

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 (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.

Kirstein, A. (2006) Telephone conversation between Lauren Flinn of ICF International and Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, FL. August 17, 2006.

Kirstein, A. (2004) Telephone conversation between Lauren Flinn of ICF International and Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, FL. June 30, 2004.

Kirstein, A. (2003) Telephone conversation between Caren Mintz of ICF International and Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, FL. August 13, 2003.

Klosterboer, A. (2003) Telephone conversation between Caren Mintz of ICF International and Arlen Klosterboer, retired Extension Agronomist, Texas A&M University. July 7, 2003.

Klosterboer, A. (2002) Telephone conversation between Caren Mintz of ICF International and Arlen Klosterboer, Extension Agronomist, Texas A&M University. August 19, 2002.

Klosterboer, A. (2001a) Telephone conversation between Caren Mintz of ICF International and Arlen Klosterboer, Extension Agronomist, Texas A & M University. August 6, 2001.

Klosterboer, A. (2001b) Telephone conversation between Caren Mintz of ICF International and Arlen Klosterboer, Extension Agronomist, Texas A & M University. October 8, 2001.

Klosterboer, A. (2000) Telephone conversation between Payton Deeks of ICF International and Arlen Klosterboer, Extension Agronomist, Texas A & M University. May 18, 2000.

Klosterboer, A. (1999) Telephone conversation between Catherine Leining of ICF International and Arlen Klosterboer, Extension Agronomist, Texas A & M University. June 10, 1999.

Klosterboer, A. (1997) Telephone conversation between Holly Simpkins of ICF Incorporated and Arlen Klosterboer, Texas A & M University. December 1, 1997.

Lee, D. (2006) Email correspondence between Lauren Flinn of ICF International and Danny Lee, OK Farm Service Agency. July 13, 2006.

Lee, D. (2005) Email correspondence between Lauren Flinn of ICF International and Danny Lee, OK Farm Service Agency, Stillwater, OK. July and September 2005.

Lee, D. (2004) Telephone conversation between Lauren Flinn of ICF International and Danny Lee, OK Farm Service Agency, Stillwater, OK. July 23, 2004.

Lee, D. (2003) Telephone conversation and email correspondence between Caren Mintz of ICF International and Danny Lee, OK Farm Service Agency, Stillwater, OK. July 2, 2003.

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. (2006) Email correspondence between Lauren Flinn of ICF International and Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center. Slinscombe@agctr.lsu.edu. August 15, 2006.

Linscombe, S. (2005) Email correspondence between Lauren Flinn of ICF International and Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center. July 2005.

Linscombe, S. (2004) Telephone conversation between Lauren Flinn of ICF International and Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center. June 23, 2004.

Linscombe, S. (2003) Telephone conversation between Caren Mintz of ICF International and Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center. June 10, 2003.

Linscombe, S. (2002) Telephone conversation between Caren Mintz of ICF International and Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center. August 21, 2002.

Linscombe, S. (2001a) Telephone conversation between Caren Mintz of ICF International and Steve Linscombe, Research Agronomist, Rice Research Station in Crowley, LA. July 30-August 1, 2001.

Linscombe, S. (2001b) Email correspondence between Caren Mintz of ICF International and Steve Linscombe, Research Agronomist, Rice Research Station in Crowley, LA. October 4, 2001.

Linscombe, S. (1999) Telephone conversation between Catherine Leining of ICF International and Steve Linscombe, Research Agronomist, Rice Research Station in Crowley, LA. June 3, 1999.

Mayhew, W. (1997) Telephone conversation between Holly Simpkins of ICF Incorporated and Walter Mayhew, University of Arkansas, Little Rock. November 24, 1997.

Mutters, C. (2005) Email correspondence between Lauren Flinn of ICF International and Mr. Cass Mutters, Rice Farm Advisor for Butte, Glen, and Tehama Counties. University of California Cooperative Extension Service. July 2004.

Mutters, C. (2004) Telephone conversation between Lauren Flinn of ICF International and Mr. Cass Mutters, Rice Farm Advisor for Butte, Glen, and Tehama Counties. University of California Cooperative Extension Service. June 25, 2004.

Mutters, C. (2003) Telephone conversation between Caren Mintz of ICF International and Mr. Cass Mutters, Rice Farm Advisor for Butte, Glen, and Tehama Counties. University of California Cooperative Extension Service. June 23, 2003.

Mutters, C. (2002) Telephone conversation between Caren Mintz of ICF International and Mr. Cass Mutters, Rice Farm Advisor for Butte, Glen, and Tehama Counties. University of California Cooperative Extension Service. August 27, 2002.

Mutters, C. (2001) Telephone conversation between Caren Mintz of ICF International and Mr. Cass Mutters, Rice Farm Advisor for Butte, Glen, and Tehama Counties, University of California Cooperative Extension Service. September 5, 2001.

Saichuk, J. (1997) Telephone conversation between Holly Simpkins of ICF Incorporated and John Saichuk of Louisiana State University. 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. (2001a) Telephone conversation between Caren Mintz of ICF International and Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL. July 30, 2001.

Schueneman, T. (2001b) Telephone conversation between Caren Mintz of ICF International and Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL. October 9, 2001.

Schueneman, T. (2000) Telephone conversation between Payton Deeks of ICF International and Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL. May 16, 2000.

Schueneman, T. (1999a) Telephone conversation between Catherine Leining of ICF International and Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL. June 7, 1999.

Schueneman, T. (1999b) Telephone conversation between Payton Deeks of ICF International and Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL. August 10, 1999.

Schueneman, T. (1999c) Telephone conversation between John Venezia of ICF International and Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL. August 7, 1999.

Schueneman, T. (1997) Telephone conversation between Barbara Braatz of ICF Incorporated and Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL. November 7, 1997.

Slaton, N. (2001a) Telephone conversation between Caren Mintz of ICF International and Nathan Slaton, Extension Agronomist—Rice, University of Arkansas Division of Agriculture Cooperative Extension Service. August 23, 2001.

Slaton, N. (2001b) Telephone conversation between Caren Mintz of ICF International and Nathan Slaton, Extension Agronomist—Rice, University of Arkansas Division of Agriculture Cooperative Extension Service. October 3, 2001.

Slaton, N. (2000) Telephone conversation between Payton Deeks of ICF International and Nathan Slaton, Extension Agronomist-Rice, University of Arkansas Division of Agriculture Cooperative Extension Service. May 20, 2000.

Slaton, N. (1999) Telephone conversation between Catherine Leining of ICF International and Nathan Slaton, Extension Agronomist—Rice, University of Arkansas Division of Agriculture Cooperative Extension Service. June 3, 1999.

Stansel, J. (2005) Email correspondence between Lauren Flinn of ICF International and Dr. Jim Stansel, Resident Director and Professor Emeritus, Texas A&M University Agricultural Research and Extension Center. July 2005.

Stansel, J. (2004) Telephone conversation between Lauren Flinn of ICF International and Dr. Jim Stansel, Resident Director and Professor Emeritus, Texas A&M University Agricultural Research and Extension Center. July 12, 2004.

Stevens, G. (1997) Telephone conversation between Holly Simpkins of ICF Incorporated and Gene Stevens, Extension Specialist, Missouri Commercial Agriculture Program, Delta Research Center. December 17, 1997.

Street, J. (2003) Telephone conversation and email correspondence between Caren Mintz of ICF International and Joe Street, Rice Specialist, Mississippi State University, Delta Research Center. June 19, 2003.

Street, J. (2002) Telephone conversation and email correspondence between Caren Mintz of ICF International and Joe Street, Rice Specialist, Mississippi State University, Delta Research Center. August 19, 2002.

Street, J. (2001a) Telephone conversation between Caren Mintz of ICF International and Dr. Joe Street, Mississippi State University, Delta Research and Extension Center and Delta Branch Station. August 1, 2001.

Street, J. (2001b) Telephone conversation between Caren Mintz of ICF International and Dr. Joe Street, Mississippi State University, Delta Research and Extension Center and Delta Branch Station. October 3, 2001.

Street, J. (2000) Telephone conversation between Payton Deeks of ICF International and Joe Street, Rice Specialist, Mississippi State University, Delta Research Center. May 17, 2000.

Street, J. (1999) Telephone conversation between Catherine Leining of ICF International and Joe Street, Rice Specialist, Mississippi State University, Delta Research Center. June 8, 1999.

Street, J. (1997) Telephone conversation between Holly Simpkins of ICF Incorporated and Dr. Joe Street, Mississippi State University, Delta Research and Extension Center and Delta Branch Station. December 1, 1997.

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 (2006) *Crop Production 2005 Summary*, National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu>.

USDA (2005) *Crop Production 2004 Summary*. National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/>. Accessed June 2005.

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/>. Accessed September 2005.

USDA (1998) *Field Crops Final Estimates 1992–97*. Statistical Bulletin Number 947 a. National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/>. Accessed July 2001.

USDA (1994) *Field Crops Final Estimates 1987–1992*. Statistical Bulletin Number 896. National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/>. Accessed July 2001.

Walker, T. (2005) Email correspondence between Lauren Flinn of ICF International and Tim Walker, Assistant Research Professor, Mississippi State University Delta Branch Exp. Station. July 2005.

Wilson, C. (2006) Email coorespondence between Lauren Flinn of ICF International and Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service. (870) 673-2661. Wilson@uamont.edu. August 8, 2006.

Wilson, C. (2005) Email correspondence between Lauren Flinn of ICF International and Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service. August 2005.

Wilson, C. (2004) Telephone conversation between Lauren Flinn of ICF International and Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service. June 23, 2004.

Wilson, C. (2003) Telephone conversation between Caren Mintz of ICF International and Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service. June 11, 2003.

Wilson, C. (2002) Telephone conversation between Caren Mintz of ICF International and Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service. August 23, 2002.

Agricultural Soil Management

AAPFCO (2006) *Commercial Fertilizers 2005*. Association of American Plant Food Control Officials and The Fertilizer Institute, University of Kentucky, Lexington, KY.

AAPFCO (2005) *Commercial Fertilizers 2004*. Association of American Plant Food Control Officials and The Fertilizer Institute University of Kentucky, Lexington, KY.

AAPFCO (2004) *Commercial Fertilizers 2003*. Association of American Plant Food Control Officials and The Fertilizer Institute University of Kentucky, Lexington, KY.

AAPFCO (2003) *Commercial Fertilizers 2002*. Association of American Plant Food Control Officials and The Fertilizer Institute University of Kentucky, Lexington, KY.

AAPFCO (2002) *Commercial Fertilizers 2001*. Association of American Plant Food Control Officials and The Fertilizer Institute, 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.

AAPFCO (2000b) *Commercial Fertilizers 2000*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1999) *Commercial Fertilizers 1999*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1998) *Commercial Fertilizers 1998*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1997) *Commercial Fertilizers 1997*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1996) *Commercial Fertilizers 1996*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1995) *Commercial Fertilizers 1995*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

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.

Anderson, S. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Steve Anderson, Agricultural Statistician, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. May 31, 2000.

Anonymous (1924) Fertilizer Used on Cotton, 1923–1924. "Miscellaneous Agricultural Statistics," Table 753. *1924 Yearbook of the Department of Agriculture*, 1171.

ASAE (1999) *ASAE Standards 1999, 46th Edition*. American Society of Agricultural Engineers, St. Joseph, MI.

Bastian, R. (2006) Telephone conversation between Lauren Flinn of ICF International and Robert Bastian, Office of Water, U.S. Environmental Protection Agency, Washington, DC. July 17, 2006.

Bastian, R. (2005) Telephone conversation between Lauren Flinn of ICF International and Robert Bastian, Office of Water, U.S. Environmental Protection Agency, Washington, DC. September 2005.

Bastian, R. (2003) Telephone conversation between Caren Mintz of ICF International and Robert Bastian, Office of Water, U.S. Environmental Protection Agency, Washington, DC. August 13, 2003.

Bastian, R. (2002) Telephone conversation between Caren Mintz of ICF International and Robert Bastian, Office of Water, U.S. Environmental Protection Agency, Washington, DC. August 23, 2002.

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.

Bouwman, A.F., L.J.M. Boumans, and N.H. Batjes. (2002a) "Emissions of N_2O and NO from fertilised fields: Summary of available measurement data." *Glob. Biogeochem. Cycles*, 16(4), art. no. 1058.

Bouwman, A.F., L.J.M. Boumans, and N.H. Batjes (2002b) "Modeling global annual N_2O and NO emissions from fertilised fields." *Glob. Biogeochem. Cycles*, 16(4), art. no. 1080.

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 USDA Natural Resources Conservation Service, 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.

Brumme, R., Borken, W., and Finke, S. (1999) "Hierarchical control on nitrous oxide emission in forest ecosystems." *Global Biochem. Cycles* 13:1137–1148.

Butterbach-Bahl, K., R. Gasche, L. Breuer, and H. Papen. (1997) "Fluxes of NO and N_2O from temperate forest soils: impact of forest type, N deposition and of liming on the NO and N_2O emissions." *Nutr. Cycl. Agroecosyst*. 48:79–90.

Carpenter, G.H. (1992) "Current Litter Practices and Future Needs." In *1992 National Poultry Waste Management Symposium Proceedings*. J.P. Blake, J.O. Donald, and P.H. Patterson (eds.); Auburn University Printing Service, Auburn, AL, 268-273.

Chilcott E.C. (1910) *A Study of Cultivation Methods and Crop Rotations for the Great Plains Area*. U.S. Department of Agriculture Bureau of Plant Industry Bulletin Number 187. Government Printing Office, Washington, DC.

Clough, T., J.E. Bertram, R.R. Sherlock, R.L. Leonard, and B.L. Nowicki (2006) "Comparison of measured and EF5-r-derived N_2O fluxes from a spring-fed river." *Glob. Change Biol*. 12:477–488.

Corre, M.D., D.J. Pennock, C. van Kessel, and D.K. Elliott (1999) "Estimation of annual nitrous oxide emissions from a transitional grassland-forest region in Saskatchewan, Canada. *Biogeochem*. 44:29–49.

CTIC (1998) *1998 Crop Residue Management Executive Summary*. Conservation Technology Information Center. Data available online at <http://www.ctic.purdue.edu/Core4/CT/CT.html>.

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.

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.

DAYMET (No date) *Daily Surface Weather and Climatological Summaries*. Numerical Terradynamic Simulation Group (NTSG), University of Montana. Available online at <http://www.daymet.org>.

Deal, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Peter B. Deal, Rangeland Management Specialist, Florida Natural Resource Conservation Service. June 21, 2000.

de Klein, C.A.M (2004) "Review of the N_2O emission factor for excreta deposited by grazing animals (EF_{3PRP})." Paper prepared as part of the 2006 Revised Guidelines for Greenhouse Gas Inventories of IPCC.

Del Grosso, S.J., A.R. Mosier, W.J. Parton, and D.S. Ojima (2005) "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA." *Soil Tillage and Research*, 83: 9–24. doi: 10.1016/j.still.2005.02.007.

Del Grosso, S.J., S.M. Ogle, and F.J. Breidt (in prep.) "Uncertainty in estimating nitrous oxide emissions from cropped and grazed soils in the USA." Manuscript in preparation.

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.

Denier van der Gon, H., and A. Bleeker (2005) "Indirect N_2O emission due to atmospheric N deposition for the Netherlands." *Atmos. Environ.* 39:5827–5838.

Dong, L.F., D.B. Nedwell, I. Colbeck, and J. Finch (2004) "Nitrous oxide emission from some English and Welsh rivers and estuaries." *Water Air Soil Pollution: Focus* 4:127–134.

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 Fertilizer Review*. The National Fertilizer Association, 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 (2002) *Cost Methodology for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations*. EPA-821-R-03-004. December 2002.

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 (1997) 1*996 Clean Watersheds 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*, U.S. Environmental Protection Agency, Washington, DC. Available online at <http://www.epa.gov/owm/mtb/cwns/1996rtc/toc.htm>.

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.

EPA (1992) *Global Methane Emissions from Livestock and Poultry Manure*. Office of Air and Radiation, U.S. Environmental Protection Agency. February 1992.

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. September 26, 2003.

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 (1997) *Cropping Practices Survey Data—1995*. Economic Research Service, U.S. Department of Agriculture. Available online at <http://www.ers.usda.gov/data/archive/93018/>.

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.

Eve, M. (2001) E-mail from Marlen Eve of the Natural Resources Ecology Laboratory to Barbara Braatz and Caren Mintz of ICF International, containing 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.

FAO (2006) Yearly U.S. total horse population data from the Food and Agriculture Organization of the United Nations database. Available online at <http://apps.fao.org>.

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.

Hargreaves, M.W.M. (1993) *Dry Farming in the Northern Great Plains: Years of Readjustment, 1920–1990*. University Press of Kansas, Lawrence, KS.

Hiscock, K.M., A.S. Bateman, T. Fukada, and P.F. Dennis (2002) “The concentration and distribution of groundwater N_2O in the Chalk aquifer of eastern England.” In J. Van Ham, A.P.M. Baede, R. Guicherit, and J.G.F.M Williams-Jacobse (eds.); *Proc. 3rd Internat. Symp. Non-CO_2 Greenhouse Gases*, Maastricht, The Netherlands,185–190.

Hiscock, K.M., A.S. Bateman, I. H. Muhlherr, T. Fukada, and P.F. Dennis (2003) “Indirect emissions of nitrous oxide from regional aquifers in the United Kingdom.” *Environ. Sci. Technol*. 37:3507–3512.

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. (1930) *Cropping Systems in Iowa Past and Present*. Agricultural Experiment Station Bulletin Number 268. Iowa State College of Agriculture and Mechanic Arts, Ames, IA.

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.

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.

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, H.S. Eggleston, L. Buenida, K. Miwa, T Ngara, and K. Tanabe, eds.; Institute for Global Environmental Strategies (IGES). 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 (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.

Johnson, D. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Dan Johnson, State Water Management Engineer, California Natural Resource Conservation Service. June 23, 2000.

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.

Klemedtsson, L., A. Kasimir Klemedtsson, M. Escala, and A. Kulmala (1999) “Inventory of N_2O emission from farmed European peatlands.” In A. Freibauer and M. Kaltschmitt (eds.); *Approaches to Greenhouse Gas Inventories of Biogenic Sources in Agriculture*, Proc. Workshop at Lökeberg, Sweden, 79–91. 9–10 July 1998.

Kuchler, AW. (1964) “The Potential Natural Vegetation of the Conterminous United States.” *Amer. Geographical Soc. NY*, Special Publication No. 36.

Lange, J. (2000) Telephone conversation between Lee-Ann Tracy of ERG and John Lange, Agricultural Statistician, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. May 8, 2000.

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.

Metcalf and Eddy, Inc. (1991) *Wastewater Engineering: Treatment, Disposal, and Reuse*, Third Edition. McGraw-Hill Publishing Company, New York, 772.

Miller, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Paul Miller, Iowa Natural Resource Conservation Service. June 12, 2000.

Milton, B. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Bob Milton, Chief of Livestock Branch, U.S. Department of Agriculture, National Agriculture Statistics Service. May 1, 2000.

Mosier, A.R. (2004) E-mail correspondence between Arvin Mosier of Agricultural Research Service, USDA and Stephen Del Grosso of 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>.

NFA (1946) *Charting the Fertilizer Course: Results of NFA's Third Practice Survey*. National Fertilizer Association. The Fertilizer Review. Vol. XXI, 2:7-13.

Novoa, R. and H.R. Tejeda (2006) Evaluation of the N_2O emissions from N in plant residues as affected by environmental and management factors. Nutr. Cycl. Agroecosyst. (in press; available on-line).

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. Natural Resources Inventory and Analysis Institute, Natural Resources Conservation Service. U.S. Department of Agriculture.

Ogle, S. (2002) E-mail from Stephen Ogle of the Natural Resources Ecology Laboratory to Barbara Braatz of ICF International, containing revised statistics on U.S. histosol areas cultivated in 1982, 1992, and 1997, which were extracted from the *1997 National Resources Inventory* by Marlen Eve, January 9, 2002.

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*, accepted for publication, but not yet published.

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.

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." Y*earbook of the Department of Agriculture*, 285–376.

Poe, G., N. Bills, B. Bellows, P. Crosscombe, R. Koelsch, M. Kreher, and P. Wright (1999) *Documenting the Status of Dairy Manure Management in New York: Current Practices and Willingness to Participate in Voluntary Programs*. Staff Paper, Dept. of Agricultural, Resource, and Managerial Economics, Cornell University, Ithaca, NY, September 1999.

Reay, D.S., K.A. Smith, and A.C. Edwards (2004) "Nitrous oxide in agricultural drainage waters following field fertilisation." *Water Air Soil Pollution: Focus*, 4:437-451.

Reay, D., K.A. Smith, A.C. Edwards, K.M. Hiscock, L.F. Dong, and D. Nedwell (2005) "Indirect nitrous oxide emissions: revised emission factors." *Environ. Sciences*, 2:153–158.

Rochette, P., D.A. Angers, G. Belanger, M.H. Chantigny, D. Prevost, G. Levesque, (2004) "Emissions of N_2O from alfalfa and soybean crops in eastern Canada." *Soil Sci. Soc. Am. J.* 68:493–506.

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.

Safley, L.M. (2000) Telephone conversation between Deb Bartram of ERG and L.M. Safley, President, Agri-Waste Technology. June 2000.

Safley, L.M., M.E. Casada, J.W. Woodbury, and J.F. Roos (1992) *Global Methane Emissions from Livestock and Poultry Manure*. EPA/400/1-91/048, Office of Air and Radiation, U.S. Environmental Protection Agency. February 1992.

Sawamoto, T., Y. Nakajima, M. Kasuya, H. Tsuruta, and K. Yagi (2005) "Evaluation of emission factors for indirect N_2O emission due to nitrogen leaching in agro-ecosystems." *Geophys. Res. Lett.* 32(3), doi:10.1029/2004GL021625.

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.

Stehfest, E. and A.F. Bouwman (2006) "N_2O and NO emission from agricultural fields and soils under natural vegetation: summarising available measurement data and modelling of global annual emissions." *Nutr. Cycl. Agroecosyst.*, (in press; available on-line).

Stettler, D. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Don Stettler, Environmental Engineer, National Climate Center, Oregon Natural Resource Conservation Service. June 27, 2000.

Sweeten, J. (2000) Telephone conversation between Indra Mitra of ERG and John Sweeten, Texas A&M University. June 2000.

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." *Agricultural 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 (1994) *Commercial Fertilizers 1994*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1993) *Commercial Fertilizers 1993*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1992a) *Commercial Fertilizers 1992*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1992b) *Fertilizer Summary Data 1992*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1991) *Commercial Fertilizers 1991*. Tennessee Valley Authority, Muscle Shoals, AL.

USDA (2006a) *Agriculture Statistics 2006*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC.

USDA (2006b) *Crop Production 2005 Summary*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu>.

USDA (2005a) *Cattle*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. January 28, 2005. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2005b) *Cattle on Feed*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. January 21, 2005. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2005c) *Hogs and Pigs*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. March 24, 2005. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2005d) *Chicken and Eggs Annual Summary*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. February 2005. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2005e) *Poultry Production and Value Annual Summary*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. April 28, 2005. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2005f) *Sheep and Goats*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. January 28, 2005. Available online at <http://www.usda.gov/nass/pubs/reportname.htm>.

USDA (2005g) 1992, 1997, and 2002 *Census of Agriculture*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://www.nass.usda.gov/census/>.

USDA (2005h) *Agriculture Statistics 2005*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <ftp://www.nass.usda.gov/pub/nass/county/byyear/> or <http://www.usda.gov/nass/pubs/agstats.htm>.

USDA (2005i) *Crop Production 2004 Summary*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu>.

USDA (2004a) *Cattle—Final Estimates 1999–2003*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. April 2004. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (2004b) *Hogs and Pigs—Final Estimates 1998–2002*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. March 2004. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (2004c) *Chicken and Eggs—Final Estimates 1998–2003*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. April 2004. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (2004d) *Poultry Production and Value—Final Estimates 1998–2002*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. April 2004. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (2004e) *Sheep and Goats—Final Estimates 1999–2003*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. April 2004. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (2004f) Statistics on county level total crop area data for 1990–2003, extracted from the *Agricultural Statistics Database*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://www.nass.usda.gov:81/ipedb/>.

USDA (2003) *Crop Production 2002 Summary*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu>. Accessed May 2003.

USDA (2000a) *Cattle on Feed*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. April 14, 2000. Data also available online at <http://www.nass.usda.gov:81/ipedb/>.

USDA (2000b) *1997 National Resources Inventory*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://www.nrcs.usda.gov/technical/NRI/>.

USDA (2000c) *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 (1999a) *Cattle—Final Estimates 1994–98*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1999. Data also available online at <http://www.nass.usda.gov:81/ipedb/>.

USDA (1999b) *Poultry Production and Value—Final Estimates 1994–97*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. March.

USDA (1999c) *Sheep and Goats—Final Estimates 1994–1998*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1999.

USDA (1998a) *Chicken and Eggs—Final Estimates 1994–97*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. December 1998.

USDA (1998b) *Field Crops Final Estimates 1992–97*. 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 (1998c) *Hogs and Pigs—Final Estimates 1993–97*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. December 1998. Data also available online at <http://www.nass.usda.gov:81/ipedb/>.

USDA (1996) *Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH)*, Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture. July 1996.

USDA (1995a) *Cattle—Final Estimates 1989–93*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1995. Data also available online at <http://www.nass.usda.gov:81/ipedb/>.

USDA (1995b) *Poultry Production and Value—Final Estimates 1989–1993*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC.

USDA (1994a) *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 (1994b) *Hogs and Pigs—Final Estimates 1988–92*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. December 1994. Data also available online at <http://www.nass.usda.gov:81/ipedb/>.

USDA (1994c) *Sheep and Goats—Final Estimates 1989–1993*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1994.

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.

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.

Vogelmann, 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) From an unpublished manuscript and data compiled for the Consortium for Agricultural Soils Mitigation of Greenhouse Gases (CASMGS). Natural Resource Ecology Laboratory, Colorado State University.

Williams-Jacobse, J.G.F.M. (ed.) (2002) *Proceedings 3rd International Symposium Non-CO_2 Greenhouse Gases*, Maastricht, the Netherlands, 185–190.

Wright, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Peter Wright, Cornell University, College of Agriculture and Life Sciences. June 23, 2000.

Field Burning of Agricultural Residues

Anonymous (2006) Telephone conversation with Lauren Flinn of ICF International. August 11, 2006.

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.

Bollich, P. (2000) Telephone conversation between Payton Deeks of ICF International and Pat Bollich, Professor with Louisiana State University Agriculture Center. May 17, 2000.

California Air Resources Board (2001) *Progress Report on the Phase Down and the 1998–2000 Pause in the Phase Down of Rice Straw Burning in the Sacramento Valley Air Basin*, Proposed 2001 Report to the Legislature. June 2001.

California Air Resources Board (1999) *Progress Report on the Phase Down of Rice Straw Burning in the Sacramento Valley Air Basin*, Proposed 1999 Report to the Legislature. December 1999.

Cantens, G. (2005) Telephone conversation between Lauren Flinn of ICF International and Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company. July 2005.

Cantens, G. (2004) Telephone conversation between Lauren Flinn of ICF International and Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company. July 30, 2004.

Cibrowski, P. (1996) Telephone conversation between Heike Mainhardt of ICF Incorporated and Peter Cibrowski, Minnesota Pollution Control Agency. July 29, 1996.

Deren, C. (2002) Telephone conversation between Caren Mintz of ICF International and Dr. Chris Deren, Everglades Research and Education Centre at the University of Florida. 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.

Fife, L. (1999) Telephone conversation between Catherine Leining of ICF International and Les Fife, President and General Manager, Fife Environmental. June 9, 1999.

ILENR (1993) Illinois Inventory of Greenhouse Gas Emissions and Sinks: 1990. Office of Research and Planning, Illinois Department of Energy and Natural Resources. Springfield, IL.

IPCC (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.

Ketzis, J. (1999) Telephone conversation between Marco Alcaraz of ICF International and Jen Ketzis of Cornell University. June/July 1999.

Kirstein, A. (2004) Telephone conversation between Lauren Flinn of ICF International and Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, Florida. June 30, 2004.

Kirstein, A. (2003) Telephone conversation between Caren Mintz of ICF International and Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, Florida. August 13, 2003.

Klosterboer, A. (2003) Telephone conversation between Caren Mintz of ICF International and Arlen Klosterboer, retired Extension Agronomist, Texas A&M University. July 7, 2003.

Klosterboer, A. (2002) Telephone conversation between Caren Mintz of ICF International and Arlen Klosterboer, Extension Agronomist, Texas A & M University. August 19, 2002.

Klosterboer, A. (2001) Telephone conversation between Caren Mintz of ICF International and Arlen Klosterboer, Extension Agronomist, Texas A & M University. August 6, 2001.

Klosterboer, A. (2000) Telephone conversation between Payton Deeks of ICF International and Arlen Klosterboer, Extension Agronomist, Texas A & M University. May 18, 2000.

Klosterboer, A. (1999a) Telephone conversation between Catherine Leining of ICF International and Arlen Klosterboer, Extension Agronomist, Texas A & M University. June 10, 1999.

Klosterboer, A. (1999b) Telephone conversation between Payton Deeks of ICF International and Arlen Klosterboer, Extension Agronomist, Texas A & M University. August 12, 1999.

Lancero, J. (2006) Email correspondence between Lauren Flinn of ICF International and Jeff Lancero, California Air Resources Board. August 11, 2006.

Lee, D. (2006) Email correspondence between Lauren Flinn of ICF International and Danny Lee, OK Farm Service Agency. July 13, 2006.

Lee, D. (2005) Email correspondence between Lauren Flinn of ICF International and Danny Lee, OK Farm Service Agency, Stillwater, OK. July and September 2005.

Lee, D. (2004) Telephone conversation between Lauren Flinn of ICF International and Danny Lee, OK Farm Service Agency, Stillwater, OK. July 23, 2006.

Lee, D. (2003) Telephone conversation and email correspondence between Caren Mintz of ICF International and Danny Lee, OK Farm Service Agency, Stillwater, OK. July 2, 2003.

Lindberg, J. (2005) Email correspondence between Lauren Flinn of ICF International and Jeff Lindberg, California Air Resources Board. July 2005.

Lindberg, J. (2004) Email correspondence between Lauren Flinn of ICF International and Jeff Lindberg, California Air Resources Board. June–July 2004.

Lindberg, J. (2003) Email correspondence between Caren Mintz of ICF International and Jeff Lindberg, California Air Resources Board. June–July 2003.

Lindberg, J. (2002) Telephone conversation and email correspondence between Caren Mintz of ICF International and Jeff Lindberg, California Air Resources Board. September 12–13, 2002.

Linscombe, S. (2006) Email correspondence between Lauren Flinn of ICF International and Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center. August 15, 2006.

Linscombe, S. (2005) Email correspondence between Lauren Flinn of ICF International and Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center. July 2005.

Linscombe, S. (2004) Telephone conversation between Lauren Flinn of ICF International and Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center. June 23, 2004.

Linscombe, S. (2003) Telephone conversation between Caren Mintz of ICF International and Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center. June 10, 2003.

Linscombe, S. (2002) Email correspondence between Caren Mintz of ICF International and Steve Linscombe, Research Agronomist, Louisiana State University Agricultural Center. August 21, 2002.

Linscombe, S. (2001) Email correspondence between Caren Mintz of ICF International and Steve Linscombe, Research Agronomist, Louisiana State University Agricultural Center. July 30–August 1, 2001.

Linscombe, S. (1999a) Telephone conversation between Catherine Leining of ICF International and Steve Linscombe, Research Agronomist, Louisiana State University Agricultural Center. June 3, 1999.

Linscombe, S. (1999b) Telephone conversation between Payton Deeks of ICF International and Steve Linscombe, Research Agronomist, Louisiana State University Agricultural Center. August 9, 1999.

Najita, T. (2001) Telephone conversation between Caren Mintz of ICF International and Theresa Najita, Air Pollution Specialist, California Air Resources Board. July 31, 2001.

Najita, T. (2000) Telephone conversation between Payton Deeks of ICF International and Theresa Najita, Air Pollution Specialist, California Air Resources Board. August 17, 2000.

Noller, J. (1996) Telephone conversation between Heike Mainhardt of ICF Incorporated and John Noller, Missouri Department of Natural Resources. July 30, 1996.

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.

Sacramento Valley Basinwide Air Pollution Control Council (2005) Report on the Conditional Rice Straw Burning Permit Program. May 25, 2005. Available online at <http://www.bcaqmd.org/default.asp?docpage=html/bcc.htm>.

Schueneman, T. (2001) Telephone conversation between Caren Mintz of ICF International and Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL. July 30, 2001.

Schueneman, T. (1999a) Telephone conversation between Catherine Leining of ICF International and Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL. June 7, 1999.

Schueneman, T. (1999b) Telephone conversation between Payton Deeks of ICF International and Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL. August 10, 1999.

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.

Stansel, J. (2005) Email correspondence between Lauren Flinn of ICF International and Dr. Jim Stansel, Resident Director and Professor Emeritus, Texas A&M University Agricultural Research and Extension Center. July 2005.

Stansel, J. (2004) Telephone conversation between Lauren Flinn of ICF International and Dr. Jim Stansel, Resident Director and Professor Emeritus, Texas A&M University Agricultural Research and Extension Center. July 12, 2004.

Street, J. (2003) Telephone conversation between Caren Mintz of ICF International and Joe Street, Rice Specialist, Mississippi State University, Delta Research Center. June 19, 2003.

Street, J. (2002) Telephone conversation and email correspondence between Caren Mintz of ICF International and Joe Street, Rice Specialist, Mississippi State University, Delta Research Center. August 19, 2002.

Street, J. (2001) Telephone conversation and email correspondence between Caren Mintz of ICF International and Joe Street, Rice Specialist, Mississippi State University, Delta Research Center. August 1, 2001.

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.

University of California (1977) *Emission Factors From Burning of Agricultural Waste Collected in California*. University of California, Davis.

USDA (2006) *Crop Production 2005 Summary*. National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/>. Accessed July 2006.

USDA (2005) *Crop Production 2004 Summary*. National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/>. Accessed June 2005.

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/>. Accessed September 2005.

USDA (1998) *Field Crops, Final Estimates 1992–1997*. Statistical Bulletin No. 947a. 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/b9471298.pdf>.

USDA (1994) *Field Crops, Final Estimates 1987–1992*. Statistical Bulletin No. 896. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/data-sets/crops/94896/sb896.txt>.

Walker, T. (2006) Telephone conversation between Lauren Flinn of ICF International and Tim Walker, Assistant Research Professor, Mississippi State University Delta Branch Exp. Station. August 17, 2006.

Walker, T. (2005) Email correspondence between Lauren Flinn of ICF International and Tim Walker, Assistant Research Professor, Mississippi State University Delta Branch Exp. Station. July 2005.

Walker, T. (2004) Telephone conversation between Lauren Flinn of ICF International and Tim Walker, Assistant Research Professor, Mississippi State University Delta Branch Exp. Station. July 12, 2004.

Wilson, C. (2006) Email coorespondence between Lauren Flinn of ICF International and Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service. (870) 673-2661. Wilson@uamont.edu. August 8, 2006.

Wilson, C. (2005) Email correspondence between Lauren Flinn of ICF International and Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service. July 2005.

Wilson, C. (2004) Telephone conversation between Lauren Flinn of ICF International and Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service. June 23, 2004.

Wilson, C. (2003) Telephone conversation between Caren Mintz of ICF International and Dr. Chuck Wilson, Rice Specialist, University of Arkansas Cooperative Extension Service. June 11, 2003.

Wisconsin Department of Natural Resources (1993) *Wisconsin Greenhouse Gas Emissions: Estimates for 1990*. Bureau of Air Management, Wisconsin Department of Natural Resources, Madison, WI.

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>.

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.

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 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. 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.

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 (2006a) *Inventory of U. S. Greenhouse Gas Emissions and Sinks: 1990–2004*. EPA, Office of Atmospheric Programs, Washington, DC.

EPA (2006b) *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.

Gillespie, A.J.R. (1999) "Rationale for a National Annual Forest Inventory Program." *Journal of Forestry* 97(12): 16–20.

Hair, D. (1958) "Historical forestry statistics of the United States." Statistical Bull. 228. U.S. Department of Agriculture Forest Service, 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.

Heath, L.S. (2006a) E-mail correspondence between Linda Heath of the U.S. Department of Agriculture Forest Service and Kimberly Klunich of the 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) E-mail correspondence between Linda Heath of the U.S. Department of Agriculture Forest Service and Kimberly Klunich of the U.S. Environmental Protection Agency regarding the 95 percent CI for average carbon density for Alaska (+/-1.2%). October 27, 2006.

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, 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.

Howard, James L. (forthcoming) *U.S. timber production, trade, consumption, and price statistics 1965 to 2005*. Res. Pap. FPL-RP-XXX. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

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>.

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.

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.

Perry, C.H., C.W. Woodall, and M. Schoeneberger (2005) Inventorying trees in agricultural landscapes: towards an accounting of "working trees". In: Brooks, K.N. and Ffolliott, P.F. (eds); "Moving Agroforestry into the Mainstream." *Proc. 9th N. Am. Agroforestry Conf.*, 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. (in preparation) “Sequestration of carbon in harvested wood products for the United States.”

Smith, James E., Linda S. Heath, and Michael C. Nichols (In preparation). U.S. Forest Carbon Calculation Tool User’s Guide: Forestland Carbon Stocks and Net Annual Stock Change. Gen Tech Report, U.S. Department of Agriculture Forest Service, Northern Research Station.

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, Newtowne Square, PA.

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 a) “How to estimate forest carbon for large areas from inventory data.” *Journal of Forestry* 102:25–31.

Smith, W. B., P. D. Miles, J. S. Vissage, and S. A. Pugh (2004b) *Forest Resources of the United States, 2002*. General Technical Report NC-241, U.S. Department of Agriculture Forest Service, North Central Research Station, St. Paul, MN.

Steer, Henry B. (1948) *Lumber production in the United States*. Misc. Pub. 669, 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.

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.

USDA Forest Service. (2006a) Forest Inventory and Analysis National Program, FIA library. Available online at <http://www.fia.fs.fed.us/library/field-guides-methods-proc/>. Accessed September 20, 2006.

USDA Forest Service. (2006b) Forest Inventory and Analysis Data Center. Available online at <http://ncrs2.fs.fed.us/4801/fiadb/>. Accessed September 20, 2006.

USDA Forest Service. (2006c) FIA Data Mart: Download. Available online at <http://www.ncrs2.fs.fed.us/FIADatamart/fiadatamart.aspx>. Click on documentation link to download Users Guide to the Forest Inventory Snapshot Database Version 2.1. Accessed September 20, 2006.

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.

USDC Bureau of Census (1976) *Historical Statistics of the United States, Colonial Times to 1970, Vol. 1*. Washington, DC.

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.

Forest Land Remaining Forest Land: Direct N_2O Fluxes from Forest Soils

Binkley, D. (2004) E-mail correspondence between Dan Binkley, Department of Forest, Rangeland, and Watershed Stewardship, Colorado State University and Stephen Del Grosso, Natural Resource Ecology Laboratory, Colorado State University 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). 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.

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.

North Carolina State Forest Nutrition Cooperative (2002) 31st Annual Report. Available online at <http://www.ncsu.edu/ncsfnc>. Accessed October 2004.

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.

Barbarika, A. (2006) *Conservation Reserve Program Summary and Enrollment Statistics - 2005*. Farm Service Agency, U.S. Department of Agriculture, Washington, DC.

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.

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/>.

Euliss, N., and R. Gleason (2002) Personal communication between 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 on wetland restoration factor estimates and restoration activity data. August 2002.

FAO (2006) 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/>. Accessed July 2006.

FSA (2006) *Conservation Reserve Program: Summary and Enrollment Statistics—2005*. U.S. Department of Agriculture, Farm Services Agency, Washington, DC.

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.

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.

Lange, J. (2000) Telephone conversation between Lee-Ann Tracy of ERG and John Lange, Agricultural Statistician, U. S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. May 8, 2000.

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 <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, 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 <http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txt>.

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 Center, Lincoln, NE, pp. 156.

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*, accepted.

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 of NREL to Barbara Braatz of ICF International. September 23, 2002.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management." In *Quantitative Modeling of Soil Forming Processes*. Special Publication 39, Soil Science Society of America, Madison, WI, 147–167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173–1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109–131.

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.

Tepordei, V.V. (2006) "Crushed Stone," In *Minerals Yearbook 2004*. 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 2006.

Tepordei, V.V. (2005) "Crushed Stone," In *Minerals Yearbook 2003*. 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 2005.

Tepordei, V.V. (2004) "Crushed Stone," In *Minerals Yearbook 2002*. 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 2004. Accessed August 2004.

Tepordei, V.V. (2003) "Crushed Stone," In *Minerals Yearbook 2001*. 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 June 2003.

Tepordei, V.V. (2002) "Crushed Stone," In *Minerals Yearbook 2000*. 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 September 2002.

Tepordei, V.V. (2001) "Crushed Stone," In *Minerals Yearbook 1999*. 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 2001.

Tepordei, V.V. (2000) "Crushed Stone," In *Minerals Yearbook 1998*. 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 2000.

Tepordei, V.V. (1999) "Crushed Stone," In *Minerals Yearbook 1997*. 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 2000.

Tepordei, V.V. (1998) "Crushed Stone," In *Minerals Yearbook 1996*. 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 2000.

Tepordei, V.V. (1997) "Crushed Stone," In *Minerals Yearbook 1995*. U.S. Department of the Interior/U.S. Geological Survey, Washington, DC. pp. 783–809. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

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. (1995) "Crushed Stone," In *Minerals Yearbook 1993*. U.S. Department of the Interior/Bureau of Mines, Washington, DC. pp. 1107–1147.

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.

Towery, D. (2001) Personal communication between Dan Towery of the Conservation Technology Information Center, West Lafayette, IN, and Marlen Eve of the National Resource Ecology Laboratory, Fort Collins, CO regarding adjustments to the CTIC (1998) tillage data to reflect long-term trends. February 2001.

USDA (2006a) *Cattle*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 2006. Available online at <http://www.nass.usda.gov>.

USDA (2006b) *Cattle on Feed*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. April 2006. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2006c) *Chicken and Eggs 2005 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 2006. Available online at <http://www.nass.usda.gov>.

USDA (2006d) *Poultry - Production and Value 2005 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. April 2006. Available online at <http://www.nass.usda.gov>.

USDA (2006e) *Published Estimates Database*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://www.nass.usda.gov>. Accessed May 2006.

USDA (2005a) *Cattle*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 28, 2005. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2005b) *Cattle on Feed*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 21, 2005. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2005c) *Hogs and Pigs*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. March 24, 2005. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2005d) *Chicken and Eggs Annual Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. February 2005. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2005e) *Poultry Production and Value Annual Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. April 28, 2005. Available online at <http://www.usda.gov/nass/pubs/estindx1.htm>.

USDA (2005f) *Sheep and Goats*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 28, 2005. Available online at <http://www.usda.gov/nass/pubs/reportname.htm>.

USDA (2005g) *Census of Agriculture*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. Data for 1992, 1997, and 2002 available from <http://www.nass.usda.gov/census/> in June 2005.

USDA (2004a) *Cattle—Final Estimates 1999–2003*. 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) *Hogs and Pigs—Final Estimates 1998–2002*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. March 2004. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (2004c) *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 (2004d) *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 (2004e) *Sheep and Goats—Final Estimates 1999–2003*. 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 (2000) *Chicken and Eggs—Final Estimates 1988–1993*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/data-sets/livestock/95908/sb908.txt>. May 3, 2000.

USDA (1999a) *Cattle—Final Estimates 1994–98*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1999. Available online at <http://www.nass.usda.gov:81/ipedb/>.

USDA (1999b) *Poultry Production and Value—Final Estimates 1994–97*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. March 1999.

USDA (1999c) *Sheep and Goats—Final Estimates 1994–1998*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1999.

USDA (1998a) *Chicken and Eggs—Final Estimates 1994–97*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. December 1998.

USDA (1998b) *Hogs and Pigs–Final Estimates 1993–97*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. December 1998. Available online at <http://www.nass.usda.gov:81/ipedb/>.

USDA (1995a) *Cattle—Final Estimates 1989–93*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1995. Available online at <http://www.nass.usda.gov:81/ipedb/>.

USDA (1995b) *Poultry Production and Value—Final Estimates 1989–1993*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC.

USDA (1994a) *Hogs and Pigs—Final Estimates 1988–92*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. December 1994. Available online at <http://www.nass.usda.gov:81/ipedb/>.

USDA (1994b) *Sheep and Goats—Final Estimates 1989–1993*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 1994.

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.

USGS (2005) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2005*. 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.

Settlements Remaining Settlements: Changes in Carbon Stocks in Urban Trees

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*. New Brunswick, NJ: Rutgers University, M.S. thesis.

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 (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.

Nowak, D.J. (2002a) E-mail from David Nowak of the USDA Forest Service to Barbara Braatz at ICF International, containing information on possible urban tree carbon and forest carbon overlap, January 10, 2002.

Nowak, D.J. (2002b) E-mail from David Nowak of the USDA Forest Service to Barbara Braatz at ICF International, regarding significant digits. October 29, 2002.

Nowak, D.J. (1994) "Atmospheric Carbon Dioxide Reduction by Chicago's Urban Forest." In: E.G. McPherson, D.J. Nowak, and R.A. Rowntree (eds.); *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project*. U.S. Department of Agriculture Forest Service General Technical Report NE-186, Radnor, PA, 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*.

Smith, W.B. and S.R. Shifley (1984) *Diameter Growth, Survival, and Volume Estimates for Trees in Indiana and Illinois*. Res. Pap. NC-257. North Central Forest Experiment Station, U.S. Department of Agriculture Forest Service, St. Paul, MN.

Settlements Remaining Settlements: Direct N_2O Fluxes from Settlement Soils

AAPFCO (2006) *Commercial Fertilizers 2005*. Association of American Plant Food Control Officials and The Fertilizer Institute, University of Kentucky, Lexington, KY.

AAPFCO (2005) *Commercial Fertilizers 2004*. Association of American Plant Food Control Officials and The Fertilizer Institute, University of Kentucky, Lexington, KY.

AAPFCO (2004) *Commercial Fertilizers 2003*. Association of American Plant Food Control Officials and The Fertilizer Institute, University of Kentucky, Lexington, KY.

AAPFCO (2003) *Commercial Fertilizers 2002*. Association of American Plant Food Control Officials and The Fertilizer Institute, University of Kentucky, Lexington, KY.

AAPFCO (2002) *Commercial Fertilizers 2001*. Association of American Plant Food Control Officials and The Fertilizer Institute, University of Kentucky, Lexington, KY.

AAPFCO (2000a) *1999–2000 Commercial Fertilizers Data*. ASCII files. Available: David Terry, Secretary, AAPFCO, Lexington, KY.

AAPFCO (2000b) *Commercial Fertilizers 2000*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1999) *Commercial Fertilizers 1999*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1998) *Commercial Fertilizers 1998*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1997) *Commercial Fertilizers 1997*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1996) *Commercial Fertilizers 1996*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1995) *Commercial Fertilizers 1995*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

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.

Qian, Y. (2004) Meeting between Yaling Qian of Horticulture and Landscape Architecture Department, Colorado State University and William Patron and Stephen Del Grosso of Natural Resource Ecology Laboratory, Colorado State University, regarding the percentage of national fertilizer applied to turf grass (10% of national N) and the confidence interval for this estimate (-50 to +20%). September 17, 2004.

TVA (1994) *Commercial Fertilizers 1994*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1993) *Commercial Fertilizers 1993*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1992) *Commercial Fertilizers 1992*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1991) *Commercial Fertilizers 1991*. Tennessee Valley Authority, Muscle Shoals, AL.

Other: Changes in Yard Trimming and Food Scrap Stocks in Landfills

Barlaz, M.A. (2005) "Decomposition of Leaves in Simulated Landfill." Letter report to Randall Freed, ICF International. 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. Barlaz (1997) "Biodegradability of Municipal Solid Waste Components in Laboratory-Scale Landfills" *Environmental Science Technology*, 31:911–917.

EPA (2005) *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: 2003 Facts and Figures*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. Available online at <http://www.epa.gov/epaoswer/non-hw/muncpl/pubs/msw05rpt.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/epaoswer/non-hw/muncpl/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, H.S. Eggleston, L. Buenida, K. Miwa, T. Ngara, and K. Tanabe (eds.); Institute for Global Environmental Strategies (IGES). 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>.

Oshins, C., and D. Block (2000) "Feedstock Composition at Composting Sites." *Biocycle* 41(9):31–34.

Schneider, S. (2007) E-mail between Shelly Schneider of Franklin Associates, a Division of ERG and Sarah Shapiro of ICF International. January 10, 2007.

Tchobanoglous, G., H. Theisen, and S.A. Vigil (1993) *Integrated Solid Waste Management, 1st edition*. McGraw-Hill, NY. Cited by Barlaz (1998).

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. (2005) "Decomposition of Leaves in Simulated Landfill." Letter report to Randall Freed, ICF International. 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.

Bingemer, H. and J. Crutzen (1987) "The Production of Methane from Solid Wastes," *Journal of Geophysical Research*, 92:2181–2187.

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.

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.

Energy Information Agency (EIA) (2006) Voluntary Greenhouse Gas Reports for EIA Form 1605B (Reporting Year 2004). Available online at <ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/>.

EPA (2006) *Landfill Gas-to-Energy Project Database*. Landfill Methane and Outreach Program. July 2006.

EPA (2005) *Municipal Solid Waste in the United States: 2003 Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, DC. Available at <http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm>.

EPA (1998) *Compilation of Air Pollution Emission Factors, Publication AP-42*, Section 2.4 Municipal Solid Waste Landfills. November 1998.

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.

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.

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>.

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 1984.

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. September 2004.

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 (2006) International Data Base. April 2006. Available online at <http://www.census.gov/ipc/www/idbnew.html>.

Wastewater Treatment

ARCADIS (2004) Memorandum from M.Doorn of ARCADIS to D. Pape of ICF International and E. Scheehle of the U.S. Environmental Protection Agency, "Response to ERG Review and New US M&P estimates." August 16, 2004.

Doorn, M. and E. Scheehle (2002) "Estimate of U.S. Methane Emissions from Industrial Wastewater; Enhancing Completeness of the Annual National Greenhouse Gas Inventory." *Third Int. Symposium on Non- CO_2 Greenhouse Gases* (NCGG-3), Maastricht, Netherlands. January 21-23, 2002.

Eckenfelder, W.W. (1980) *Principles of Water Quality Management*. CBI Publishing Company, Inc. Boston MA.

EPA (2004a) *Clean Watersheds Needs Survey 2004—Report to Congress*. U.S. Environmental Protection Agency, Office of Wastewater Management, Washington, DC.

EPA (2004b) *Technical Development Document for the Final Effluent Limitations Guidelines and Standards for the Meat and Poultry Products Point Source Category (40 CFR 432)*. Office of Water, U.S. Environmental Protection Agency, Washington. DC, EPA-821-R-04-011. July 2004.

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)*. Office of Water, U.S. Environmental Protection Agency, Washington, DC, EPA-821-B-01-007. January 2002.

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>.

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 (1997a) *Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment*. Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency, Washington, DC, EPA-600/R-97-091. 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 (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>.

EPA (1993a) *Anthropogenic Methane Emissions in the U.S.: Estimates for 1990, Report to Congress*. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC. April 1993.

EPA (1993b) *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 (1992) *Clean Watersheds Needs Survey 1992—Report to Congress*. Office of Wastewater Management, U.S. Environmental Protection Agency, Washington, DC.

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.

FAO (2006) FAOSTAT Statistical Database, United Nations Food and Agriculture Organization. Available online at <http://faostat.fao.org/site/346/DesktopDefault.aspx?PageID=346>. Accessed August 21, 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, H.S. Eggleston, L. Buenida, K. Miwa, T Ngara, and K. Tanabe, eds.; Institute for Global Environmental Strategies (IGES). 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.

Lockwood-Post (2002) Lockwood-Post's Directory of Pulp, Paper and Allied Trades, Miller-Freeman Publications, San Francisco, CA.

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.

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 (2003–2006) "Month in Statistics." January 2003-June 2006.

Scheehle, E.A., and Doorn, M.R. (2001) "Improvements to the U.S. Wastewater Methane and Nitrous Oxide Emissions Estimate." July 2001.

U.S. Census Bureau (2006a) International Database. Available online at <http://www.census.gov/ipc/www/idbnew.html> and <http://www.census.gov/ipc/www/idbprint.html>.

U.S. Census Bureau (2006b) "American Housing Survey." Table 1A-4: Selected Equipment and Plumbing—All Housing Units. From 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003 and 2005 reports. Available online at <http://www.census.gov/hhes/www/housing/ahs/nationaldata.html>.

USDA (2006) 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:8080/QuickStats/>.

USPoultry (2006) Email from John Starkey, USPOULTRY to D. Bartram, ERG. 30 August 2006.

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.

Waste Sources of Indirect Greenhouse Gases

EPA (2006) Air Emissions Trends—Continued Progress Through 2005. U.S. Environmental Protection Agency, Washington, DC. December 19, 2006. Available online at <http://www.epa.gov/air/airtrends/index.html>.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data between the Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency (EPA). 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.

Recalculations and Improvements

EIA (2006) *Annual Energy Review 2005*. Energy Information Administration, U.S. Department of Energy. Washington, DC, Tables 10.2a and 10.2b. July 2006. DOE/EIA-0384(2005).

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.

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.

USDA (2005e) 1992, 1997, and 2002 *Census of Agriculture*. National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://www.nass.usda.gov/census/>. Accessed March 2006.

United States
Enviromental Protection
Agency

EPA 430-R-07-002 April 2007
Office of Atmospheric Programs (6207J)
Washington, DC 20460

Official Business
Penalty for Private Use
$300