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INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990 – 2006

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PUBLIC REVIEW DRAFT

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[Inside Front Cover]

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All data tables of this document are available for the full time series 1990 through 2006, inclusive, at the internet site mentioned above.

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

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Preface

The United States Environmental Protection Agency (EPA) prepares the official *U.S. Inventory of Greenhouse Gas Emissions and Sinks* to comply with existing commitments under the United Nations Framework Convention on Climate Change (UNFCCC).[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://www.epa.gov/globalwarming/publications/emissions>.

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Executive Summary

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

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

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

This chapter summarizes the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 2006. 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.

[BEGIN BOX]

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

[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>.

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 2005) 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.

[END BOX]

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

Beginning in the 1950s, the use of CFCs and other stratospheric ozone depleting substances (ODS) increased by nearly 10 percent per year until the mid-1980s, when international concern about ozone depletion led to the entry into force of the *Montreal Protocol*. Since then, the production of ODS is being phased out. In recent years, use of ODS substitutes such as HFCs and PFCs has grown as they begin to be phased in as replacements for CFCs and HCFCs. Accordingly, atmospheric concentrations of these substitutes have been growing (IPCC 2007).

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

Global Warming Potentials

Gases in the atmosphere can contribute to the greenhouse effect both directly and indirectly. Direct effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations of the substance produce other greenhouse gases, when a gas influences the atmospheric lifetimes of other gases, and/or when a gas affects atmospheric processes that alter the radiative balance of the earth (e.g., affect cloud formation or albedo).[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 2006 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.

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.

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

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

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).

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

In 2006, total U.S. greenhouse gas emissions were 7,201.9 Tg CO_2 Eq. Overall, total U.S. emissions have risen by 14.1 percent from 1990 to 2006, while the U.S. gross domestic product has increased by 59 percent over the same period (BEA 2007). Emissions fell from 2005 to 2006, decreasing by 1.5 percent (111.8 Tg CO_2 Eq.). The following factors were primary contributors to this decrease: (1) compared to 2005, 2006 had warmer winter conditions, which decreased consumption of heating fuels, as well as cooler summer conditions, which reduced demand for electricity, (2) restraint on fuel consumption caused by rising fuel prices, primarily in the transportation sector and (3) increased use of natural gas and renewables in the electric power sector.

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 2006.

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

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	2006
CO_2	**5,067.2**	**5,392.8**	**5,938.2**	**5,844.8**	**5,907.2**	**5,971.1**	**6,055.9**	**6,093.4**	**5,983.1**
Fossil Fuel Combustion	4,724.1	5,032.4	5,577.1	5,507.4	5,564.8	5,636.9	5,700.5	5,751.5	5,639.4
Electricity Generation	1,809.6	1,939.3	2,282.3	2,244.3	2,253.7	2,283.1	2,314.9	2,380.2	2,328.2
Transportation	1,473.5	1,590.2	1,791.9	1,770.3	1,823.8	1,821.4	1,868.5	1,883.1	1,850.1
Industrial	849.9	880.6	863.2	855.0	857.3	858.8	861.0	850.9	866.1
Residential	344.4	359.9	374.3	365.4	362.3	385.0	370.8	360.9	328.7
Commercial	218.5	227.5	229.2	223.3	223.7	237.6	231.9	223.2	211.4
U.S. Territories	28.3	35.0	36.2	49.0	44.0	51.0	53.5	53.2	54.9
Non-Energy Use of Fuels	117.2	133.2	141.4	131.9	135.9	131.8	148.9	139.1	138.0
Iron and Steel Production	84.9	73.3	65.1	57.9	54.6	53.4	51.3	45.2	47.7
Cement Manufacture	33.3	36.8	41.2	41.4	42.9	43.1	45.6	45.9	45.7
Natural Gas Systems	33.7	33.8	29.4	28.8	29.6	28.4	28.1	29.5	28.5
Municipal Solid Waste Combustion	10.9	15.7	17.5	18.0	18.5	19.1	20.1	20.7	20.9
Lime Manufacture	12.0	14.0	14.9	14.3	13.7	14.5	15.2	15.1	15.8
Ammonia Manufacture and Urea Consumption	16.9	17.8	16.4	13.3	14.2	12.5	13.2	12.8	12.4
Limestone and Dolomite Use	5.5	7.4	6.0	5.7	5.9	4.7	6.7	7.4	8.6
Cropland Remaining Cropland	7.1	7.0	7.5	7.8	8.5	8.3	7.6	7.9	8.0
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.1	4.1	4.1	4.2	4.2	4.2

Aluminum Production	6.8	5.7	6.1	4.4	4.5	4.5	4.2	4.2	3.9
Petrochemical Production	2.2	2.8	3.0	2.8	2.9	2.8	2.9	2.8	2.6
Titanium Dioxide Production	1.2	1.5	1.8	1.7	1.8	1.8	2.1	1.8	1.9
Carbon Dioxide Consumption	1.4	1.4	1.4	0.8	1.0	1.3	1.2	1.3	1.6
Ferroalloy Production	2.2	2.0	1.9	1.5	1.3	1.3	1.4	1.4	1.5
Phosphoric Acid Production	1.5	1.5	1.4	1.3	1.3	1.4	1.4	1.4	1.2
Zinc Production	0.9	1.0	1.1	1.0	0.9	0.5	0.5	0.5	0.5
Petroleum Systems	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Lead Production	0.3	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	0.2
Land Use, Land-Use Change, and Forestry (Sink)[a]	*(736.6)*	*(774.5)*	*(672.9)*	*(749.6)*	*(826.0)*	*(860.3)*	*(873.0)*	*(877.9)*	*(882.9)*
Biomass—Wood[b]	*215.2*	*229.1*	*218.1*	*193.5*	*192.8*	*193.8*	*205.1*	*204.8*	*204.4*
International Bunker Fuels[b]	*113.7*	*100.6*	*101.1*	*97.6*	*89.1*	*83.7*	*99.8*	*102.1*	*125.7*
Biomass—Ethanol[b]	*4.2*	*7.7*	*9.2*	*9.7*	*11.5*	*15.7*	*19.7*	*22.6*	*30.3*
CH_4	**608.7**	**598.2**	**569.3**	**555.4**	**557.5**	**558.7**	**545.6**	**539.0**	**542.3**
Enteric Fermentation	126.9	132.3	124.6	123.6	123.8	124.6	122.4	124.5	126.2
Landfills	149.6	144.0	120.8	117.6	120.1	125.6	122.6	123.7	125.7
Natural Gas Systems	124.7	128.1	126.5	125.3	124.9	123.3	114.0	102.5	102.4
Coal Mining	84.1	67.1	60.4	60.3	56.8	56.9	59.8	57.1	58.5
Manure Management	31.0	35.2	38.8	40.2	41.3	40.7	40.1	41.8	41.4
Petroleum Systems	33.9	32.0	30.3	30.2	29.9	29.2	28.7	28.3	28.4
Wastewater Treatment	23.0	24.3	24.6	24.2	24.1	23.9	24.0	23.8	23.9
Forest Land Remaining Forest Land	7.1	4.0	14.0	6.0	10.4	8.1	6.9	11.6	11.6
Stationary Combustion	7.4	7.2	6.7	6.2	6.2	6.4	6.6	6.5	6.2
Rice Cultivation	7.1	7.6	7.5	7.6	6.8	6.9	7.6	6.8	5.9
Abandoned Underground Coal Mines	6.0	8.2	7.4	6.7	6.2	6.0	5.8	5.6	5.4
Mobile Combustion	4.7	4.3	3.4	3.3	3.0	2.8	2.7	2.5	2.4
Composting	0.3	0.7	1.3	1.3	1.3	1.5	1.6	1.6	1.6
Petrochemical Production	0.9	1.1	1.2	1.1	1.1	1.1	1.2	1.1	1.0
Iron and Steel Production	1.3	1.3	1.2	1.1	1.0	1.0	1.0	1.0	0.9
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.8	0.7	0.8	0.9	0.9	0.8
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*	*0.2*
N_2O	**544.9**	**559.2**	**556.2**	**575.4**	**544.3**	**518.9**	**516.3**	**537.8**	**531.7**
Agricultural Soil Management	430.6	428.3	432.6	459.6	430.5	409.2	409.1	432.5	429.7
Mobile Combustion	43.5	53.4	52.5	49.9	45.9	42.5	39.8	36.5	33.1
Nitric Acid Production	17.0	18.9	18.6	15.1	16.4	15.4	15.2	15.8	15.6
Stationary Combustion	12.8	13.4	14.6	14.1	14.0	14.4	14.6	14.8	14.5
Manure Management	12.1	12.8	13.7	14.0	14.0	13.6	13.8	13.9	14.3
Wastewater Treatment	6.3	6.9	7.6	7.8	7.6	7.7	7.8	8.0	8.1
Adipic Acid Production	15.3	17.3	6.2	5.1	6.1	6.3	5.9	5.9	5.9
N_2O from Product Uses	4.4	4.6	4.9	4.9	4.4	4.4	4.4	4.4	4.4
Settlements Remaining Settlements	1.0	1.4	1.5	1.8	1.8	1.9	1.9	1.8	1.8

Composting	0.4	0.8	1.4	1.4	1.4	1.6	1.7	1.7	1.8
Forest Land Remaining Forest Land	0.8	0.6	1.7	1.0	1.4	1.2	1.1	1.5	1.5
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.4	0.4	0.5	0.5	0.5
Municipal Solid Waste Combustion	0.5	0.5	0.4	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*	*1.1*
HFCs	**35.5**	**56.4**	**100.0**	**96.3**	**103.0**	**102.3**	**112.4**	**119.1**	**121.3**
Substitution of Ozone Depleting Substances[c]	0.3	29.1	70.0	76.3	83.0	89.8	96.6	102.3	107.3
HCFC-22 Production	35.0	27.0	29.8	19.8	19.8	12.3	15.6	16.5	13.8
Semiconductor Manufacture	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.3
PFCs	**20.8**	**15.6**	**13.5**	**7.0**	**8.7**	**7.1**	**6.1**	**6.2**	**6.1**
Semiconductor Manufacture	2.2	3.8	4.9	3.5	3.5	3.3	3.3	3.2	3.6
Aluminum Production	18.5	11.8	8.6	3.5	5.2	3.8	2.8	3.0	2.5
SF_6	**32.7**	**28.0**	**19.2**	**18.7**	**18.0**	**18.1**	**18.0**	**18.3**	**17.4**
Electrical Transmission and Distribution	26.7	21.5	15.1	15.0	14.4	13.9	14.0	14.0	13.2
Magnesium Production and Processing	5.4	5.6	3.0	2.9	2.9	3.4	3.2	3.3	3.2
Semiconductor Manufacture	0.5	0.9	1.1	0.7	0.7	0.8	0.8	1.0	1.0
Total	**6,309.7**	**6,650.1**	**7,196.4**	**7,097.6**	**7,138.7**	**7,176.3**	**7,254.4**	**7,313.7**	**7,201.9**
Net Emissions (Sources and Sinks)	**5,573.1**	**5,875.6**	**6,523.6**	**6,348.0**	**6,312.7**	**6,316.0**	**6,381.4**	**6,435.8**	**6,318.9**

+ 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.
[c] Small amounts of PFC emissions also result from this source.
Note: Totals may not sum due to independent rounding.

Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 2006. The primary greenhouse gas emitted by human activities in the United States was CO_2, representing approximately 83.1 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 declined from 1990 levels, 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_2O 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.

Figure ES-4: 2006 Greenhouse Gas Emissions by Gas (percents based on Tg CO_2 Eq.)

Overall, from 1990 to 2006, total emissions of CO_2 increased by 915.9 Tg CO_2 Eq. (18.1 percent), while CH_4 and N_2O emissions decreased by 66.4 Tg CO_2 Eq. (10.9 percent) and 13.2 Tg CO_2 Eq. (2.4 percent), respectively. During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 55.8 Tg CO_2 Eq. (62.8 percent). From 1990 to 2006, HFCs increased by 85.8 Tg CO_2 Eq. (241.9 percent), PFCs decreased by 14.7 Tg CO_2 Eq. (70.8 percent), and SF_6 decreased by 15.3 Tg CO_2 Eq. (46.9 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 12.3 percent of total emissions in 2006. The following sections describe each gas' contribution to total U.S. greenhouse gas emissions in more detail.

Carbon Dioxide Emissions

The global carbon cycle is made up of large carbon flows and reservoirs. Billions of tons of carbon in the form of CO_2 are absorbed by oceans and living biomass (i.e., sinks) and are emitted to the atmosphere annually through natural processes (i.e., sources). When in equilibrium, carbon fluxes among these various reservoirs are roughly balanced. Since the Industrial Revolution (i.e., about 1750), global atmospheric concentrations of CO_2 have risen about 36 percent (IPCC 2007), principally due to the combustion of fossil fuels. Within the United States, fuel combustion accounted for 94.3 percent of CO_2 emissions in 2006. Globally, approximately 28,193 Tg of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2005, of which the United States accounted for about 20 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).

Figure ES-5: 2006 Sources of CO_2

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 75 percent of total GWP-weighted emissions in 1990 to 78 percent in 2006. Emissions of CO_2 from fossil fuel combustion increased at an average annual rate of 1.1 percent from 1990 to 2006. The fundamental factors influencing this trend include (1) a generally growing domestic economy over the last 16 years, and (2) significant overall growth in emissions from electricity generation and transportation activities. Between 1990 and 2006, CO_2 emissions from fossil fuel combustion increased from 4,724.1 Tg CO_2 Eq. to 5,639.4 Tg CO_2 Eq.—a 19.4 percent total increase over the sixteen-year period. From 2005 to 2006, these emissions decreased by 112.1 Tg CO_2 Eq. (1.9 percent).

Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends. Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population and economic growth, energy price fluctuations, technological changes, and seasonal temperatures. 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.

Figure ES-6: 2006 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Figure ES-7: 2006 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

[9] Global CO_2 emissions from fossil fuel combustion were taken from Energy Information Administration *International Energy Annual 2005* (EIA 2007b).

The four major fuel consuming 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 each end-use sector on the basis of each sector's share of aggregate electricity consumption. This method of distributing emissions assumes that each end-use sector consumes electricity that is generated from the national average mix of fuels according to their carbon intensity. Emissions from electricity generation are also addressed separately after the end-use sectors have been discussed.

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

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

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

End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005	2006
Transportation	**1,476.5**	**1,593.3**	**1,795.3**	**1,774.0**	**1,827.2**	**1,825.7**	**1,873.0**	**1,887.8**	**1,855.1**
Combustion	1,473.5	1,590.2	1,791.9	1,770.3	1,823.8	1,821.4	1,868.5	1,883.1	1,850.1
Electricity	3.0	3.0	3.4	3.6	3.4	4.2	4.5	4.7	4.9
Industrial	**1,532.5**	**1,593.6**	**1,648.0**	**1,586.4**	**1,574.9**	**1,594.8**	**1,600.0**	**1,583.1**	**1,571.0**
Combustion	849.9	880.6	863.2	855.0	857.3	858.8	861.0	850.9	866.1
Electricity	682.5	713.1	784.7	731.4	717.7	736.1	739.0	732.3	704.9
Residential	**933.7**	**998.8**	**1,131.9**	**1,123.5**	**1,147.4**	**1,180.4**	**1,175.6**	**1,208.8**	**1,154.1**
Combustion	344.4	359.9	374.3	365.4	362.3	385.0	370.8	360.9	328.7
Electricity	589.4	639.0	757.6	758.1	785.1	795.4	804.9	847.9	825.4
Commercial	**753.1**	**811.7**	**965.8**	**974.5**	**971.2**	**984.9**	**998.4**	**1,018.6**	**1,004.3**
Combustion	218.5	227.5	229.2	223.3	223.7	237.6	231.9	223.2	211.4
Electricity	534.7	584.2	736.6	751.1	747.5	747.3	766.5	795.4	792.9
U.S. Territories	**28.3**	**35.0**	**36.2**	**49.0**	**44.0**	**51.0**	**53.5**	**53.2**	**54.9**
Total	**4,724.1**	**5,032.4**	**5,577.1**	**5,507.4**	**5,564.8**	**5,636.9**	**5,700.5**	**5,751.5**	**5,639.4**
Electricity Generation	**1,809.6**	**1,939.3**	**2,282.3**	**2,244.3**	**2,253.7**	**2,283.1**	**2,314.9**	**2,380.2**	**2,328.2**

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.

Transportation End-Use Sector. Transportation activities (excluding international bunker fuels) accounted for 33 percent of CO_2 emissions from fossil fuel combustion in 2006.[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.

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 28 percent of CO_2 from fossil fuel combustion in 2006. Just less than half of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The remaining emissions resulted from consuming electricity for motors, electric furnaces, ovens, lighting, and other applications.

[10] If emissions from international bunker fuels are included, the transportation end-use sector accounted for 34 percent of U.S. emissions from fossil fuel combustion in 2006.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 20 and 18 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2006. Both sectors relied heavily on electricity for meeting energy demands, with 72 and 79 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 2006. 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 94 percent of all coal consumed for energy in the United States in 2006. 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 20.8 Tg CO_2 Eq. (18 percent) from 1990 through 2006. Emissions from non-energy uses of fossil fuels were 138.0 Tg CO_2 Eq. in 2006, which constituted 2.4 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 iron and steel production increased by 5.4 percent to 47.7 Tg CO_2 Eq. in 2006, but have declined overall by 37.2 Tg CO_2 Eq. (44 percent) from 1990 through 2006, due to restructuring of the industry, technological improvements, and increased scrap utilization.

- In 2006, CO_2 emissions from cement manufacture decreased slightly by 0.2 Tg CO_2 Eq. (0.4 percent) from 2005 to 2006. This decrease occurs despite the overall increase over the time series. After falling in 1991 by two percent from 1990 levels, cement production emissions grew every year through 2005. Overall, from 1990 to 2006, emissions from cement manufacture increased by 37 percent, an increase of 12.5 Tg CO_2 Eq..

- CO_2 emissions from municipal solid waste combustion (20.9 Tg CO_2 Eq. in 2006) increased by 10.0 Tg CO_2 Eq. (91 percent) from 1990 through 2006, as the volume of plastics and other fossil carbon-containing materials in municipal solid waste grew.

- CO_2 emissions from ammonia manufacture and urea consumption (12.4 Tg CO_2 Eq. in 2006) have decreased by 4.5 Tg CO_2 Eq. (27 percent) since 1990. The decrease in emissions from ammonia manufacture and urea consumption is associated with an overall decrease in domestic ammonia manufacture, and is due to several factors including market fluctuations and high natural gas prices.

- Net CO_2 sequestration from Land Use, Land-Use Change, and Forestry increased by 146.3 Tg CO_2 Eq. (20 percent) from 1990 through 2006. 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 148 percent (IPCC 2007). 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).

Figure ES-8: 2006 Sources of CH_4

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

- Enteric Fermentation is the largest anthropogenic source of CH_4 emissions in the United States. In 2006, enteric fermentation CH_4 emissions were 126.2 Tg CO_2 Eq. (approximately 23.3 percent of total CH_4 emissions), which represents a decline of 0.7 Tg CO_2 Eq., or 0.6 percent, since 1990. Despite this overall decline in emissions, the last two years have shown a slight increase in emissions.

- Landfills are the second largest anthropogenic source of CH_4 emissions in the United States, accounting for approximately 23.2 percent of total CH_4 emissions (125.7 Tg CO_2 Eq.) in 2006. From 1990 to 2006, net CH_4 emissions from landfills decreased by 23.9 Tg CO_2 Eq. (16 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,[11] which has more than offset the additional CH_4 emissions resulting from an increase in the amount of municipal solid waste landfilled.

- CH_4 emissions from natural gas systems were 102.4 Tg CO_2 Eq. in 2006; emissions have declined by 22.3 Tg CO_2 Eq. (18 percent) since 1990. This decline has been due to improvements in technology and management practices, as well as some replacement of old equipment.

- In 2006, CH_4 emissions from coal mining were 58.5 Tg CO_2 Eq. This decline of 25.6 Tg CO_2 Eq. (30 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 manure management increased by 34 percent for CH_4, from 31.0 Tg CO_2 Eq. in 1990 to 41.4 Tg CO_2 Eq. in 2006. The majority of this increase was from swine and dairy cow manure, since the general trend in manure management is one of increasing use of liquid systems, which tends to produce greater CH_4 emissions. The increase in liquid systems is the combined result of a shift to larger facilities, and to facilities in the West and Southwest, all of which tend to use liquid systems. Also, new regulations limiting the application of manure nutrients have shifted manure management practices at smaller dairies from daily spread to manure managed and stored on site.

- In 2006, CH_4 emissions from composting increased by less than 0.1 Tg CO_2 Eq. (1.1 percent) from 2005 to 2006. Emissions from composting have been continually increasing since 1990, from 0.3 Tg CO_2 Eq. to 1.6 Tg CO_2 Eq. in 2006, a four-fold increase over the time series.

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 2007). The main anthropogenic activities producing N_2O in the United States are agricultural soil management, fuel combustion in motor vehicles, nitric acid production, stationary fuel combustion, manure management, and wastewater treatment (see Figure ES-9).

Figure ES-9: 2006 Sources of N_2O

[11] 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.

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

- Agricultural soils produced approximately 81 percent of N_2O emissions in the United States in 2006. Estimated emissions from this source in 2006 were 429.7 Tg CO_2 Eq. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2006, although overall emissions were 0.2 percent lower in 2006 than in 1990. 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, and to weather patterns and crop type.

- In 2006, N_2O emissions from mobile combustion were 33.1 Tg CO_2 Eq. (approximately 6 percent of U.S. N_2O emissions). From 1990 to 2006, N_2O emissions from mobile combustion decreased by 24 percent. However, from 1990 to 1998 emissions increased by 26 percent, due to control technologies that reduced NO_x emissions while increasing N_2O emissions. Since 1998, newer control technologies have led to a steady decline in N_2O from this source.

- N_2O emissions from adipic acid production were 5.9 Tg CO_2 Eq. in 2006, and have decreased significantly in recent years from the widespread installation of pollution control measures. Emissions from adipic acid production have decreased 61 percent since 1990, and emissions from adipic acid production have fluctuated by less than 1 Tg CO_2 Eq. annually since 1998.

- In 2006, N_2O emissions from composting were 1.8 Tg CO_2 Eq., an increase of less than 0.1 Tg CO_2 Eq. (1.1 percent) from 2005 to 2006. Emissions from composting have been continually increasing since 1990, from 0.4 Tg CO_2 Eq. to 1.8 Tg CO_2 Eq. in 2006, a four-fold increase over the time series.

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).

Figure ES-10: 2006 Sources of HFCs, PFCs, and SF_6

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

- Emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) have been increasing from small amounts in 1990 to 107.3 Tg CO_2 Eq. in 2006. 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.

- HFC emissions from the production of HCFC-22 decreased by 61 percent (21.2 Tg CO_2 Eq.) from 1990

through 2006, due to a steady decline in the emission rate of HFC-23 (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) and the use of thermal oxidation at some plants to reduce HFC-23 emissions.

- SF_6 missions from electric power transmission and distribution systems decreased by 51 percent (13.5 Tg CO_2 Eq.) from 1990 to 2006, primarily because of higher purchase prices for SF_6 and efforts by industry to reduce emissions.

- PFC emissions from aluminum production decreased by 87 percent (16.1 Tg CO_2 Eq.) from 1990 to 2006, due to both industry emission reduction efforts and lower domestic aluminum production.

Overview of Sector Emissions and Trends

In accordance with the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997), and the 2003 *UNFCCC Guidelines on Reporting and Review* (UNFCCC 2003), 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. Emissions of all gases can be summed from each source category from Intergovernmental Panel on Climate Change (IPCC) guidance. Over the sixteen-year period of 1990 to 2006, total emissions in the Energy, Industrial Processes, and Agriculture sectors climbed by 874.4 Tg CO_2 Eq. (17 percent), 19.2 Tg CO_2 Eq. (6 percent), and 10.2 Tg CO_2 Eq. (2 percent), respectively. Emissions decreased in the Waste and Solvent and Other Product Use sectors by 18.6 Tg CO_2 Eq. (10 percent) and less than 0.01 Tg CO_2 Eq. (less than 1 percent), respectively. Over the same period, estimates of net C sequestration in the Land Use, Land-Use Change, and Forestry sector increased by 139.4 Tg CO_2 Eq. (20 percent).

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

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

Chapter/IPCC Sector	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Energy	5,204.0	5,529.6	6,067.8	5,982.8	6,036.3	6,098.4	6,170.2	6,195.0	6,078.4
Industrial Processes	297.1	308.9	324.9	294.9	303.9	297.7	310.3	311.8	316.3
Solvent and Other Product Use	4.4	4.6	4.9	4.9	4.4	4.4	4.4	4.4	4.4
Agriculture	608.7	617.3	618.4	646.3	617.5	596.2	594.3	620.9	618.9
Land Use, Land-Use Change, and Forestry (Emissions)	16.0	13.0	24.8	16.5	22.1	19.3	17.4	22.8	22.9
Waste	179.6	176.8	155.6	152.1	154.5	160.3	157.7	158.7	161.0
Total Emissions	**6,309.7**	**6,650.1**	**7,196.4**	**7,097.6**	**7,138.7**	**7,176.3**	**7,254.4**	**7,313.7**	**7,201.9**
Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Sinks)*	(736.6)	(774.5)	(672.9)	(749.6)	(826.0)	(860.3)	(873.0)	(877.9)	(882.9)
Net Emissions (Sources and Sinks)	**5,573.1**	**5,875.6**	**6,523.6**	**6,348.0**	**6,312.7**	**6,316.0**	**6,381.4**	**6,435.8**	**6,318.9**

* 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.

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 2006. In 2006, approximately 83 percent of the energy consumed in the United States (on a Btu basis) was produced through the

combustion of fossil fuels. The remaining 17 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy (see Figure ES-12). Energy related activities are also responsible for CH_4 and N_2O emissions (37 percent and 9 percent of total U.S. emissions of each gas, respectively). Overall, emission sources in the Energy chapter account for a combined 84.4 percent of total U.S. greenhouse gas emissions in 2006.

Figure ES-12: 2006 U.S. Energy Consumption by Energy Source

Industrial Processes

The Industrial Processes chapter contains by-product or fugitive emissions of greenhouse gases from industrial processes not directly related to energy activities such as fossil fuel combustion. For example, industrial processes can chemically transform raw materials, which often release waste gases such as CO_2, CH_4, and N_2O. These processes include iron and steel production, cement manufacture, ammonia manufacture and urea consumption, 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, silicon carbide production and consumption, aluminum production, petrochemical production, nitric acid production, adipic acid production, lead production, and zinc production. Additionally, emissions from industrial processes release HFCs, PFCs, and SF_6. Overall, emission sources in the Industrial Process chapter account for 4.4 percent of U.S. greenhouse gas emissions in 2006.

Solvent and Other Product Use

The Solvent and Other Product Use chapter contains greenhouse gas emissions that are produced as a by-product of various solvent and other product uses. In the United States, emissions from N_2O from Product Uses, the only source of greenhouse gas emissions from this sector, accounted for less than 0.1 percent of total U.S. anthropogenic greenhouse gas emissions on a carbon equivalent basis in 2006.

Agriculture

The Agricultural chapter contains anthropogenic emissions from agricultural activities (except fuel combustion, which is addressed in the Energy chapter, and agricultural CO_2 fluxes, which are addressed in the Land Use, Land-Use Change, and Forestry Chapter). Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes, including the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues. CH_4 and N_2O were the primary greenhouse gases emitted by agricultural activities. CH_4 emissions from enteric fermentation and manure management represented about 23 percent and 8 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2006. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions in 2006, accounting for 80 percent. In 2006, emission sources accounted for in the Agricultural chapters were responsible for 8.6 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 2006 net CO_2 flux, urban trees accounted for 11 percent, mineral and organic soil carbon stock changes accounted for 4 percent, and landfilled yard trimmings and food scraps accounted for 1 percent of the total net flux in 2006. The net forest sequestration is a result of net forest growth and increasing forest area, as well as a net accumulation of carbon

stocks in harvested wood pools. The net sequestration in urban forests is a result of net tree growth in these areas. In agricultural soils, mineral and organic soils sequester approximately 70 percent more C than is emitted through these soils, liming, and urea fertilization, combined. 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 2006 resulted in a net C sequestration of 882.9 Tg CO_2 Eq. (Table ES-5). This represents an offset of approximately 14.8 percent of total U.S. CO_2 emissions, or 12.3 percent of total greenhouse gas emissions in 2006. Total land use, land-use change, and forestry net C sequestration increased by approximately 20 percent between 1990 and 2006, 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 13.4 percent from 1990 to 2006.

Table ES-5: 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	2006
Forest Land Remaining Forest Land	**(621.7)**	**(659.9)**	**(550.7)**	**(623.4)**	**(697.3)**	**(730.9)**	**(741.4)**	**(743.6)**	**(745.1)**
Changes in Forest Carbon Stocks	(621.7)	(659.9)	(550.7)	(623.4)	(697.3)	(730.9)	(741.4)	(743.6)	(745.1)
Cropland Remaining Cropland	**(30.1)**	**(39.4)**	**(38.4)**	**(40.0)**	**(40.3)**	**(40.5)**	**(40.9)**	**(41.0)**	**(41.8)**
Mineral and Organic Soil Carbon Stock Changes	(30.1)	(39.4)	(38.4)	(40.0)	(40.3)	(40.5)	(40.9)	(41.0)	(41.8)
Land Converted to Cropland	**14.7**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**
Mineral and Organic Soil Carbon Stock Changes	14.7	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4
Grassland Remaining Grassland	**(1.9)**	**16.6**	**16.4**	**16.4**	**16.4**	**16.4**	**16.3**	**16.3**	**16.2**
Mineral and Organic Soil Carbon Stock Changes	(1.9)	16.6	16.4	16.4	16.4	16.4	16.3	16.3	16.2
Land Converted to Grassland	**(14.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**
Mineral and Organic Soil Carbon Stock Changes	(14.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)
Settlements Remaining Settlements	**(60.6)**	**(71.5)**	**(82.4)**	**(84.6)**	**(86.8)**	**(88.9)**	**(91.1)**	**(93.3)**	**(95.5)**
Urban Trees	(60.6)	(71.5)	(82.4)	(84.6)	(86.8)	(88.9)	(91.1)	(93.3)	(95.5)
Other	**(22.8)**	**(13.3)**	**(10.8)**	**(10.9)**	**(11.0)**	**(9.4)**	**(8.9)**	**(9.3)**	**(9.8)**
Landfilled Yard Trimmings and Food Scraps	(22.8)	(13.3)	(10.8)	(10.9)	(11.0)	(9.4)	(8.9)	(9.3)	(9.8)
Total	**(736.6)**	**(774.5)**	**(672.9)**	**(749.6)**	**(826.0)**	**(860.3)**	**(873.0)**	**(877.9)**	**(882.9)**

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

Emissions from Land Use, Land-Use Change, and Forestry are shown in Table ES-6. The application of crushed

limestone and dolomite to managed land (i.e., soil liming) and urea fertilization resulted in CO_2 emissions of 8.0 Tg CO_2 Eq. in 2006, and increase of 13 percent relative to 1990. The application of synthetic fertilizers to forest and settlement soils in 2006 resulted in direct N_2O emissions of 2.2 Tg CO_2 Eq. Direct N_2O emissions from fertilizer application increased by approximately 97 percent between 1990 and 2006. Non-CO_2 emissions from forest fires in 2006 resulted in CH_4 emissions of 11.6 Tg CO_2 Eq., and in N_2O emissions of 1.2 Tg CO_2 Eq.

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

Source Category	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	**7.1**	**7.0**	**7.5**	**7.8**	**8.5**	**8.3**	**7.6**	**7.9**	**8.0**
Cropland Remaining Cropland:									
Liming of Agricultural Soils & Urea Fertilization	7.1	7.0	7.5	7.8	8.5	8.3	7.6	7.9	8.0
CH_4	**7.1**	**4.0**	**14.0**	**6.0**	**10.4**	**8.1**	**6.9**	**11.6**	**11.6**
Forest Land Remaining Forest Land:									
Forest Fires	7.1	4.0	14.0	6.0	10.4	8.1	6.9	11.6	11.6
N_2O	**1.8**	**1.9**	**3.3**	**2.7**	**3.2**	**3.0**	**3.0**	**3.3**	**3.3**
Forest Land Remaining Forest Land:									
Forest Fires	0.7	0.4	1.4	0.6	1.1	0.8	0.7	1.2	1.2
Forest Land Remaining Forest Land:									
Forest Soils	0.1	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Settlements Remaining Settlements:									
Settlement Soils	1.0	1.4	1.5	1.8	1.8	1.9	1.9	1.8	1.8
Total	**16.0**	**13.0**	**24.8**	**16.5**	**22.1**	**19.3**	**17.4**	**22.8**	**22.9**

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

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 in the Waste chapter, accounting for 23 percent of total U.S. CH_4 emissions.[12] Additionally, wastewater treatment accounts for 4 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. Emissions of CH_4 and N_2O from composting grew from 1990 to 2006, and resulted in emissions of 1.6 Tg CO_2 Eq. and 1.8 Tg CO_2 Eq., respectively. Overall, in 2006, emission sources accounted for in the Waste chapter generated 2.2 percent of total U.S. greenhouse gas emissions.

Other Information

Emissions by Economic Sector

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

[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 of the Inventory report.

Transportation, Electricity Generation, Agriculture, and U.S. Territories.

Table ES-7 summarizes emissions from each of these sectors, and Figure ES-13 shows the trend in emissions by sector from 1990 to 2006.

Figure ES-13: Emissions Allocated to Economic Sectors

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**	**2006**
Electric Power Industry	1,859.1	1,989.7	2,328.9	2,290.9	2,300.4	2,329.4	2,363.5	2,430.0	2,377.8
Transportation	1,532.5	1,677.2	1,910.0	1,888.8	1,941.4	1,937.7	1,985.1	1,997.6	1,960.4
Industry	1,462.6	1,474.8	1,435.5	1,385.6	1,384.7	1,376.8	1,389.1	1,357.2	1,372.0
Agriculture	670.8	686.7	693.0	712.2	691.2	659.1	661.5	687.9	686.1
Commercial	399.3	406.2	391.5	384.0	389.1	411.3	405.9	401.7	395.9
Residential	351.2	374.4	390.2	381.5	378.7	402.1	388.4	378.8	347.4
U.S. Territories	34.1	41.1	47.3	54.5	53.3	59.7	61.0	60.5	62.4
Total Emissions	**6,309.7**	**6,650.1**	**7,196.4**	**7,097.6**	**7,138.7**	**7,176.3**	**7,254.4**	**7,313.7**	**7,201.9**
Land Use, Land-Use Change, and Forestry (Sinks)	(736.6)	(774.5)	(672.9)	(749.6)	(826.0)	(860.3)	(873.0)	(877.9)	(882.9)
Net	**5,573.1**	**5,875.6**	**6,523.6**	**6,348.0**	**6,312.7**	**6,316.0**	**6,381.4**	**6,435.8**	**6,318.9**

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

Using this categorization, emissions from electricity generation accounted for the largest portion (33 percent) of U.S. greenhouse gas emissions in 2006. Transportation activities, in aggregate, accounted for the second largest portion (27 percent). Emissions from industry accounted for 19 percent of U.S. greenhouse gas emissions in 2006. In contrast to electricity generation and transportation, emissions from industry have in general declined over the past decade. The long-term decline in these emissions has been due to structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and energy efficiency improvements. The remaining 21 percent of U.S. greenhouse gas emissions were contributed by 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 10 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 5 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.

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

[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.

combustion, CH_4 and N_2O from stationary sources, and SF_6 from electrical transmission and distribution systems.

When emissions from electricity are distributed among these sectors, industry accounts for the largest share of U.S. greenhouse gas emissions (28 percent) in 2006. 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 (27 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 2006.

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**	**2006**
Industry	2,102.6	2,137.9	2,176.9	2,062.4	2,051.4	2,065.8	2,075.6	2,041.1	2,029.8
Transportation	1,535.6	1,680.3	1,913.5	1,892.5	1,944.8	1,942.0	1,989.7	2,002.4	1,965.4
Commercial	948.6	1,005.6	1,143.1	1,150.8	1,152.0	1,173.9	1,188.5	1,213.7	1,205.7
Residential	956.7	1,030.0	1,163.3	1,155.4	1,180.1	1,213.7	1,210.1	1,244.4	1,190.4
Agriculture	732.0	755.2	752.4	782.0	757.0	721.1	729.5	751.5	748.3
U.S. Territories	34.1	41.1	47.3	54.5	53.3	59.7	61.0	60.5	62.4
Total Emissions	**6,309.7**	**6,650.1**	**7,196.4**	**7,097.6**	**7,138.7**	**7,176.3**	**7,254.4**	**7,313.7**	**7,201.9**
Land Use, Land-Use Change, and Forestry (Sinks)	(736.6)	(774.5)	(672.9)	(749.6)	(826.0)	(860.3)	(873.0)	(877.9)	(882.9)
Net Emissions (Sources and Sinks)	**5,573.1**	**5,875.6**	**6,523.6**	**6,348.0**	**6,312.7**	**6,316.0**	**6,381.4**	**6,435.8**	**6,318.9**

See Table 2-14 for more detailed data.

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

[BEGIN BOX]

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

Total emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: 1) emissions per unit of aggregate energy consumption, because energy-related activities are the largest sources of emissions; 2) emissions per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; 3) emissions per unit of electricity consumption, because the electric power industry—utilities and nonutilities combined—was the largest source of U.S. greenhouse gas emissions in 2006; 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 0.8 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**	**2006**	**Growt**

											h Rate[a]
GDP[b]	100		113		138	139	141	145	150	155	159	3.0%
Electricity Consumption[c]	100		112		127	125	128	129	131	134	135	1.9%
Fossil Fuel Consumption[c]	100		107		117	115	116	116	119	119	117	1.0%
Energy Consumption[c]	100		108		116	112	115	115	118	118	117	1.0%
Population[d]	100		107		113	114	115	116	117	118	119	1.1%
Greenhouse Gas Emissions[e]	100		105		114	112	113	114	115	116	114	0.8%

[a] Average annual growth rate
[b] Gross Domestic Product in chained 2000 dollars (BEA 2007)
[c] Energy content-weighted values (EIA 2007b)
[d] U.S. Census Bureau (2007)
[e] GWP-weighted values

Figure ES-15: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product
Source: BEA (2007), U.S. Census Bureau (2007), and emission estimates in this report.

[END BOX]

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 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 2008),[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.

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

Gas/Activity	1990		1995		2000	2001	2002	2003	2004	2005	2006
NO_x	**21,645**		**21,272**		**19,203**	**18,410**	**17,938**	**17,043**	**16,177**	**15,569**	**14,869**
Mobile Fossil Fuel Combustion	10,920		10,622		10,310	9,819	10,154	9,642	9,191	8,739	8,287
Stationary Fossil Fuel Combustion	9,883		9,821		8,002	7,667	6,791	6,419	6,004	5,853	5,610
Industrial Processes	591		607		626	656	534	528	524	519	515
Oil and Gas Activities	139		100		111	113	321	316	316	316	315
Municipal Solid Waste Combustion	82		88		114	114	98	97	97	97	97
Agricultural Burning	28		29		35	35	33	34	39	39	38
Solvent Use	1		3		3	3	5	5	5	5	5

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

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

Waste	0	1	2	2	2	2	2	2	2
CO	**130,461**	**109,032**	**92,777**	**89,212**	**84,609**	**80,221**	**76,342**	**72,365**	**68,372**
Mobile Fossil Fuel Combustion	119,360	97,630	83,559	79,851	75,421	71,038	67,096	63,154	59,213
Stationary Fossil Fuel Combustion	5,000	5,383	4,340	4,377	4,965	4,893	4,876	4,860	4,844
Industrial Processes	4,125	3,959	2,217	2,339	1,744	1,724	1,724	1,724	1,724
Municipal Solid Waste Combustion	978	1,073	1,670	1,672	1,439	1,437	1,437	1,437	1,437
Agricultural Burning	691	663	792	774	709	800	879	860	825
Oil and Gas Activities	302	316	146	147	323	321	321	321	322
Waste	1	2	8	8	7	7	7	7	7
Solvent Use	5	5	46	45	1	1	1	1	1
NMVOCs	**20,930**	**19,520**	**15,228**	**15,048**	**15,640**	**15,170**	**14,807**	**14,444**	**14,082**
Mobile Fossil Fuel Combustion	10,932	8,745	7,230	6,872	7,235	6,885	6,587	6,289	5,991
Solvent Use	5,216	5,609	4,384	4,547	3,881	3,862	3,854	3,846	3,839
Industrial Processes	2,422	2,642	1,773	1,769	2,036	1,972	1,931	1,890	1,849
Stationary Fossil Fuel Combustion	912	973	1,077	1,080	1,585	1,560	1,553	1,545	1,538
Oil and Gas Activities	554	582	389	400	545	538	533	528	523
Municipal Solid Waste Combustion	222	237	257	258	243	239	237	235	232
Waste	673	731	119	122	115	114	112	111	110
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA	NA
SO_2	**20,935**	**16,891**	**14,829**	**14,452**	**13,403**	**13,631**	**13,232**	**13,114**	**12,258**
Stationary Fossil Fuel Combustion	18,407	14,724	12,848	12,461	11,613	11,956	11,625	11,573	10,784
Industrial Processes	1,307	1,117	1,031	1,047	850	804	800	797	793
Mobile Fossil Fuel Combustion	793	672	632	624	683	621	564	508	451
Oil and Gas Activities	390	335	286	289	233	226	220	213	207
Municipal Solid Waste Combustion	38	42	29	30	23	22	22	22	22
Waste	0	1	1	1	1	1	1	1	1
Solvent Use	0	1	1	1	0	0	0	0	0
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA	NA

Source: (EPA 2008, 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.

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 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 2006 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

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

and sink category names which differ from those used elsewhere in the inventory report. For more information regarding key categories, see section 1.5 and Annex 1 of the inventory report.

Figure ES-16: 2006 Key Categories—Tier 1 Level Assessment

Quality Assurance and Quality Control (QA/QC)

The United States seeks to continually improve the quality, transparency, and credibility of the Inventory of U.S. Greenhouse Gas Emissions and Sinks. To assist in these efforts, the United States implemented a systematic approach to QA/QC. While QA/QC has always been an integral part of the U.S. national system for inventory development, the procedures followed for the current inventory have been formalized in accordance with the QA/QC plan and the UNFCCC reporting guidelines.

Uncertainty Analysis of Emission Estimates

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

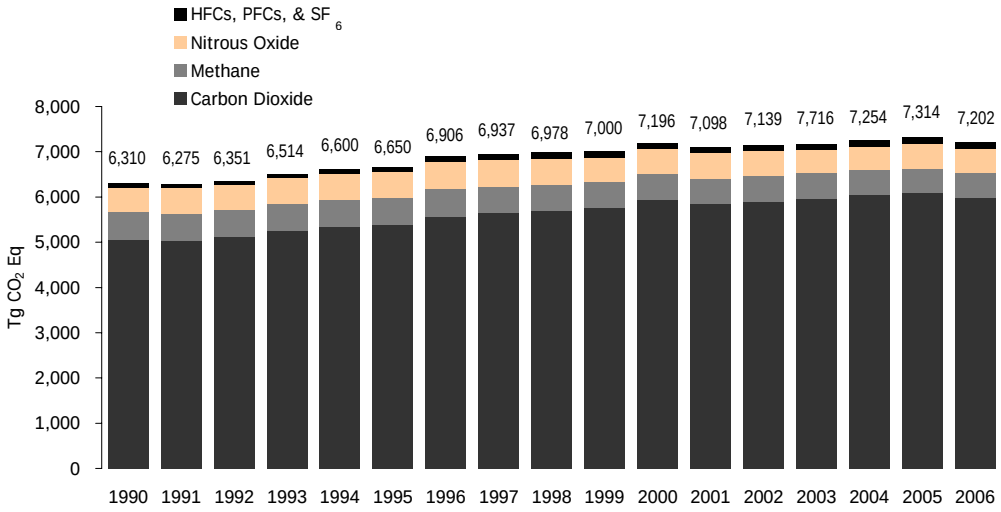


Figure ES-1: U.S. Greenhouse Gas Emissions by Gas

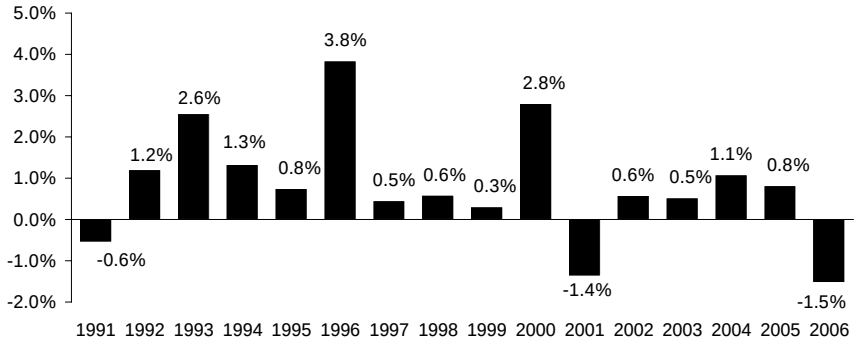


Figure ES-2: Annual Percent Change in U.S. Greenhouse Gas Emissions

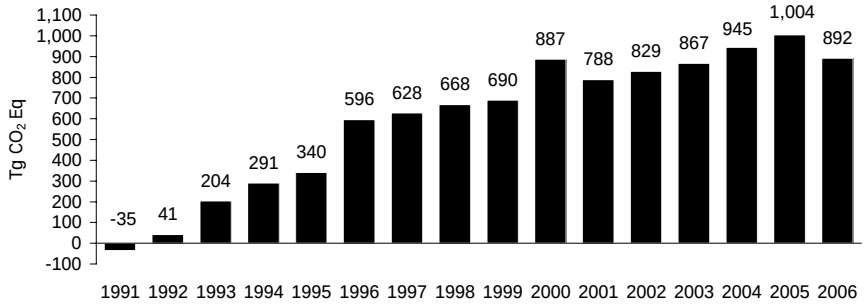


Figure ES-3: Cumulative Change in U.S. Greenhouse Gas Emissions Relative to 1990

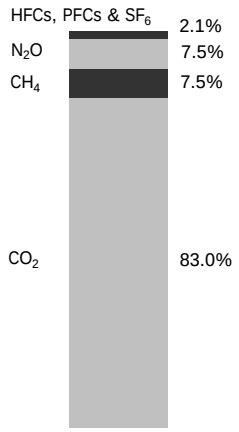


Figure ES-4: 2006 Greenhouse Gas Emissions by Gas (percents based on Tg CO_2 Eq.)

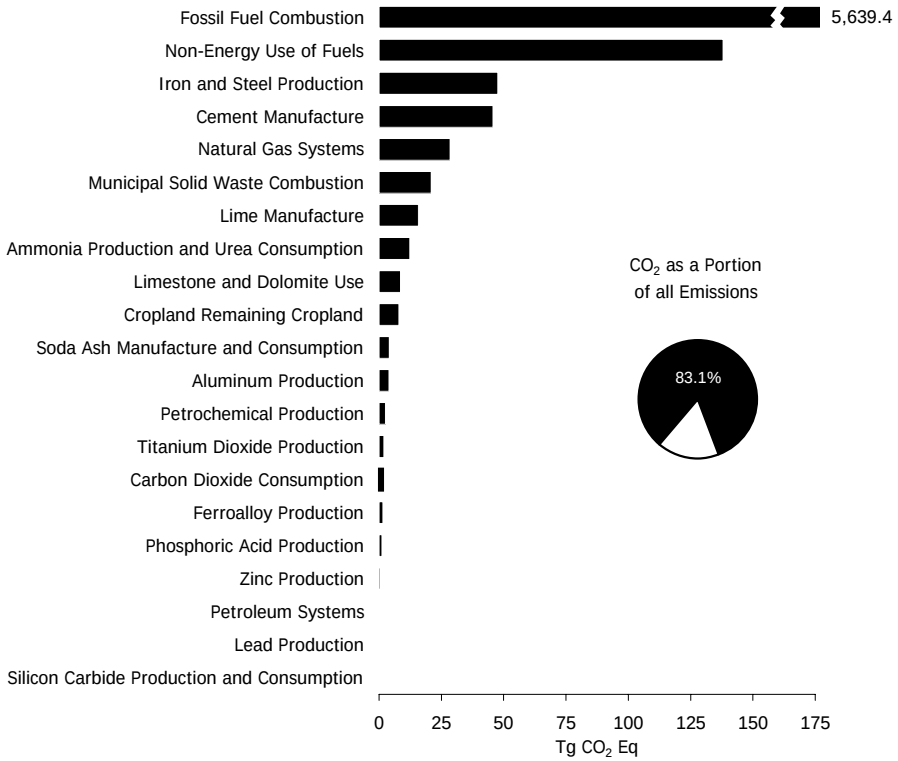


Figure ES-5: 2006 Sources of CO_2

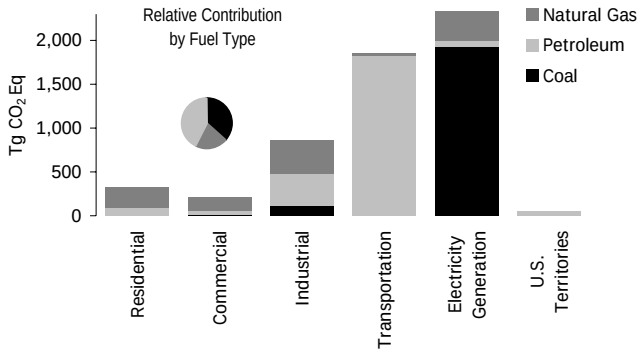


Figure ES-6: 2006 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

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

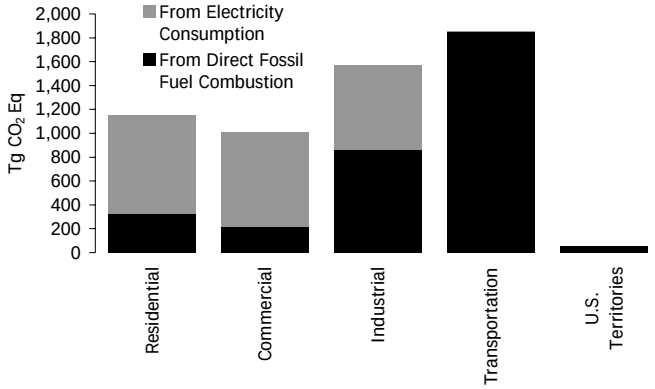


Figure ES-7: 2006 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

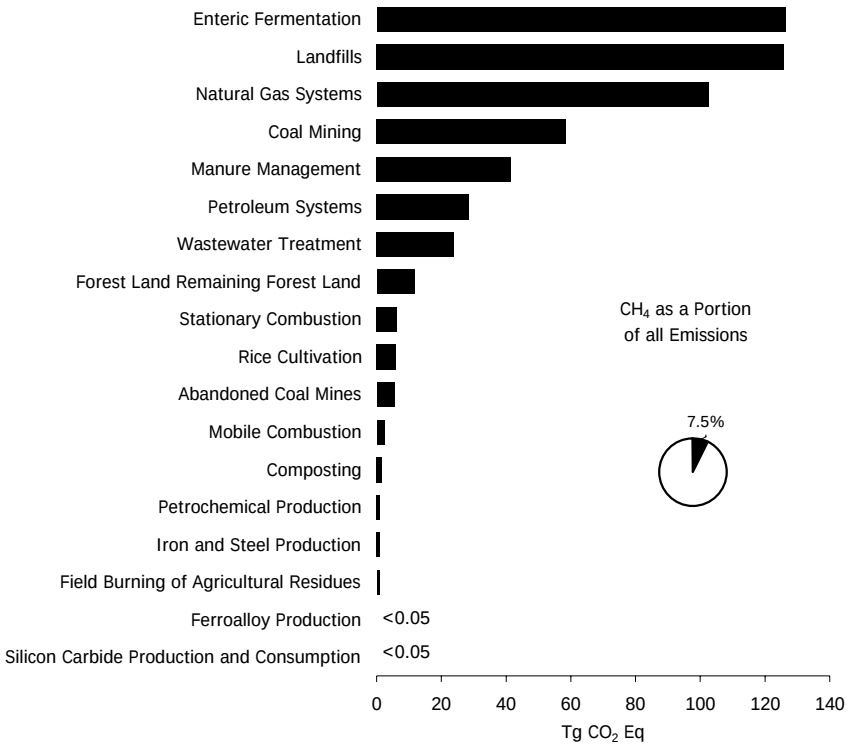


Figure ES-8: 2006 Sources of CH_4

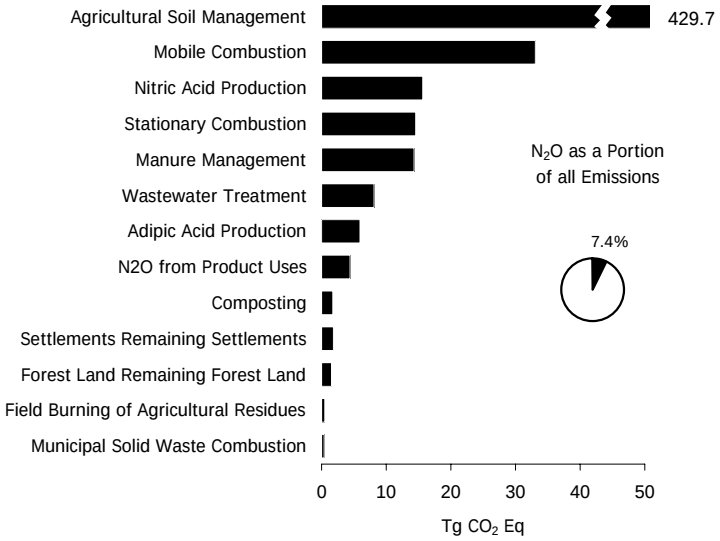


Figure ES-9: 2006 Sources of N_2O

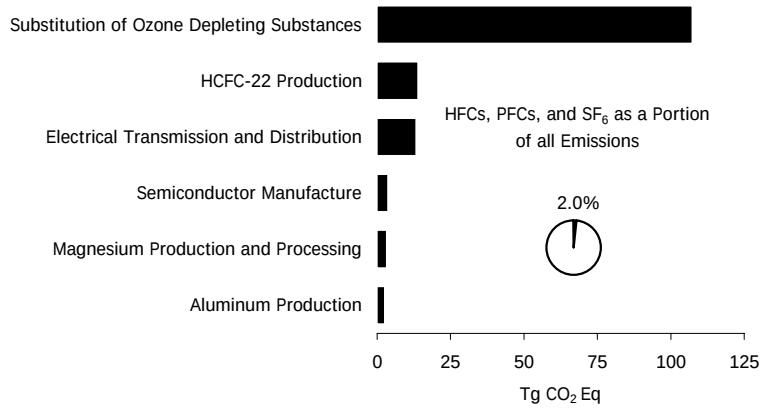
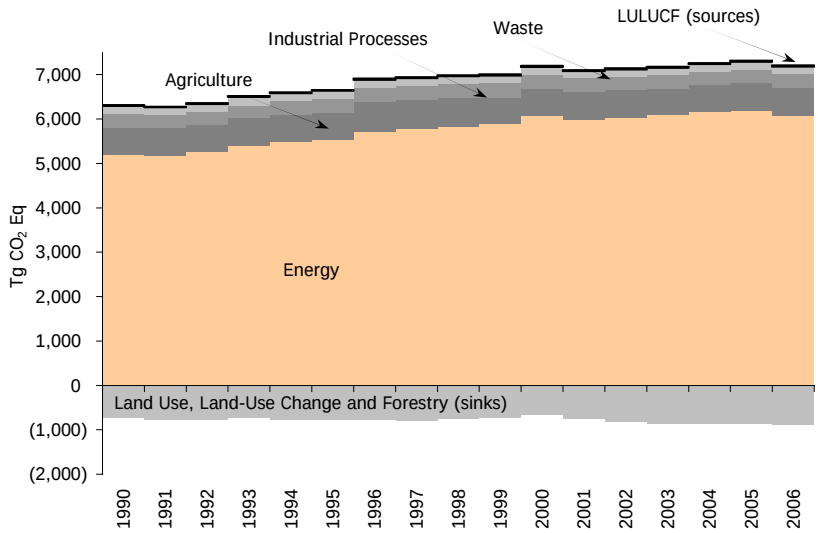


Figure ES-10: 2006 Sources of HFCs, PFCs, and SF_6



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

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

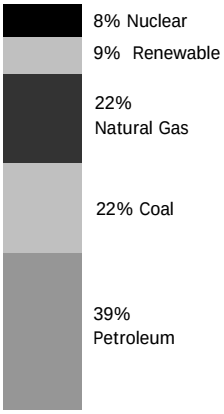


Figure ES-12: 2006 U.S. Energy Consumption by Energy Source

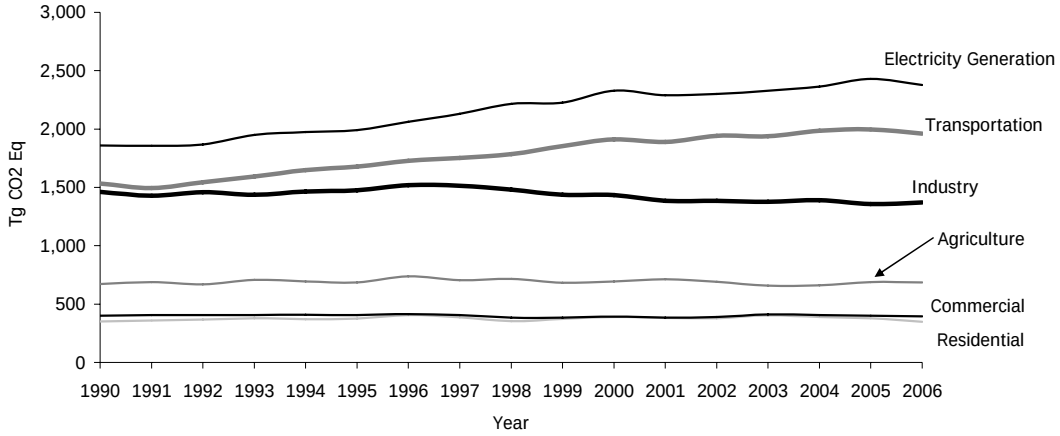


Figure ES-13: Emissions Allocated to Economic Sectors
Note: Does not include U.S. territories.

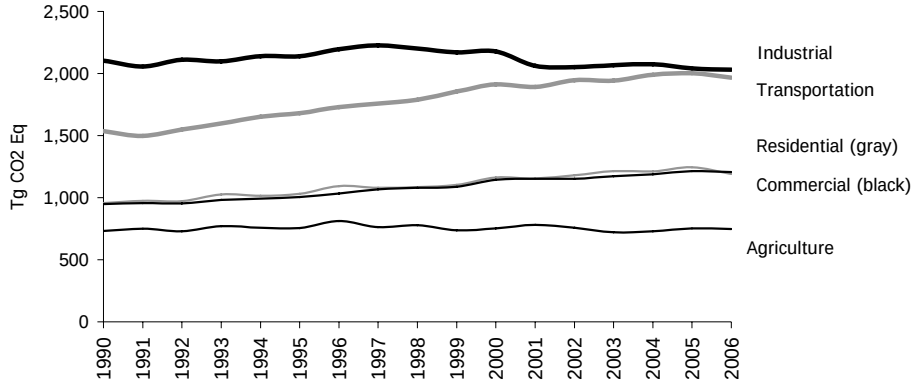


Figure ES-14: Emissions with Electricity Distributed to Economic Sectors
Note: Does not include U.S. territories.

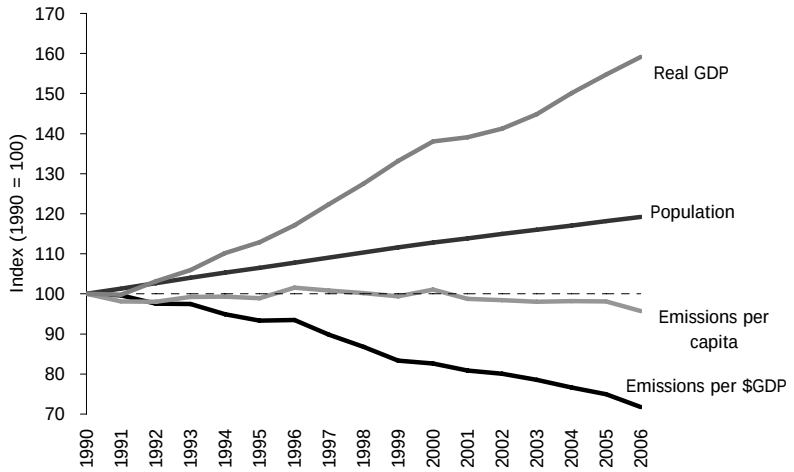


Figure ES-15: U.S. Greenhouse Gas Emissions Per Capita
and Per Dollar of Gross Domestic Product

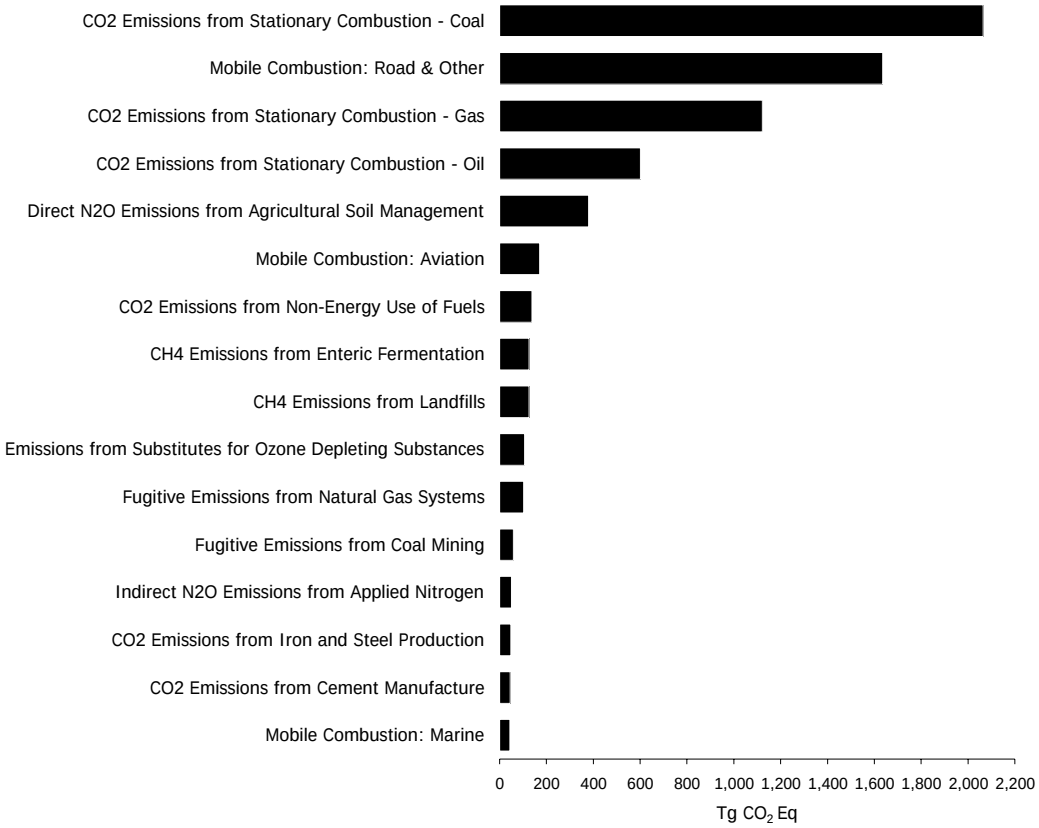


Figure ES-16: 2006 Key Categories - Tier 1 Level Assessment
Note: For a complete discussion of the key source analysis see Annex 1.

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 2006. A summary of these estimates is provided in Table 2-1 and Table 2-2 by gas and source category in the Trends in Greenhouse Gas Emissions chapter. The emission estimates in these tables are presented on both a full molecular mass basis and on a Global Warming Potential (GWP) weighted basis in order to show the relative contribution of each gas to global average radiative forcing.[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. 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

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[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>.

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 ozone is formed by two precursor pollutants, volatile organic compounds (VOCs) and nitrogen oxides (NO_x) in the presence of ultraviolet light (sunlight). Aerosols are extremely small particles or liquid droplets that are often composed of sulfur compounds, carbonaceous combustion products, crustal materials and other human induced pollutants. They can affect the absorptive characteristics of the atmosphere. Comparatively, however, the level of scientific understanding of aerosols is still very low (IPCC 2001).

CO_2, CH_4, and N_2O are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities, however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes, except when directly or

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[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.

indirectly perturbed out of equilibrium by anthropogenic activities, generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 1-1.

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

Atmospheric Variable	**CO_2**	**CH_4**	**N_2O**	**SF_6**	**CF_4**
Pre-industrial atmospheric concentration	280 ppm	0.722 ppm	0.270 ppm	0 ppt	40 ppt
Atmospheric concentration[a]	380.9 ppm	1.774 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 and CO_2 are from Hofmann (2004) and IPCC (2007), data for CF_4 are from IPCC (2001), and data for CO_2 are from Hoffman (2004). Pre-industrial atmospheric concentration and atmospheric lifetime taken from IPCC (2001 and 2007).

[a] Concentration for CO_2 was measured in 2006. Concentration for CF_4 was measured in 2000. Concentrations for all other gases were measured in 2005.

[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.

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 379 ppmv in 2005, a 35 percent increase (IPCC 2007 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, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of CO_2.

[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).

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 1,774 ppb in 2005, although the rate of increase has been declining. The IPCC has estimated that slightly more than half of the current CH_4 flux to the atmosphere is anthropogenic, from human activities such as agriculture, fossil fuel use, and waste disposal (IPCC 2007).

CH_4 is removed from the atmosphere through a reaction with the hydroxyl radical (OH) and is ultimately converted to CO_2. Minor removal processes also include reaction with chlorine in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of CH_4 reduce the concentration of OH, a feedback that may increase the atmospheric lifetime of CH_4 (IPCC 2001).

Nitrous Oxide. 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 2005, a concentration that has not been exceeded during the last thousand years. N_2O is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere (IPCC 2007).

Ozone. Ozone is present in both the upper stratosphere,[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

[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.

[HFCs]) result in stratospheric ozone depletion and are therefore controlled under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. Although CFCs and HCFCs include potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which itself is an important greenhouse gas in addition to shielding the Earth from harmful levels of ultraviolet radiation. Under the *Montreal Protocol*, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the *Protocol*, a cap was placed on the production and importation of HCFCs by non-Article 5[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 also likely to decrease CH_4 concentrations, thus having a negative radiative forcing effect (IPCC 1999). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning (both natural and anthropogenic fires) fuel combustion, and, in the stratosphere, from the photo-degradation of N_2O. Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

Nonmethane Volatile Organic Compounds (NMVOCs). Non-CH_4 volatile organic compounds include substances such as propane, butane, and ethane. These compounds participate, along with NO_x, in the formation of tropospheric ozone and other photochemical oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents. Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable.

Aerosols. Aerosols are extremely small particles or liquid droplets found in the atmosphere. They can be produced by natural events such as dust storms and volcanic activity, or by anthropogenic processes such as fuel combustion and biomass burning. Aerosols affect radiative forcing differently than greenhouse gases, and their radiative effects occur through direct and indirect mechanisms: directly by scattering and absorbing solar radiation; and indirectly by

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[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.

increasing droplet counts that modify the formation, precipitation efficiency, and radiative properties of clouds. Aerosols are removed from the atmosphere relatively rapidly by precipitation. Because aerosols generally have short atmospheric lifetimes, and have concentrations and compositions that vary regionally, spatially, and temporally, their contributions to radiative forcing are difficult to quantify (IPCC 2001).

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

Various categories of aerosols exist, including naturally produced aerosols such as soil dust, sea salt, biogenic 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 CO_2 Equivalents

[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^{ths} of carbon dioxide by weight.

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]

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, ozone precursors (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and carbonaceous particles), however, vary regionally, and consequently it is difficult to quantify their global radiative forcing impacts. No GWP values are attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere.

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

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

Source: (IPCC 1996)
[a] 100-year time horizon
[b] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

[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)

[BEGIN BOX]

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 2006 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 below and in even more detail in Annex 6.1 of this report. All estimates provided throughout this report are also presented in unweighted units.

[END BOX]

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

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 calculations for individual sources are the responsibility of individual source leads, who are most familiar with each source category and the unique characteristics of its emissions profile. The individual source leads determine the most appropriate methodology and collect the best activity data to use in the emission calculations, based upon their expertise in the source category, as well as coordinating with researchers and contractors familiar with the sources. A multi-stage process for collecting information from the individual source leads and producing the Inventory is undertaken annually to compile all information and data.

Methodology Development, Data Collection, and Emissions and Sink Estimation

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

Once the methodology is in place and the data are collected, the individual source leads calculate emissions and sink

estimates. The source leads then update or create the relevant text and accompanying annexes for the Inventory. Source leads are also responsible for completing the relevant sectoral background tables of the Common Reporting Format, conducting quality assurance and quality control (QA/QC) checks, and uncertainty analyses.

Summary Spreadsheet Compilation and Data Storage

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

National Inventory Report Preparation

The NIR is compiled from the sections developed by each individual source lead. In addition, the inventory coordinator prepares a brief overview of each chapter that summarizes the emissions from all sources discussed in the chapters. The inventory coordinator then carries out a key category analysis for the Inventory, consistent with the IPCC *Good Practice Guidance*, IPCC *Good Practice Guidance for Land Use, Land Use Change and Forestry*, and in accordance with the reporting requirements of the UNFCCC. Also at this time, the Introduction, Executive Summary, and Recent Trends sections are drafted, to reflect the trends for the most recent year of the current Inventory. The analysis of trends necessitates gathering supplemental data, including weather and temperature conditions, economic activity and gross domestic product, population, atmospheric conditions, and the annual consumption of electricity, energy, and fossil fuels. Changes in these data are used to explain the trends observed in greenhouse gas emissions in the United States. Furthermore, specific factors that affect individual sectors are researched and discussed. Many of the factors that affect emissions are included in the Inventory document as separate analyses or side discussions in boxes within the text. Text boxes are also created to examine the data aggregated in different ways than in the remainder of the document, such as a focus on transportation activities or emissions from electricity generation. The document is prepared to match the specification of the UNFCCC reporting guidelines for National Inventory Reports.

Common Reporting Format Table Compilation

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

QA/QC and Uncertainty

QA/QC and uncertainty analyses are supervised by the QA/QC 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.

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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.

[END BOX]

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 global warming potential-weighted emissions in 2006. 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.

Table 1-4: Key Categories for the United States (1990-2006) Based on Tier 1 Approach

IPCC Source Categories	Gas	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Qual[a]	2006 Emissions (Tg CO_2 Eq.)
Energy							
CO_2 Emissions from Stationary Combustion - Coal	CO_2	✓	✓	✓	✓		2,065.3
Mobile Combustion: Road & Other	CO_2	✓	✓	✓	✓		1,635.9
CO_2 Emissions from Stationary Combustion - Gas	CO_2	✓	✓	✓			1,121.9
CO_2 Emissions from Stationary Combustion - Oil	CO_2	✓	✓	✓	✓		601.7
Mobile Combustion: Aviation	CO_2	✓	✓	✓	✓		170.6
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	✓		✓			138.0
Mobile Combustion: Marine	CO_2	✓	✓	✓	✓		43.6
CO_2 Emissions from Natural Gas Systems	CO_2	✓	✓	✓	✓		28.5

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

IPCC Source Categories	Gas	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Qual[a]	2006 Emissions (Tg CO_2 Eq.)
CO_2 Emissions from Municipal Solid Waste Combustion	CO_2		✓		✓		20.9
Fugitive Emissions from Natural Gas Systems	CH_4	✓	✓	✓	✓		102.4
Fugitive Emissions from Coal Mining	CH_4	✓	✓	✓	✓		58.5
Fugitive Emissions from Petroleum Systems	CH_4	✓	✓	✓	✓		28.4
Mobile Combustion: Road & Other	N_2O	✓	✓	✓	✓		31.1
International Bunker Fuels[b]	Several					✓	126.9
Industrial Processes							
CO_2 Emissions from Iron and Steel Production	CO_2	✓	✓	✓	✓		47.7
CO_2 Emissions from Cement Manufacture	CO_2	✓	✓	✓	✓		45.7
CO_2 Emissions from Ammonia Manufacture and Urea Application	CO_2		✓		✓		12.4
N_2O Emissions from Adipic Acid Production	N_2O		✓		✓		5.9
Emissions from Substitutes for Ozone Depleting Substances	Several	✓	✓	✓	✓		107.3
HFC-23 Emissions from HCFC-22 Production	HFCs	✓	✓	✓	✓		13.8
SF_6 Emissions from Electrical Transmission and Distribution	SF_6		✓		✓		13.2
PFC Emissions from Aluminum Production	PFCs		✓		✓		2.5
Agriculture							
CH_4 Emissions from Enteric Fermentation	CH_4	✓	✓	✓	✓		126.2
CH_4 Emissions from Manure Management	CH_4			✓			41.4
Direct N_2O Emissions from Agricultural Soil Management	N_2O	✓	✓	✓	✓		379.3
Indirect N_2O Emissions from Applied Nitrogen	N_2O	✓	✓	✓	✓		50.4
Waste							
CH_4 Emissions from Landfills	CH_4	✓	✓	✓	✓		125.7
Land Use, Land Use Change, and Forestry							
CO_2 Emissions from Forest Land Remaining Forest Land	CO_2			✓	✓		(745.1)
Emissions from Settlements Remaining Settlements	CO_2			✓	✓		(95.5)
CO_2 Emissions from Cropland Remaining Cropland	CO_2				✓		(33.8)
CO_2 Emissions from Grassland Remaining Grassland	CO_2				✓		16.2
CO_2 Emissions from Landfilled Yard Trimmings and Food Scraps	CO_2				✓		(9.8)
CO_2 Emissions from Land Converted to Cropland	CO_2				✓		9.4
Subtotal Without LULUCF							6,941.7
Total Emissions Without LULUCF							7,179.0
Percent of Total Without LULUCF							96.7%
Subtotal With LULUCF							6,083.1
Total Emissions With LULUCF							6,318.9
Percent of Total With LULUCF							96.3%

[a]Qualitative criteria.
[b]Emissions from this source not included in totals.
Note: The Tier 1 approach for identifying key source categories does not directly include assessment of uncertainty in emissions

estimates.

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 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.

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**

Notes:
[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.

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.

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 2006. 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.

Table 1-6: IPCC Sector Descriptions

Chapter/IPCC Sector	Activities Included
Energy	Emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions.
Industrial Processes	By-product or fugitive emissions of greenhouse gases from industrial processes not directly related to energy activities such as fossil fuel combustion.
Solvent and Other Product Use	Emissions, of primarily NMVOCs, resulting from the use of solvents and N_2O from product uses.
Agriculture	Anthropogenic emissions from agricultural activities except fuel

	combustion, which is addressed under Energy.
Land Use, Land-Use Change, and Forestry	Emissions and removals of CO_2, CH_4, and N_2O from forest management, other land-use activities, and land-use change.
Waste	Emissions from waste management activities.

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

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

Chapter/IPCC Sector: Overview of emission trends for each IPCC defined sector

Source category: Description of source pathway and emission trends.

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

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

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

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

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

Special attention is given to CO_2 from fossil fuel combustion relative to other sources because of its share of emissions and its dominant influence on emission trends. For example, each energy consuming end-use sector (i.e., residential, commercial, industrial, and transportation), as well as the electricity generation sector, is described individually. Additional information for certain source categories and other topics is also provided in several Annexes listed in Table 1-7.

Table 1-7: List of Annexes

ANNEX 1 Key Category Analysis	
ANNEX 2 Methodology and Data for Estimating CO_2 Emissions from Fossil Fuel Combustion	
2.1.	Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion
2.2.	Methodology for Estimating the Carbon Content of Fossil Fuels
2.3.	Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels
ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories	
3.1.	Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Stationary Combustion
3.2.	Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related Greenhouse Gas Emissions
3.3.	Methodology for Estimating CH_4 Emissions from Coal Mining
3.4.	Methodology for Estimating CH_4 Emissions from Natural Gas Systems
3.5.	Methodology for Estimating CH_4 and CO_2 Emissions from Petroleum Systems
3.6.	Methodology for Estimating CO_2 and N_2O Emissions from 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 Analyses by Source

2. Trends in Greenhouse Gas Emissions

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

In 2006, total U.S. greenhouse gas emissions were 7,201.9 teragrams of carbon dioxide equivalents (Tg CO_2 Eq.).[1] Overall, total U.S. emissions have risen by 14.1 percent from 1990 to 2006, while the U.S. gross domestic product has increased by 59 percent over the same period (BEA 2007). Emissions decreased from 2005 to 2006 by 1.5 percent (111.8 Tg CO_2 Eq.). The following factors were primary contributors to this decrease: (1) compared to 2005, 2006 had warmer winter conditions, which decreased consumption of heating fuels, as well as cooler summer conditions, which reduced demand for electricity, (2) restraint on fuel consumption caused by rising fuel prices, primarily in the transportation sector and (3) increased use of natural gas and renewables in the electric power sector. 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.

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

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

Figure 2-3: Cumulative Change in U.S. Greenhouse Gas Emissions Relative to 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 75 percent of total GWP-weighted emissions in 1990 to 78 percent in 2006. Emissions from this source category grew by 19.4 percent (915.2 Tg CO_2 Eq.) from 1990 to 2006 and were responsible for most of the increase in national emissions during this period. From 2005 to 2006, these emissions decreased by 2.0 percent (112.1 Tg CO_2 Eq.). Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends.

Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors., including population and economic growth, energy price fluctuations, technological changes, and seasonal temperatures. On an annual basis, the overall consumption of fossil fuels in the United States 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 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).

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[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, Executive Summary.)

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

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.

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 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 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.

From 2005 to 2006, emissions from fuel combustion decreased for the first time since 2000 to 2001. This decrease occurred primarily in the electricity generation, transportation, residential, and commercial sectors due to a number of factors. The decrease in emissions from electricity generation is a result of a smaller share of electricity by coal and a greater share generated by natural gas. Coal and natural gas consumption for electricity generation decreased by 1.2 percent and increased by 6.4 percent, respectively, in 2006, and nuclear power increased by less than 1 percent. The transportation decrease is primarily a result of the restraint on fuel consumption caused by rising fuel prices, which directly resulted in a decrease of petroleum consumption within this sector of 2 percent in 2006. The decrease in emissions from the residential sector is primarily a result of decreased electricity consumption due to increases in the price of electricity, and warmer winter weather conditions. The decrease in emissions in the

industrial sector is a result of a decrease in electricity sales to this sector. A moderate increase in the industrial sector is a result of growth in industrial output and growth in the U.S. economy. Renewable fuels used to generate electricity increased in 2006, with the greatest growth occurring in wind.

Overall, from 1990 to 2006, total emissions of CO_2 increased by 915.9 Tg CO_2 Eq. (18 percent), while CH_4 and N_2O emissions decreased by 66.4 Tg CO_2 Eq. (11 percent) and 13.2 Tg CO_2 Eq. (2 percent) respectively. During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 55.8 Tg CO_2 Eq. (63 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 12 percent of total emissions in 2006.

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

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

Gas/Source	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
CO_2	**5,067.2**	**5,392.8**	**5,938.2**	**5,844.8**	**5,907.2**	**5,971.1**	**6,055.9**	**6,093.4**	**5,983.1**
Fossil Fuel Combustion	4,724.1	5,032.4	5,577.1	5,507.4	5,564.8	5,636.9	5,700.5	5,751.5	5,639.4
Electricity Generation	1,809.6	1,939.3	2,282.3	2,244.3	2,253.7	2,283.1	2,314.9	2,380.2	2,328.2
Transportation	1,473.5	1,590.2	1,791.9	1,770.3	1,823.8	1,821.4	1,868.5	1,883.1	1,850.1
Industrial	849.9	880.6	863.2	855.0	857.3	858.8	861.0	850.9	866.1
Residential	344.4	359.9	374.3	365.4	362.3	385.0	370.8	360.9	328.7
Commercial	218.5	227.5	229.2	223.3	223.7	237.6	231.9	223.2	211.4
US Territories	28.3	35.0	36.2	49.0	44.0	51.0	53.5	53.2	54.9
Non-Energy Use of Fuels	117.2	133.2	141.4	131.9	135.9	131.8	148.9	139.1	138.0
Iron and Steel Production	84.9	73.3	65.1	57.9	54.6	53.4	51.3	45.2	47.7
Cement Manufacture	33.3	36.8	41.2	41.4	42.9	43.1	45.6	45.9	45.7
Natural Gas Systems	33.7	33.8	29.4	28.8	29.6	28.4	28.1	29.5	28.5
Municipal Solid Waste Combustion	10.9	15.7	17.5	18.0	18.5	19.1	20.1	20.7	20.9
Lime Manufacture	12.0	14.0	14.9	14.3	13.7	14.5	15.2	15.1	15.8
Ammonia Manufacture and Urea Consumption	16.9	17.8	16.4	13.3	14.2	12.5	13.2	12.8	12.4
Limestone and Dolomite Use	5.5	7.4	6.0	5.7	5.9	4.7	6.7	7.4	8.6
Cropland Remaining Cropland	7.1	7.0	7.5	7.8	8.5	8.3	7.6	7.9	8.0
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.1	4.1	4.1	4.2	4.2	4.2
Aluminum Production	6.8	5.7	6.1	4.4	4.5	4.5	4.2	4.2	3.9
Petrochemical Production	2.2	2.8	3.0	2.8	2.9	2.8	2.9	2.8	2.6
Titanium Dioxide Production	1.2	1.5	1.8	1.7	1.8	1.8	2.1	1.8	1.9
Carbon Dioxide Consumption	1.4	1.4	1.4	0.8	1.0	1.3	1.2	1.3	1.6
Ferroalloy Production	2.2	2.0	1.9	1.5	1.3	1.3	1.4	1.4	1.5
Phosphoric Acid Production	1.5	1.5	1.4	1.3	1.3	1.4	1.4	1.4	1.2
Zinc Production	0.9	1.0	1.1	1.0	0.9	0.5	0.5	0.5	0.5
Petroleum Systems	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Lead Production	0.3	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	0.2
Land Use, Land-Use Change, and Forestry (Sink)[a]	*(736.6)*	*(774.5)*	*(672.9)*	*(749.6)*	*(826.0)*	*(860.3)*	*(873.0)*	*(877.9)*	*(882.9)*
Biomass—Wood[b]	*215.2*	*229.1*	*218.1*	*193.5*	*192.8*	*193.8*	*205.1*	*204.8*	*204.4*
International Bunker Fuels[b]	*113.7*	*100.6*	*101.1*	*97.6*	*89.1*	*83.7*	*99.8*	*102.1*	*125.7*
Biomass—Ethanol[b]	*4.2*	*7.7*	*9.2*	*9.7*	*11.5*	*15.7*	*19.7*	*22.6*	*30.3*
CH_4	**608.7**	**598.2**	**569.3**	**555.4**	**557.5**	**558.7**	**545.6**	**539.0**	**542.3**

Enteric Fermentation	126.9	132.3	124.6	123.6	123.8	124.6	122.4	124.5	126.2
Landfills	149.6	144.0	120.8	117.6	120.1	125.6	122.6	123.7	125.7
Natural Gas Systems	124.7	128.1	126.5	125.3	124.9	123.3	114.0	102.5	102.4
Coal Mining	84.1	67.1	60.4	60.3	56.8	56.9	59.8	57.1	58.5
Manure Management	31.0	35.2	38.8	40.2	41.3	40.7	40.1	41.8	41.4
Petroleum Systems	33.9	32.0	30.3	30.2	29.9	29.2	28.7	28.3	28.4
Wastewater Treatment	23.0	24.3	24.6	24.2	24.1	23.9	24.0	23.8	23.9
Forest Land Remaining Forest Land	7.1	4.0	14.0	6.0	10.4	8.1	6.9	11.6	11.6
Stationary Combustion	7.4	7.2	6.7	6.2	6.2	6.4	6.6	6.5	6.2
Rice Cultivation	7.1	7.6	7.5	7.6	6.8	6.9	7.6	6.8	5.9
Abandoned Underground Coal Mines	6.0	8.2	7.4	6.7	6.2	6.0	5.8	5.6	5.4
Mobile Combustion	4.7	4.3	3.4	3.3	3.0	2.8	2.7	2.5	2.4
Composting	0.3	0.7	1.3	1.3	1.3	1.5	1.6	1.6	1.6
Petrochemical Production	0.9	1.1	1.2	1.1	1.1	1.1	1.2	1.1	1.0
Iron and Steel Production	1.3	1.3	1.2	1.1	1.0	1.0	1.0	1.0	0.9
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.8	0.7	0.8	0.9	0.9	0.8
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*	*0.2*
N_2O	**544.9**	**559.2**	**556.2**	**575.4**	**544.3**	**518.9**	**516.3**	**537.8**	**531.7**
Agricultural Soil Management	430.6	428.3	432.6	459.6	430.5	409.2	409.1	432.5	429.7
Mobile Combustion	43.5	53.4	52.5	49.9	45.9	42.5	39.8	36.5	33.1
Nitric Acid Production	17.0	18.9	18.6	15.1	16.4	15.4	15.2	15.8	15.6
Stationary Combustion	12.8	13.4	14.6	14.1	14.0	14.4	14.6	14.8	14.5
Manure Management	12.1	12.8	13.7	14.0	14.0	13.6	13.8	13.9	14.3
Wastewater Treatment	6.3	6.9	7.6	7.8	7.6	7.7	7.8	8.0	8.1
Adipic Acid Production	15.3	17.3	6.2	5.1	6.1	6.3	5.9	5.9	5.9
N_2O from Product Uses	4.4	4.6	4.9	4.9	4.4	4.4	4.4	4.4	4.4
Settlements Remaining Settlements	1.0	1.4	1.5	1.8	1.8	1.9	1.9	1.8	1.8
Composting	0.4	0.8	1.4	1.4	1.4	1.6	1.7	1.7	1.8
Forest Land Remaining Forest Land	0.8	0.6	1.7	1.0	1.4	1.2	1.1	1.5	1.5
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.4	0.4	0.5	0.5	0.5
Municipal Solid Waste Combustion	0.5	0.5	0.4	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*	*1.1*
HFCs	**35.5**	**56.4**	**100.0**	**96.3**	**103.0**	**102.3**	**112.4**	**119.1**	**121.3**
Substitution of Ozone Depleting Substances[c]	0.3	29.1	70.0	76.3	83.0	89.8	96.6	102.3	107.3
HCFC-22 Production	35.0	27.0	29.8	19.8	19.8	12.3	15.6	16.5	13.8
Semiconductor Manufacture	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.3
PFCs	**20.8**	**15.6**	**13.5**	**7.0**	**8.7**	**7.1**	**6.1**	**6.2**	**6.1**
Semiconductor Manufacture	2.2	3.8	4.9	3.5	3.5	3.3	3.3	3.2	3.6
Aluminum Production	18.5	11.8	8.6	3.5	5.2	3.8	2.8	3.0	2.5
SF_6	**32.7**	**28.0**	**19.2**	**18.7**	**18.0**	**18.1**	**18.0**	**18.3**	**17.4**
Electrical Transmission and Distribution	26.7	21.5	15.1	15.0	14.4	13.9	14.0	14.0	13.2
Magnesium Production and Processing	5.4	5.6	3.0	2.9	2.9	3.4	3.2	3.3	3.2
Semiconductor Manufacture	0.5	0.9	1.1	0.7	0.7	0.8	0.8	1.0	1.0
Total	**6,309.7**	**6,650.1**	**7,196.4**	**7,097.6**	**7,138.7**	**7,176.3**	**7,254.4**	**7,313.7**	**7,201.9**
Net Emissions (Sources and Sinks)	**5,573.1**	**5,875.6**	**6,523.6**	**6,348.0**	**6,312.7**	**6,316.0**	**6,381.4**	**6,435.8**	**6,318.9**

+ 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.
[c] Small amounts of PFC emissions also result from this source.
Note: Totals may not sum due to independent rounding.

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

Gas/Source	1990	2000	2001	2002	2003	2004	2005	2006
CO_2	**5,067,156**	**5,938,232**	**5,844,829**	**5,907,225**	**5,971,137**	**6,055,896**	**6,093,381**	**5,983,105**
Fossil Fuel Combustion	4,724,146	5,577,072	5,507,406	5,564,795	5,636,941	5,700,510	5,751,515	5,639,368
Electricity Generation	1,809,614	2,282,278	2,244,279	2,253,729	2,283,069	2,314,907	2,380,222	2,328,153
Transportation	1,473,500	1,791,883	1,770,341	1,823,772	1,821,435	1,868,453	1,883,093	1,850,136
Industrial	849,927	863,229	855,028	857,289	858,767	861,012	850,886	866,092
Residential	344,352	374,272	365,400	362,253	385,034	370,761	360,920	328,724
Commercial	218,468	229,215	223,332	223,737	237,606	231,892	223,181	211,381
US Territories	28,285	36,195	49,027	44,014	51,030	53,486	53,213	54,882
Non-Energy Use of Fuels	117,170	141,427	131,887	135,857	131,772	148,931	139,057	137,980
Iron and Steel Production	84,904	65,115	57,927	54,595	53,370	51,309	45,235	47,679
Cement Manufacture	33,278	41,190	41,357	42,898	43,082	45,603	45,910	45,739
Natural Gas Systems	33,729	29,390	28,793	29,629	28,445	28,122	29,462	28,504
Municipal Solid Waste Combustion	10,950	17,518	17,971	18,458	19,058	20,097	20,673	20,922
Lime Manufacture	12,004	14,872	14,261	13,652	14,458	15,154	15,131	15,825
Ammonia Manufacture and Urea Consumption	16,889	16,402	13,305	14,194	12,488	13,241	12,817	12,376
Limestone and Dolomite Use	5,533	5,960	5,733	5,885	4,720	6,702	7,397	8,615
Cropland Remaining Cropland	7,084	7,541	7,825	8,549	8,260	7,555	7,854	8,012
Soda Ash Manufacture and Consumption	4,141	4,181	4,147	4,139	4,111	4,205	4,228	4,162
Aluminum Production	6,831	6,086	4,381	4,490	4,503	4,231	4,207	3,923
Petrochemical Production	2,221	3,004	2,787	2,857	2,777	2,895	2,804	2,573
Titanium Dioxide Production	1,195	1,752	1,697	1,824	1,839	2,064	1,755	1,876
Carbon Dioxide Consumption	1,416	1,421	829	989	1,311	1,198	1,321	1,579
Ferroalloy Production	2,152	1,893	1,459	1,349	1,305	1,419	1,392	1,505
Phosphoric Acid Production	1,529	1,382	1,264	1,338	1,382	1,395	1,383	1,167
Zinc Production	949	1,140	986	937	507	477	465	529
Petroleum Systems	376	325	325	320	316	302	287	293
Lead Production	285	311	291	286	289	262	267	270
Silicon Carbide Production and Consumption	375	248	199	183	202	224	219	207
Land Use, Land-Use Change, and Forestry	*(736,621)*	*(672,885)*	*(749,550)*	*(825,993)*	*(860,298)*	*(872,969)*	*(877,901)*	*(882,948)*

(Sink)[a]								
Biomass—Wood[b]	*215,186*	*218,088*	*193,489*	*192,830*	*193,833*	*205,086*	*204,812*	*204,435*
International Bunker Fuels[b]	*113,683*	*101,125*	*97,563*	*89,101*	*83,690*	*99,828*	*102,110*	*125,659*
Biomass—Ethanol[b]	*4,155*	*9,188*	*9,673*	*11,520*	*15,704*	*19,740*	*22,554*	*30,291*
CH_4	**28,986**	**27,109**	**26,446**	**26,547**	**26,606**	**25,981**	**25,666**	**25,825**
Enteric Fermentation	6,044	5,933	5,886	5,896	5,931	5,828	5,928	6,010
Landfills	7,124	5,751	5,598	5,720	5,981	5,838	5,890	5,985
Natural Gas Systems	5,937	6,024	5,968	5,946	5,874	5,426	4,880	4,877
Coal Mining	4,003	2,874	2,874	2,707	2,709	2,846	2,717	2,784
Manure Management	1,474	1,847	1,915	1,964	1,938	1,908	1,988	1,972
Petroleum Systems	1,612	1,442	1,436	1,422	1,390	1,368	1,346	1,354
Wastewater Treatment	1,096	1,173	1,150	1,148	1,140	1,141	1,131	1,136
Forest Land Remaining Forest Land	337	667	285	494	384	330	551	551
Stationary Combustion	354	317	295	295	307	312	309	296
Rice Cultivation	339	357	364	325	328	360	326	282
Abandoned Underground Coal Mines	288	350	319	293	284	276	265	257
Mobile Combustion	224	162	157	141	132	127	120	112
Composting	15	60	60	61	69	74	75	75
Petrochemical Production	41	58	51	52	51	55	51	48
Iron and Steel Production	63	58	51	48	49	50	45	45
Field Burning of Agricultural Residues	33	38	37	34	38	42	41	39
Ferroalloy Production	1	1	+	+	+	+	+	+
Silicon Carbide Production and Consumption	1	1	+	+	+	+	+	+
International Bunker Fuels[b]	*8*	*6*	*5*	*4*	*4*	*5*	*5*	*7*
N_2O	**1,758**	**1,794**	**1,856**	**1,756**	**1,674**	**1,666**	**1,735**	**1,715**
Agricultural Soil Management	1,389	1,395	1,482	1,389	1,320	1,320	1,395	1,386
Mobile Combustion	140	169	161	148	137	128	118	107
Nitric Acid Production	55	60	49	53	50	49	51	50
Stationary Combustion	41	47	46	45	46	47	48	47
Manure Management	39	44	45	45	44	44	45	46
Wastewater Treatment	20	24	25	25	25	25	26	26
Adipic Acid Production	49	20	16	20	20	19	19	19
N_2O from Product Uses	14	16	16	14	14	14	14	14
Settlements Remaining Settlements	3	5	6	6	6	6	6	6
Composting	1	4	5	5	5	6	6	6
Forest Land Remaining Forest Land	2	6	3	5	4	3	5	5
Field Burning of Agricultural Residues	1	1	1	1	1	2	2	2

Municipal Solid Waste Combustion	2	1	1	1	1	1	1	1
International Bunker Fuels[b]	*3*	*3*	*3*	*3*	*2*	*3*	*3*	*4*
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[c]	M	M	M	M	M	M	M	M
HCFC-22 Production	3	3	2	2	1	1	1	1
Semiconductor Manufacture	+	+	+	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Semiconductor Manufacture	M	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M	M
SF_6	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Electrical Transmission and Distribution	1	1	1	1	1	1	1	1
Magnesium Production and Processing	+	+	+	+	+	+	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+	+

+ Does not exceed 0.5 Gg.
M Mixture of multiple gases
[a] The net CO_2 flux total includes both emissions and sequestration, and constitutes a sink in the United States. Sinks are only included in net emissions total. Parentheses indicate negative values or sequestration.
[b] Emissions from International Bunker Fuels and Wood Biomass and Ethanol Consumption are not included in totals.
[c] Small amounts of PFC emissions also result from this source.
Note: Totals may not sum due to independent rounding.

Emissions of all gases can be summed from each source category from Intergovernmental Panel on Climate Change (IPCC) guidance. Over the sixteen-year period of 1990 to 2006, total emissions in the Energy, Industrial Processes, and Agriculture sectors grew by 874.4 Tg CO_2 Eq. (17 percent), 19.2 Tg CO_2 Eq. (7 percent), and 10.2 Tg CO_2 Eq. (2 percent), respectively. Emissions decreased in the Waste and Solvent and Other Product Use sectors by 18.6 Tg CO_2 Eq. (10 percent) and less than 0.02 Tg CO_2 Eq. (less than 1 percent), respectively. Over the same period, estimates of net C sequestration in the Land Use, Land-Use Change, and Forestry sector increased by 139.4 Tg CO_2 Eq. (20 percent).

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

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

Chapter/IPCC Sector	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Energy	5,204.0	5,529.6	6,067.8	5,982.8	6,036.3	6,098.4	6,170.2	6,195.0	6,078.4
Industrial Processes	297.1	308.9	324.9	294.9	303.9	297.7	310.3	311.8	316.3
Solvent and Other Product Use	4.4	4.6	4.9	4.9	4.4	4.4	4.4	4.4	4.4
Agriculture	608.7	617.3	618.4	646.3	617.5	596.2	594.3	620.9	618.9
Land Use, Land-Use Change, and Forestry (Emissions)	16.0	13.0	24.8	16.5	22.1	19.3	17.4	22.8	22.9
Waste	179.6	176.8	155.6	152.1	154.5	160.3	157.7	158.7	161.0

Total Emissions	**6,309.7**	**6,650.1**	**7,196.4**	**7,097.6**	**7,138.7**	**7,176.3**	**7,254.4**	**7,313.7**	**7,201.9**
Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Sinks)*	(736.6)	(774.5)	(672.9)	(749.6)	(826.0)	(860.3)	(873.0)	(877.9)	(882.9)
Net Emissions (Sources and Sinks)	**5,573.1**	**5,875.6**	**6,523.6**	**6,348.0**	**6,312.7**	**6,316.0**	**6,381.4**	**6,435.8**	**6,318.9**

* 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 2006. In 2006, approximately 83 percent of the energy consumed in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 17 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy (see Figure 2-5 and Figure 2-6). A discussion of specific trends related to CO_2 as well as other greenhouse gas emissions from energy consumption is presented in the Energy chapter. Energy-related activities are also responsible for CH_4 and N_2O emissions (37 percent and 9 percent of total U.S. emissions of each gas, respectively). Table 2-4 presents greenhouse gas emissions from the Energy chapter, by source and gas.

Figure 2-5: 2006 Energy Chapter Greenhouse Gas Sources

Figure 2-6: 2006 U.S. Fossil C Flows (Tg CO_2 Eq.)

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

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	**4,886.4**	**5,215.5**	**5,765.7**	**5,686.4**	**5,749.1**	**5,816.5**	**5,898.0**	**5,941.0**	**5,827.1**
Fossil Fuel Combustion	4,724.1	5,032.4	5,577.1	5,507.4	5,564.8	5,636.9	5,700.5	5,751.5	5,639.4
Electricity Generation	1,809.6	1,939.3	2,282.3	2,244.3	2,253.7	2,283.1	2,314.9	2,380.2	2,328.2
Transportation	1,473.5	1,590.2	1,791.9	1,770.3	1,823.8	1,821.4	1,868.5	1,883.1	1,850.1
Industrial	849.9	880.6	863.2	855.0	857.3	858.8	861.0	850.9	866.1
Residential	344.4	359.9	374.3	365.4	362.3	385.0	370.8	360.9	328.7
Commercial	218.5	227.5	229.2	223.3	223.7	237.6	231.9	223.2	211.4
US Territories	28.3	35.0	36.2	49.0	44.0	51.0	53.5	53.2	54.9
Non-Energy Use of Fuels	117.2	133.2	141.4	131.9	135.9	131.8	148.9	139.1	138.0
Natural Gas Systems	33.7	33.8	29.4	28.8	29.6	28.4	28.1	29.5	28.5
Municipal Solid Waste Combustion	10.9	15.7	17.5	18.0	18.5	19.1	20.1	20.7	20.9
Petroleum Systems	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
*Biomass—Wood**	*215.2*	*229.1*	*218.1*	*193.5*	*192.8*	*193.8*	*205.1*	*204.8*	*204.4*
*International Bunker Fuels**	*113.7*	*100.6*	*101.1*	*97.6*	*89.1*	*83.7*	*99.8*	*102.1*	*125.7*
*Biomass—Ethanol**	*4.2*	*7.7*	*9.2*	*9.7*	*11.5*	*15.7*	*19.7*	*22.6*	*30.3*
CH_4	**260.8**	**246.8**	**234.5**	**232.0**	**226.9**	**224.6**	**217.5**	**202.4**	**203.3**
Natural Gas Systems	124.7	128.1	126.5	125.3	124.9	123.3	114.0	102.5	102.4
Coal Mining	84.1	67.1	60.4	60.3	56.8	56.9	59.8	57.1	58.5
Petroleum Systems	33.9	32.0	30.3	30.2	29.9	29.2	28.7	28.3	28.4
Stationary Combustion	7.4	7.2	6.7	6.2	6.2	6.4	6.6	6.5	6.2

Abandoned Underground Coal Mines	6.0	8.2	7.4	6.7	6.2	6.0	5.8	5.6	5.4
Mobile Combustion	4.7	4.3	3.4	3.3	3.0	2.8	2.7	2.5	2.4
*International Bunker Fuels**	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.2*
N_2O	**56.8**	**67.3**	**67.5**	**64.4**	**60.4**	**57.3**	**54.8**	**51.7**	**48.0**
Mobile Combustion	43.5	53.4	52.5	49.9	45.9	42.5	39.8	36.5	33.1
Stationary Combustion	12.8	13.4	14.6	14.1	14.0	14.4	14.6	14.8	14.5
Municipal Solid Waste Combustion	0.5	0.5	0.4	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*	*1.1*
Total	**5,204.0**	**5,529.6**	**6,067.8**	**5,982.8**	**6,036.3**	**6,098.4**	**6,170.2**	**6,195.0**	**6,078.4**

* 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.

CO_2 emissions from fossil fuel combustion are presented in Table 2-5 based on the underlying U.S. energy consumer data collected by EIA. Estimates of CO_2 emissions from fossil fuel combustion are calculated from these EIA "end-use sectors" based on total consumption and appropriate fuel properties (any additional analysis and refinement of the EIA data is further explained in the Energy chapter of this report). EIA's fuel consumption data for the electricity generation sector consists of privately and publicly owned establishments that generate, transmit, distribute, or sell electricity primarily for use by the public and that meet EIA's definition of an electric utility (EIA does not include nonutility power producers in this sector). EIA statistics for the industrial sector include fossil fuel consumption that occurs in the fields of manufacturing, agriculture, mining, and construction. EIA's fuel consumption data for the transportation sector consists of all vehicles whose primary purpose is transporting people and/or goods from one physical location to another. EIA's fuel consumption data for the industrial sector consists of all facilities and equipment used for producing, processing, or assembling goods (EIA includes generators that produce electricity and/or useful thermal output primarily to support on-site industrial activities in this sector). EIA's fuel consumption data for the residential sector consists of living quarters for private households. EIA's fuel consumption data for the commercial sector consists of service-providing facilities and equipment from private and public organizations and businesses (EIA includes generators that produce electricity and/or useful thermal output primarily to support the activities at commercial establishments in this sector). Table 2-5, Figure 2-7, Figure 2-8 summarize CO_2 emissions from fossil fuel combustion by end-use sector.

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

End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005	2006
Transportation	**1,476.5**	**1,593.3**	**1,795.3**	**1,774.0**	**1,827.2**	**1,825.7**	**1,873.0**	**1,887.8**	**1,855.1**
Combustion	1,473.5	1,590.2	1,791.9	1,770.3	1,823.8	1,821.4	1,868.5	1,883.1	1,850.1
Electricity	3.0	3.0	3.4	3.6	3.4	4.2	4.5	4.7	4.9
Industrial	**1,532.5**	**1,593.6**	**1,648.0**	**1,586.4**	**1,574.9**	**1,594.8**	**1,600.0**	**1,583.1**	**1,571.0**
Combustion	849.9	880.6	863.2	855.0	857.3	858.8	861.0	850.9	866.1
Electricity	682.5	713.1	784.7	731.4	717.7	736.1	739.0	732.3	704.9
Residential	**933.7**	**998.8**	**1,131.9**	**1,123.5**	**1,147.4**	**1,180.4**	**1,175.6**	**1,208.8**	**1,154.1**
Combustion	344.4	359.9	374.3	365.4	362.3	385.0	370.8	360.9	328.7
Electricity	589.4	639.0	757.6	758.1	785.1	795.4	804.9	847.9	825.4
Commercial	**753.1**	**811.7**	**965.8**	**974.5**	**971.2**	**984.9**	**998.4**	**1,018.6**	**1,004.3**
Combustion	218.5	227.5	229.2	223.3	223.7	237.6	231.9	223.2	211.4
Electricity	534.7	584.2	736.6	751.1	747.5	747.3	766.5	795.4	792.9
U.S. Territories	**28.3**	**35.0**	**36.2**	**49.0**	**44.0**	**51.0**	**53.5**	**53.2**	**54.9**
Total	**4,724.1**	**5,032.4**	**5,577.1**	**5,507.4**	**5,564.8**	**5,636.9**	**5,700.5**	**5,751.5**	**5,639.4**
Electricity Generation	**1,809.6**	**1,939.3**	**2,282.3**	**2,244.3**	**2,253.7**	**2,283.1**	**2,314.9**	**2,380.2**	**2,328.2**

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 2-7: 2006 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Figure 2-8: 2006 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

The main driver of emissions in the energy sector is CO_2 from fossil fuel combustion. The transportation end-use sector accounted for 1,855.1 Tg CO_2 Eq. in 2006, or approximately 33 percent of total CO_2 emissions from fossil fuel combustion, the largest share of any end-use economic sector.[3] The industrial end-use sector accounted for 28 percent of CO_2 emissions from fossil fuel combustion. The residential and commercial end-use sectors accounted for an average 20 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 72 and 79 percent of emissions from the residential and commercial end-use sectors, respectively. Significant trends in emissions from energy source categories over the sixteen-year period from 1990 through 2006 included the following:

- Total CO_2 emissions from fossil fuel combustion increased from 4,724.1 Tg CO_2 Eq. to 5,639.4 Tg CO_2 Eq.—a 19.4 percent total increase over the sixteen-year period. From 2005 to 2006, these emissions decreased by 112.1 Tg CO_2 Eq. (1.9 percent).
- CO_2 emissions from non-energy use of fossil fuels have increased 20.8 Tg CO_2 Eq. (18 percent) from 1990 through 2006. Emissions from non-energy uses of fossil fuels were 138.0 Tg CO_2 Eq. in 2006, which constituted 2.4 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.
- CH_4 emissions from natural gas systems were 102.4 Tg CO_2 Eq. in 2006; emissions have declined by 22.3 Tg CO_2 Eq. (18 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 coal mining were 58.5 Tg CO_2 Eq. This decline of 25.6 Tg CO_2 Eq. (30 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.
- In 2006, N_2O emissions from mobile combustion were 33.1 Tg CO_2 Eq. (approximately 6 percent of U.S. N_2O emissions). From 1990 to 2006, N_2O emissions from mobile combustion decreased by 24 percent. However, from 1990 to 1998 emissions increased by 26 percent, due to control technologies that reduced NO_x emissions while increasing N_2O emissions. Since 1998, newer control technologies have led to a steady decline in N_2O from this source.
- CO_2 emissions from municipal solid waste combustion (20.9 Tg CO_2 Eq. in 2006) increased by 10.0 Tg CO_2 Eq. (91 percent) from 1990 through 2006, as the volume of plastics and other fossil carbon-containing materials in municipal solid waste grew.

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 consumption, 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

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

production, CO_2 consumption, silicon carbide production and consumption, aluminum production, petrochemical production, nitric acid production, adipic acid production, lead production, and zinc production (see Figure 2-9). Additionally, emissions from industrial processes release HFCs, PFCs and SF_6. Table 2-6 presents greenhouse gas emissions from industrial processes by source category.

Figure 2-9: 2006 Industrial Processes Chapter Greenhouse Gas Sources

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

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	**173.7**	**170.2**	**165.0**	**150.6**	**149.6**	**146.3**	**150.4**	**144.5**	**148.0**
Iron and Steel Production	84.9	73.3	65.1	57.9	54.6	53.4	51.3	45.2	47.7
Cement Manufacture	33.3	36.8	41.2	41.4	42.9	43.1	45.6	45.9	45.7
Lime Manufacture	12.0	14.0	14.9	14.3	13.7	14.5	15.2	15.1	15.8
Ammonia Manufacture & Urea Consumption	16.9	17.8	16.4	13.3	14.2	12.5	13.2	12.8	12.4
Limestone and Dolomite Use	5.5	7.4	6.0	5.7	5.9	4.7	6.7	7.4	8.6
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.1	4.1	4.1	4.2	4.2	4.2
Aluminum Production	6.8	5.7	6.1	4.4	4.5	4.5	4.2	4.2	3.9
Petrochemical Production	2.2	2.8	3.0	2.8	2.9	2.8	2.9	2.8	2.6
Titanium Dioxide Production	1.2	1.5	1.8	1.7	1.8	1.8	2.1	1.8	1.9
Carbon Dioxide Consumption	1.4	1.4	1.4	0.8	1.0	1.3	1.2	1.3	1.6
Ferroalloy Production	2.2	2.0	1.9	1.5	1.3	1.3	1.4	1.4	1.5
Phosphoric Acid Production	1.5	1.5	1.4	1.3	1.3	1.4	1.4	1.4	1.2
Zinc Production	0.9	1.0	1.1	1.0	0.9	0.5	0.5	0.5	0.5
Lead Production	0.3	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	0.2
CH_4	**2.2**	**2.4**	**2.5**	**2.2**	**2.1**	**2.1**	**2.2**	**2.0**	**2.0**
Petrochemical Production	0.9	1.1	1.2	1.1	1.1	1.1	1.2	1.1	1.0
Iron and Steel Production	1.3	1.3	1.2	1.1	1.0	1.0	1.0	1.0	0.9
Ferroalloy Production	+	+	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+	+	+
N_2O	**32.3**	**36.2**	**24.8**	**20.2**	**22.4**	**21.7**	**21.2**	**21.7**	**21.6**
Nitric Acid Production	17.0	18.9	18.6	15.1	16.4	15.4	15.2	15.8	15.6
Adipic Acid Production	15.3	17.3	6.2	5.1	6.1	6.3	5.9	5.9	5.9
HFCs	**35.5**	**56.4**	**100.0**	**96.3**	**103.0**	**102.3**	**112.4**	**119.1**	**121.3**
Substitution of Ozone Depleting Substances[a]	0.3	29.1	70.0	76.3	83.0	89.8	96.6	102.3	107.3
HCFC-22 Production	35.0	27.0	29.8	19.8	19.8	12.3	15.6	16.5	13.8
Semiconductor Manufacture	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.3
PFCs	**20.8**	**15.6**	**13.5**	**7.0**	**8.7**	**7.1**	**6.1**	**6.2**	**6.1**
Semiconductor Manufacture	2.2	3.8	4.9	3.5	3.5	3.3	3.3	3.2	3.6
Aluminum Production	18.5	11.8	8.6	3.5	5.2	3.8	2.8	3.0	2.5
SF_6	**32.7**	**28.0**	**19.2**	**18.7**	**18.0**	**18.1**	**18.0**	**18.3**	**17.4**
Electrical Transmission and Distribution	26.7	21.5	15.1	15.0	14.4	13.9	14.0	14.0	13.2
Magnesium Production and Processing	5.4	5.6	3.0	2.9	2.9	3.4	3.2	3.3	3.2
Semiconductor Manufacture	0.5	0.9	1.1	0.7	0.7	0.8	0.8	1.0	1.0

Total	**297.1**	**308.9**	**324.9**	**294.9**	**303.9**	**297.7**	**310.3**	**311.8**	**316.3**

+ Does not exceed 0.05 Tg CO_2 Eq.
[a] Small amounts of PFC emissions also result from this source.
Note: Totals may not sum due to independent rounding.

Overall, emissions from industrial processes increased by 6.5 percent from 1990 to 2006 despite decreases in emissions from several industrial processes, such as iron and steel, aluminum production, 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. Significant trends in emissions from industrial processes source categories over the sixteen-year period from 1990 through 2006 included the following:

- HFC and PFC emissions from ODS substitutes have been increasing from small amounts in 1990 to 107.3 Tg CO_2 Eq. in 2006. This increase results from efforts to phase out CFCs and other ODSs in the United States. In the short term, this trend is expected to continue, and will likely accelerate over the next decade as HCFCs—which are interim substitutes in many applications—are phased out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*.

- CO_2 and CH_4 emissions from iron and steel production increased by 5.3 percent to 48.6 Tg CO_2 Eq. in 2006, but have declined overall by 37.6 Tg CO_2 Eq. (43.6 percent) from 1990 through 2006, due to restructuring of the industry, technological improvements, and increased scrap utilization.

- PFC emissions from aluminum production decreased by 87 percent (16.1 Tg CO_2 Eq.) from 1990 to 2006, due to both industry emission reduction efforts and lower domestic aluminum production.

- N_2O emissions from adipic acid production were 5.9 Tg CO_2 Eq. in 2006, and have decreased significantly in recent years from the widespread installation of pollution control measures. Emissions from adipic acid production have decreased 61 percent since 1990, and emissions from adipic acid production have fluctuated by less than 1 Tg CO_2 Eq. annually since 1998.

- CO_2 emissions from ammonia manufacture and urea consumption (12.4 Tg CO_2 Eq. in 2006) have decreased by 4.5 Tg CO_2 Eq. (27 percent) since 1990, due to a decrease in domestic ammonia manufacture. This decrease in ammonia manufacture can be attributed to market fluctuations and high natural gas prices.

Solvent and Other Product Use

Greenhouse gas emissions are produced as a by-product of various solvent and other product uses. In the United States, N_2O Emissions from Product Uses, the only source of greenhouse gas emissions from this sector, accounted for 4.4 Tg CO_2 Eq., or less than 0.1 percent of total U.S. emissions in 2006 (see Table 2-7).

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

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
N_2O	**4.4**	**4.6**	**4.9**	**4.9**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**
N_2O from Product Uses	4.4	4.6	4.9	4.9	4.4	4.4	4.4	4.4	4.4
Total	**4.4**	**4.6**	**4.9**	**4.9**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**

- In 2006, N_2O emissions from product uses constituted less than 1 percent of U.S. N_2O emissions. From 1990 to 2006, emissions from this source category decreased by less than 1 percent, though slight increases occurred in intermediate years.

Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes, including the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues.

In 2006, agricultural activities were responsible for emissions of 618.9 Tg CO_2 Eq., or 8.6 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 23 percent and 8 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2006. 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 81 percent.

Figure 2-10: 2006 Agriculture Chapter Greenhouse Gas Sources

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

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH_4	**165.7**	**175.8**	**171.7**	**172.2**	**172.6**	**173.0**	**170.9**	**174.0**	**174.4**
Enteric Fermentation	126.9	132.3	124.6	123.6	123.8	124.6	122.4	124.5	126.2
Manure Management	31.0	35.2	38.8	40.2	41.3	40.7	40.1	41.8	41.4
Rice Cultivation	7.1	7.6	7.5	7.6	6.8	6.9	7.6	6.8	5.9
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.8	0.7	0.8	0.9	0.9	0.8
N_2O	**443.0**	**441.5**	**446.8**	**474.1**	**444.9**	**423.2**	**423.4**	**447.0**	**444.5**
Agricultural Soil Management	430.6	428.3	432.6	459.6	430.5	409.2	409.1	432.5	429.7
Manure Management	12.1	12.8	13.7	14.0	14.0	13.6	13.8	13.9	14.3
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.4	0.4	0.5	0.5	0.5
Total	**608.7**	**617.3**	**618.4**	**646.3**	**617.5**	**596.2**	**594.3**	**620.9**	**618.9**

Note: Totals may not sum due to independent rounding.

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

- Agricultural soils produced approximately 81 percent of N_2O emissions in the United States in 2006. Estimated emissions from this source in 2006 were 429.7 Tg CO_2 Eq. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2006, although overall emissions were 0.2 percent lower in 2006 than in 1990.

- Enteric fermentation was the largest source of CH4 emissions in 2006, at 126.2 Tg CO_2 Eq. Although emissions from enteric fermentation have decreased by less than 1 percent between 1990 and 2006, emissions increased about 4 percent between 1990 and 1994 and decreased 1995 to 2004, mainly due to decreasing populations of both beef and dairy cattle and improved feed quality for feedlot cattle. The last two years have shown an increase in emissions. During this timeframe, populations of sheep have decreased 45 percent since 1990 while horse populations have increased over 80 percent, mostly over the last 5 years. Goat and swine populations have increased 1 percent and 14 percent, respectively, during this timeframe.

- Overall, emissions from manure management increased 29 percent between 1990 and 2006. This encompassed an increase of 34 percent for CH_4, from 31.0 Tg CO_2 Eq. in 1990 to 41.4 Tg CO_2 Eq. in 2006; and an increase of 18 percent for N_2O, from 12.1 Tg CO_2 Eq. in 1990 to 14.3 Tg CO_2 Eq. in 2006. The majority of this increase was from swine and dairy cow manure, since the general trend in manure management is one of increasing use of liquid systems, which tends to produce greater CH_4 emissions.

Land Use, Land-Use Change, and Forestry

When humans alter the terrestrial biosphere through land use, changes in land use, and land management practices,

they also alter the background carbon fluxes between biomass, soils, and the atmosphere. Forest management practices, tree planting in urban areas, the management of agricultural soils, and the landfilling of yard trimmings and food scraps have resulted in an uptake (sequestration) of carbon in the United States, which offset about 12 percent of total U.S. greenhouse gas emissions in 2006. Forests (including vegetation, soils, and harvested wood) accounted for approximately 84 percent of total 2006 net CO_2 flux, urban trees accounted for 11 percent, mineral and organic soil carbon stock changes accounted for 4 percent, and landfilled yard trimmings and food scraps accounted for 1 percent of the total net flux in 2006. The net forest sequestration is a result of net forest growth, increasing forest area, and a net accumulation of carbon stocks in harvested wood pools. The net sequestration in urban forests is a result of net tree growth and increased urban forest size. In agricultural soils, mineral and organic soils sequester approximately 70 percent more C than is emitted through these soils, liming, and urea fertilization, combined. The mineral soil C sequestration is largely due to the conversion of cropland to hay production fields, the limited use of bare-summer fallow areas in semi-arid areas, and an increase in the adoption of conservation tillage practices. The landfilled yard trimmings and food scraps net sequestration is due to the long-term accumulation of yard trimming carbon and food scraps in landfills.

Land use, land-use change, and forestry activities in 2006 resulted in a net C sequestration of 882.9 Tg CO_2 Eq. (Table 2-9). This represents an offset of approximately 14.8 percent of total U.S. CO_2 emissions, or 12.3 percent of total greenhouse gas emissions in 2006. Between 1990 and 2006, total land use, land-use change, and forestry net C sequestration increased by approximately 20 percent. Net U.S. emissions (all sources and sinks) increased by 13.4 percent from 1990 to 2006.

Table 2-9: 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	2006
Forest Land Remaining Forest Land	**(621.7)**	**(659.9)**	**(550.7)**	**(623.4)**	**(697.3)**	**(730.9)**	**(741.4)**	**(743.6)**	**(745.1)**
Changes in Forest Carbon Stocks	(621.7)	(659.9)	(550.7)	(623.4)	(697.3)	(730.9)	(741.4)	(743.6)	(745.1)
Cropland Remaining Cropland	**(30.1)**	**(39.4)**	**(38.4)**	**(40.0)**	**(40.3)**	**(40.5)**	**(40.9)**	**(41.0)**	**(41.8)**
Mineral and Organic Soil Carbon Stock Changes	(30.1)	(39.4)	(38.4)	(40.0)	(40.3)	(40.5)	(40.9)	(41.0)	(41.8)
Land Converted to Cropland	**14.7**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**
Mineral and Organic Soil Carbon Stock Changes	14.7	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4
Grassland Remaining Grassland	**(1.9)**	**16.6**	**16.4**	**16.4**	**16.4**	**16.4**	**16.3**	**16.3**	**16.2**
Mineral and Organic Soil Carbon Stock Changes	(1.9)	16.6	16.4	16.4	16.4	16.4	16.3	16.3	16.2
Land Converted to Grassland	**(14.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**
Mineral and Organic Soil Carbon Stock Changes	(14.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)
Settlements Remaining Settlements	**(60.6)**	**(71.5)**	**(82.4)**	**(84.6)**	**(86.8)**	**(88.9)**	**(91.1)**	**(93.3)**	**(95.5)**
Urban Trees	(60.6)	(71.5)	(82.4)	(84.6)	(86.8)	(88.9)	(91.1)	(93.3)	(95.5)
Other	**(22.8)**	**(13.3)**	**(10.8)**	**(10.9)**	**(11.0)**	**(9.4)**	**(8.9)**	**(9.3)**	**(9.8)**
Landfilled Yard Trimmings and Food Scraps	(22.8)	(13.3)	(10.8)	(10.9)	(11.0)	(9.4)	(8.9)	(9.3)	(9.8)

Total	**(736.6)**	**(774.5)**	**(672.9)**	**(749.6)**	**(826.0)**	**(860.3)**	**(873.0)**	**(877.9)**	**(882.9)**

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

Land use, land-use change, and forestry source categories also resulted in emissions of CO_2, CH_4, and N_2O that are not included in the net CO_2 flux estimates presented in Table 2-9. The application of crushed limestone and dolomite to managed land (i.e., soil liming) and urea fertilization resulted in CO_2 emissions of 8.0 Tg CO_2 Eq. in 2006, and increase of 13 percent relative to 1990. The application of synthetic fertilizers to forest and settlement soils in 2006 resulted in direct N_2O emissions of 2.2 Tg CO_2 Eq. Direct N_2O emissions from fertilizer application increased by approximately 97 percent between 1990 and 2006. 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 2006 (Table 2-10).

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

Source Category	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	**7.1**	**7.0**	**7.5**	**7.8**	**8.5**	**8.3**	**7.6**	**7.9**	**8.0**
Cropland Remaining Cropland:									
Liming of Agricultural Soils & Urea Fertilization	7.1	7.0	7.5	7.8	8.5	8.3	7.6	7.9	8.0
CH_4	**7.1**	**4.0**	**14.0**	**6.0**	**10.4**	**8.1**	**6.9**	**11.6**	**11.6**
Forest Land Remaining Forest Land:									
Forest Fires	7.1	4.0	14.0	6.0	10.4	8.1	6.9	11.6	11.6
N_2O	**1.8**	**1.9**	**3.3**	**2.7**	**3.2**	**3.0**	**3.0**	**3.3**	**3.3**
Forest Land Remaining Forest Land:									
Forest Fires	0.7	0.4	1.4	0.6	1.1	0.8	0.7	1.2	1.2
Forest Land Remaining Forest Land:									
Forest Soils	0.1	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Settlements Remaining Settlements:									
Settlement Soils	1.0	1.4	1.5	1.8	1.8	1.9	1.9	1.8	1.8
Total	**16.0**	**13.0**	**24.8**	**16.5**	**22.1**	**19.3**	**17.4**	**22.8**	**22.9**

Note: Totals may not sum due to independent rounding.

Other significant trends from 1990 to 2006 in land use, land-use change, and forestry emissions include:

- Net C sequestration by forest land has increased 20 percent. This is primarily due to increased forest management and the effects of previous reforestation. The increase in intensive forest management resulted in higher growth rates and higher biomass density. The tree planting and conservation efforts of the 1970s and 1980s continue to have a significant impact on sequestration rates. Finally, the forested area in the United States increased over the past 16 years, although only at an average rate of 0.1 percent per year.

- Net sequestration of C by urban trees has increased by 57 percent over this sixteen-year period. This is primarily due to an increase in urbanized land area in the United States.

- Annual C sequestration in landfilled yard trimmings and food scraps has decreased by 57 percent. This is due in part to a decrease in the amount of yard trimmings and food scraps generated. In addition, the proportion of yard trimmings and food scraps landfilled has decreased, as there has been a significant rise in the number of municipal composting facilities in the United States.

Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 2-11). In 2006, landfills were the second largest source of anthropogenic CH_4 emissions, accounting for 23 percent of total U.S.

CH_4 emissions.[4] Additionally, wastewater treatment accounts for 4 percent of U.S. CH_4 emissions, and 2 percent of N_2O emissions. Emissions of CH_4 and N_2O from composting grew from 1990 to 2006, and resulted in emissions of 3.3 Tg CO_2 Eq. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 2-11.

Figure 2-11: 2006 Waste Chapter Greenhouse Gas Sources

Overall, in 2006, waste activities generated emissions of 161.2 Tg CO_2 Eq., or 2.2 percent of total U.S. greenhouse gas emissions.

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

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH_4	**172.9**	**169.1**	**146.7**	**143.0**	**145.5**	**151.0**	**148.1**	**149.0**	**151.1**
Landfills	149.6	144.0	120.8	117.6	120.1	125.6	122.6	123.7	125.7
Wastewater Treatment	23.0	24.3	24.6	24.2	24.1	23.9	24.0	23.8	23.9
Composting	0.3	0.7	1.3	1.3	1.3	1.5	1.6	1.6	1.6
N_2O	**6.6**	**7.7**	**8.9**	**9.2**	**9.0**	**9.3**	**9.6**	**9.7**	**9.9**
Wastewater Treatment	6.3	6.9	7.6	7.8	7.6	7.7	7.8	8.0	8.1
Composting	0.4	0.8	1.4	1.4	1.4	1.6	1.7	1.7	1.8
Total	**179.6**	**176.8**	**155.6**	**152.1**	**154.5**	**160.3**	**157.7**	**158.7**	**161.0**

Note: Totals may not sum due to independent rounding.

Some significant trends in U.S. emissions from Waste include the following:

- From 1990 to 2006, net CH_4 emissions from landfills decreased by 23.9 Tg CO_2 Eq. (16 percent), with small increases occurring in interim years. This downward trend in overall emissions is the result of increases in the amount of landfill gas collected and combusted,[5] which has more than offset the additional CH_4 emissions resulting from an increase in the amount of municipal solid waste landfilled.

- From 1990 to 2006, CH_4 and N_2O emissions from wastewater treatment increased by 0.8 Tg CO_2 Eq. (4 percent) and 1.8 Tg CO_2 Eq. (29 percent), respectively.

- CH_4 and N_2O emissions from composting increased by less than 0.1 Tg CO_2 Eq. (1 percent), respectively, from 2005 to 2006. Emissions from composting have been continually increasing since 1990, from 0.7 Tg CO_2 Eq. to 3.3 Tg CO_2 Eq. in 2006, a four-fold increase over the time series.

2.2. Emissions by Economic Sector

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

[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.

[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.

electricity generation, and agriculture, as well as U.S. territories.

Using this categorization, emissions from electricity generation accounted for the largest portion (33 percent) of U.S. greenhouse gas emissions in 2006. Transportation activities, in aggregate, accounted for the second largest portion (27 percent). Emissions from industry accounted for about 19 percent of U.S. greenhouse gas emissions in 2006. In contrast to electricity generation and transportation, emissions from industry have in general declined over the past decade. The long-term decline in these emissions has been due to structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and efficiency improvements. The remaining 21 percent of U.S. greenhouse gas emissions were contributed by the residential, agriculture, and commercial sectors, plus emissions from U.S. territories. The residential sector accounted for 5 percent, and primarily consisted of CO_2 emissions from fossil fuel combustion. Activities related to agriculture accounted for roughly 10 percent of U.S. emissions; unlike other economic sectors, agricultural sector emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation, rather than CO_2 from fossil fuel combustion. The commercial sector accounted for roughly 5 percent of emissions, while U.S. territories accounted for about 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 2-12 presents a detailed breakdown of emissions from each of these economic sectors by source category, as they are defined in this report. Figure 2-12 shows the trend in emissions by sector from 1990 to 2006.

Figure 2-12: Emissions Allocated to Economic Sectors

Table 2-12: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg CO_2 Eq. and Percent of Total in 2006)

Sector/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006	Percent[a]
Electricity Generation	**1,859.1**	**1,989.7**	**2,328.9**	**2,290.9**	**2,300.4**	**2,329.4**	**2,363.5**	**2,430.0**	**2,377.8**	**33.0%**
CO_2 from Fossil Fuel Combustion	1,809.6	1,939.3	2,282.3	2,244.3	2,253.7	2,283.1	2,314.9	2,380.2	2,328.2	32.3%
Stationary Combustion	8.6	9.1	10.6	10.4	10.4	10.7	10.8	11.0	10.8	0.1%
Electrical Transmission and Distribution	26.7	21.5	15.1	15.0	14.4	13.9	14.0	14.0	13.2	0.2%
Municipal Solid Waste Combustion	11.4	16.2	17.9	18.4	18.9	19.5	20.5	21.1	21.3	0.3%
Limestone and Dolomite Use	2.8	3.7	3.0	2.9	2.9	2.4	3.4	3.7	4.3	0.1%
Transportation	**1,532.5**	**1,677.2**	**1,910.0**	**1,888.8**	**1,941.4**	**1,937.7**	**1,985.1**	**1,997.6**	**1,960.4**	**27.2%**
CO_2 from Fossil Fuel Combustion	1,473.5	1,590.2	1,791.9	1,770.3	1,823.8	1,821.4	1,868.5	1,883.1	1,850.1	25.7%
Mobile Combustion	47.2	56.5	54.7	51.9	47.5	44.0	41.1	37.6	34.0	0.5%
Substitution of Ozone Depleting Substances	+	19.2	51.3	55.5	59.1	62.2	65.3	66.7	66.3	0.9%
Non-Energy Use of Fuels	11.9	11.3	12.1	11.1	10.9	10.1	10.2	10.2	9.9	0.1%
Industry	**1,462.6**	**1,474.8**	**1,435.5**	**1,385.6**	**1,384.7**	**1,376.8**	**1,389.1**	**1,357.2**	**1,372.0**	**19.1%**
CO_2 from Fossil Fuel Combustion	803.2	823.3	812.4	804.3	804.4	813.7	809.9	805.4	820.6	11.4%
Non-Energy Use of Fuels	99.6	115.9	118.4	115.5	115.8	113.2	131.4	121.8	120.8	1.7%

Stationary Combustion	4.7	5.0	4.9	4.6	4.4	4.4	4.6	4.5	4.6	0.1%
Mobile Combustion	0.6	0.7	0.8	0.9	0.9	0.9	1.0	1.0	1.0	0.0%
Coal Mining	84.1	67.1	60.4	60.3	56.8	56.9	59.8	57.1	58.5	0.8%
Abandoned Underground Coal Mines	6.0	8.2	7.4	6.7	6.2	6.0	5.8	5.6	5.4	0.1%
Natural Gas Systems	158.4	161.9	155.9	154.1	154.5	151.8	142.1	132.0	130.9	1.8%
Petroleum Systems	34.2	32.3	30.6	30.5	30.2	29.5	29.0	28.6	28.7	0.4%
Titanium Dioxide Production	1.2	1.5	1.8	1.7	1.8	1.8	2.1	1.8	1.9	0.0%
Aluminum Production	25.4	17.5	14.7	7.8	9.7	8.3	7.1	7.2	6.4	0.1%
Iron and Steel Production	86.2	74.6	66.3	59.0	55.6	54.4	52.4	46.2	48.6	0.7%
Ferroalloy Production	2.2	2.0	1.9	1.5	1.4	1.3	1.4	1.4	1.5	0.0%
Ammonia Manufacture and Urea Consumption	16.9	17.8	16.4	13.3	14.2	12.5	13.2	12.8	12.4	0.2%
Cement Manufacture	33.3	36.8	41.2	41.4	42.9	43.1	45.6	45.9	45.7	0.6%
Lime Manufacture	12.0	14.0	14.9	14.3	13.7	14.5	15.2	15.1	15.8	0.2%
Limestone and Dolomite Use	2.8	3.7	3.0	2.9	2.9	2.4	3.4	3.7	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	4.2	0.1%
Carbon Dioxide Consumption	1.4	1.4	1.4	0.8	1.0	1.3	1.2	1.3	1.6	0.0%
Silicon Carbide Production and Consumption	0.4	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.0%
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.0%
Zinc Production	0.9	1.0	1.1	1.0	0.9	0.5	0.5	0.5	0.5	0.0%
Petrochemical Production	3.1	3.8	4.2	3.9	4.0	3.9	4.1	3.9	3.6	0.0%
Phosphoric Acid Production	1.5	1.5	1.4	1.3	1.3	1.4	1.4	1.4	1.2	0.0%
Adipic Acid Production	15.3	17.3	6.2	5.1	6.1	6.3	5.9	5.9	5.9	0.1%
Nitric Acid Production	17.0	18.9	18.6	15.1	16.4	15.4	15.2	15.8	15.6	0.2%
N_2O Product Uses	4.4	4.6	4.9	4.9	4.4	4.4	4.4	4.4	4.4	0.1%
HCFC-22 Production	35.0	27.0	29.8	19.8	19.8	12.3	15.6	16.5	13.8	0.2%
Semiconductor Manufacture	2.9	5.0	6.3	4.5	4.3	4.3	4.3	4.4	4.8	0.1%
Magnesium Production and Processing	5.4	5.6	3.0	2.9	2.9	3.4	3.2	3.3	3.2	0.0%
Substitution of Ozone Depleting Substances	+	1.2	3.1	3.1	3.7	4.4	4.8	5.2	5.7	0.1%
Agriculture	**670.8**	**686.7**	**693.0**	**712.2**	**691.2**	**659.1**	**661.5**	**687.9**	**686.1**	**9.5%**
CO_2 from Fossil Fuel Combustion	46.8	57.3	50.9	50.7	52.9	45.0	51.1	45.5	45.5	0.6%
Stationary Combustion	+	+	+	+	+	+	+	0.1	0.1	0.0%
Mobile Combustion	0.4	0.5	0.4	0.4	0.5	0.4	0.4	0.4	0.4	0.0%
Enteric Fermentation	126.9	132.3	124.6	123.6	123.8	124.6	122.4	124.5	126.2	1.8%
Manure Management	43.0	48.0	52.5	54.2	55.2	54.3	53.9	55.7	55.7	0.8%
Rice Cultivation	7.1	7.6	7.5	7.6	6.8	6.9	7.6	6.8	5.9	0.1%
Field Burning of Agricultural Residues	1.1	1.0	1.3	1.2	1.1	1.2	1.4	1.4	1.3	0.0%

N_2O from Agricultural Soil Management	430.6	428.3	432.6	459.6	430.5	409.2	409.1	432.5	429.7	6.0%
Liming of Agricultural Soils	4.7	4.4	4.3	4.4	5.0	4.6	3.9	4.3	4.4	0.1%
Urea Fertilization	2.4	2.7	3.2	3.4	3.6	3.7	3.7	3.5	3.6	0.1%
CH_4 and N_2O from Forest Fires	7.8	4.4	15.4	6.6	11.4	8.9	7.6	12.8	12.8	0.2%
N_2O from Forest Soils	0.1	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.0%
Commercial	**399.3**	**406.2**	**391.5**	**384.0**	**389.1**	**411.3**	**405.9**	**401.7**	**395.9**	**5.5%**
CO_2 from Fossil Fuel Combustion	218.5	227.5	229.2	223.3	223.7	237.6	231.9	223.2	211.4	2.9%
Stationary Combustion	1.2	1.3	1.3	1.2	1.2	1.3	1.3	1.2	1.2	0.0%
Substitution of Ozone Depleting Substances	+	0.7	5.5	7.4	9.6	12.1	15.0	18.5	22.4	0.3%
Landfills	149.6	144.0	120.8	117.6	120.1	125.6	122.6	123.7	125.7	1.7%
Human Sewage	6.3	6.9	7.6	7.8	7.6	7.7	7.8	8.0	8.1	0.1%
Wastewater Treatment	23.0	24.3	24.6	24.2	24.1	23.9	24.0	23.8	23.9	0.3%
Composting	0.7	1.5	2.6	2.7	2.7	3.1	3.3	3.3	3.3	0.0%
Residential	**351.2**	**374.4**	**390.2**	**381.5**	**378.7**	**402.1**	**388.4**	**378.8**	**347.4**	**4.8%**
CO_2 from Fossil Fuel Combustion	344.4	359.9	374.3	365.4	362.3	385.0	370.8	360.9	328.7	4.6%
Substitution of Ozone Depleting Substances	5.5	5.0	4.3	4.0	4.0	4.2	4.3	4.2	3.9	0.1%
Settlement Soil Fertilization	0.3	8.1	10.1	10.3	10.7	11.0	11.4	11.9	12.9	0.2%
Stationary Combustion	1.0	1.4	1.5	1.8	1.8	1.9	1.9	1.8	1.8	0.0%
U.S. Territories	**34.1**	**41.1**	**47.3**	**54.5**	**53.3**	**59.7**	**61.0**	**60.5**	**62.4**	**0.9%**
CO_2 from Fossil Fuel Combustion	34.1	41.1	47.3	54.5	53.3	59.7	61.0	60.5	62.4	0.9%
Total Emissions	**6,309.7**	**6,650.1**	**7,196.4**	**7,097.6**	**7,138.7**	**7,176.3**	**7,254.4**	**7,313.7**	**7,201.9**	**100.0%**
Sinks	**(736.6)**	**(774.5)**	**(672.9)**	**(749.6)**	**(826.0)**	**(860.3)**	**(873.0)**	**(877.9)**	**(882.9)**	**-12.3%**
CO_2 Flux from Forests	(621.7)	(659.9)	(550.7)	(623.4)	(697.3)	(730.9)	(741.4)	(743.6)	(745.1)	-10.3%
Urban Trees	(60.6)	(71.5)	(82.4)	(84.6)	(86.8)	(88.9)	(91.1)	(93.3)	(95.5)	-1.3%
CO_2 Flux from Agricultural Soil Carbon Stocks	(31.5)	(29.7)	(29.0)	(30.6)	(30.9)	(31.1)	(31.5)	(31.7)	(32.6)	-0.5%
Landfilled Yard Trimmings and Food Scraps	(22.8)	(13.3)	(10.8)	(10.9)	(11.0)	(9.4)	(8.9)	(9.3)	(9.8)	-0.1%
Net Emissions (Sources and Sinks)	**5,573.1**	**5,875.6**	**6,523.6**	**6,348.0**	**6,312.7**	**6,316.0**	**6,381.4**	**6,435.8**	**6,318.9**	**87.7%**

Note: Includes all emissions of CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6. Parentheses indicate negative values or sequestration. Totals may not sum due to independent rounding.
ODS (Ozone Depleting Substances)
+ Does not exceed 0.05 Tg CO_2 Eq. or 0.05%.
[a] Percent of total emissions for year 2005.

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 33 percent of total U.S. greenhouse gas emissions in 2006. Emissions increased by 28 percent since 1990, as electricity demand grew and fossil fuels remained the dominant energy source for generation. Electricity generation-related emissions decreased from 2005

to 2006 by 2 percent, primarily due to reduced CO_2 emissions from fossil fuel combustion. The electricity generation sector in the United States is composed of traditional electric utilities as well as other entities, such as power marketers and non-utility power producers. The majority of electricity generated by these entities was through the combustion of coal in boilers to produce high-pressure steam that is passed through a turbine. Table 2-13 provides a detailed summary of emissions from electricity generation-related activities.

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

Gas/Fuel Type or Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	**1,823.3**	**1,958.6**	**2,302.8**	**2,265.1**	**2,275.1**	**2,304.5**	**2,338.4**	**2,404.6**	**2,353.4**
CO_2 from Fossil Fuel Combustion	1,809.6	1,939.3	2,282.3	2,244.3	2,253.7	2,283.1	2,314.9	2,380.2	2,328.2
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	1,932.4
Natural Gas	176.2	229.5	280.9	289.6	306.0	278.3	296.8	319.1	339.6
Petroleum	101.8	60.7	91.5	102.0	79.1	98.1	100.1	102.3	55.7
Geothermal	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Municipal Solid Waste Combustion	10.9	15.7	17.5	18.0	18.5	19.1	20.1	20.7	20.9
Limestone and Dolomite Use	2.8	3.7	3.0	2.9	2.9	2.4	3.4	3.7	4.3
CH_4	**0.6**	**0.6**	**0.7**	**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	0.7
N_2O	**8.5**	**9.0**	**10.4**	**10.1**	**10.1**	**10.4**	**10.5**	**10.7**	**10.5**
Stationary Combustion*	8.1	8.6	10.0	9.7	9.7	10.0	10.0	10.3	10.1
Municipal Solid Waste Combustion	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
SF_6	**26.7**	**21.5**	**15.1**	**15.0**	**14.4**	**13.9**	**14.0**	**14.0**	**13.2**
Electrical Transmission and Distribution	26.7	21.5	15.1	15.0	14.4	13.9	14.0	14.0	13.2
Total	**1,859.1**	**1,989.7**	**2,328.9**	**2,290.9**	**2,300.4**	**2,329.4**	**2,363.5**	**2,430.0**	**2,377.8**

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

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 account for 27 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 2-14 presents a detailed breakdown of emissions from each of these economic sectors, with emissions from electricity generation distributed to them. Figure 2-13 shows the trend in these emissions by sector from 1990 to 2006.

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

[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 2-14: U.S Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (Tg CO_2 Eq.) and Percent of Total in 2005

Sector/Gas	1990	1995	2000	2001	2002	2003	2004	2005	2006	Percent[a]
Industry	**2,102.6**	**2,137.9**	**2,176.9**	**2,062.4**	**2,051.4**	**2,065.8**	**2,075.6**	**2,041.1**	**2,029.8**	**27.8%**
Direct Emissions	1,462.6	1,474.8	1,435.5	1,385.6	1,384.7	1,376.8	1,389.1	1,357.2	1,372.0	18.8%
CO_2	1,073.7	1,105.8	1,092.8	1,067.6	1,066.9	1,071.0	1,088.3	1,068.0	1,085.1	14.8%
CH_4	286.5	273.6	258.3	255.4	251.3	247.8	240.5	226.7	227.0	3.1%
N_2O	40.4	44.8	33.7	28.9	30.6	29.9	29.5	30.0	29.9	0.4%
HFCs, PFCs, and SF_6	61.9	50.6	50.7	33.7	36.0	28.3	30.8	32.4	29.9	0.4%
Electricity-Related	640.1	663.1	741.4	676.8	666.7	689.0	686.5	683.9	657.8	9.0%
CO_2	627.7	652.8	733.1	669.2	659.4	681.6	679.2	676.8	651.0	8.9%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.0%
N_2O	2.9	3.0	3.3	3.0	2.9	3.1	3.0	3.0	2.9	0.0%
SF_6	9.2	7.1	4.8	4.4	4.2	4.1	4.1	3.9	3.7	0.0%
Transportation	**1,535.6**	**1,680.3**	**1,913.5**	**1,892.5**	**1,944.8**	**1,942.0**	**1,989.7**	**2,002.4**	**1,965.4**	**26.9%**
Direct Emissions	1,532.5	1,677.2	1,910.0	1,888.8	1,941.4	1,937.7	1,985.1	1,997.6	1,960.4	26.8%
CO_2	1,485.4	1,601.5	1,804.0	1,781.4	1,834.7	1,831.5	1,878.7	1,893.3	1,860.0	25.4%
CH_4	4.5	4.1	3.2	3.1	2.7	2.5	2.4	2.3	2.1	0.0%
N_2O	42.7	52.5	51.5	48.8	44.8	41.4	38.7	35.4	31.9	0.4%
HFCs[b]	+	19.2	51.3	55.5	59.1	62.2	65.3	66.7	66.3	0.9%
Electricity-Related	3.1	3.1	3.5	3.7	3.5	4.3	4.6	4.8	5.0	0.1%
CO_2	3.1	3.1	3.4	3.6	3.5	4.3	4.5	4.7	5.0	0.1%
CH_4	+	+	+	+	+	+	+	+	+	0.0%
N_2O	+	+	+	+	+	+	+	+	+	0.0%
SF_6	+	+	+	+	+	+	+	+	+	0.0%
Commercial	**948.6**	**1,005.6**	**1,143.1**	**1,150.8**	**1,152.0**	**1,173.9**	**1,188.5**	**1,213.7**	**1,205.7**	**16.5%**
Direct Emissions	399.3	406.2	391.5	384.0	389.1	411.3	405.9	401.7	395.9	5.4%
CO_2	218.5	227.5	229.2	223.3	223.7	237.6	231.9	223.2	211.4	2.9%
CH_4	173.8	170.0	147.6	143.8	146.4	151.9	149.0	149.9	152.0	2.1%
N_2O	7.0	8.0	9.3	9.5	9.4	9.7	9.9	10.1	10.2	0.1%
HFCs	+	0.7	5.5	7.4	9.6	12.1	15.0	18.5	22.4	0.3%
Electricity-Related	549.3	599.4	751.6	766.7	763.0	762.5	782.6	812.0	809.8	11.1%
CO_2	538.7	590.0	743.2	758.1	754.6	754.4	774.3	803.5	801.5	11.0%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.0%
N_2O	2.5	2.7	3.3	3.4	3.4	3.4	3.5	3.6	3.6	0.0%
SF_6	7.9	6.5	4.9	5.0	4.8	4.5	4.6	4.7	4.5	0.1%
Residential	**956.7**	**1,030.0**	**1,163.3**	**1,155.4**	**1,180.1**	**1,213.7**	**1,210.1**	**1,244.4**	**1,190.4**	**16.3%**
Direct Emissions	351.2	374.4	390.2	381.5	378.7	402.1	388.4	378.8	347.4	4.7%
CO_2	344.4	359.9	374.3	365.4	362.3	385.0	370.8	360.9	328.7	4.5%
CH_4	4.4	4.0	3.4	3.1	3.1	3.3	3.3	3.3	3.1	0.0%
N_2O	2.1	2.4	2.5	2.6	2.7	2.8	2.8	2.7	2.7	0.0%
HFCs	0.3	8.1	10.1	10.3	10.7	11.0	11.4	11.9	12.9	0.2%
Electricity-Related	605.5	655.6	773.0	773.9	801.4	811.6	821.7	865.6	843.0	11.5%

CO_2	593.8	645.4	764.4	765.2	792.6	802.9	813.0	856.6	834.4	11.4%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.0%
N_2O	2.8	3.0	3.4	3.4	3.5	3.6	3.6	3.8	3.7	0.1%
SF_6	8.7	7.1	5.0	5.1	5.0	4.8	4.9	5.0	4.7	0.1%
Agriculture	**732.0**	**755.2**	**752.4**	**782.0**	**757.0**	**721.1**	**729.5**	**751.5**	**748.3**	**10.2%**
Direct Emissions	670.8	686.7	693.0	712.2	691.2	659.1	661.5	687.9	686.1	9.4%
CO_2	53.8	64.4	58.4	58.5	61.4	53.3	58.7	53.4	53.5	0.7%
CH_4	172.9	180.0	185.8	178.3	183.1	181.1	178.0	185.7	186.1	2.5%
N_2O	444.1	442.4	448.8	475.3	446.6	424.7	424.8	448.8	446.4	6.1%
Electricity-Related	61.2	68.5	59.4	69.8	65.8	62.0	68.1	63.6	62.2	0.9%
CO_2	60.0	67.4	58.7	69.0	65.1	61.4	67.3	63.0	61.6	0.8%
CH_4	+	+	+	+	+	+	+	+	+	0.0%
N_2O	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.0%
SF_6	0.9	0.7	0.4	0.5	0.4	0.4	0.4	0.4	0.3	0.0%
U.S. Territories	**34.1**	**41.1**	**47.3**	**54.5**	**53.3**	**59.7**	**61.0**	**60.5**	**62.4**	**0.9%**
Total	**6,309.7**	**6,650.1**	**7,196.4**	**7,097.6**	**7,138.7**	**7,176.3**	**7,254.4**	**7,313.7**	**7,201.9**	**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

When electricity-related emissions are distributed to economic end-use sectors, transportation activities accounted for 27 percent of U.S. greenhouse gas emissions in 2006. Table 2-15 provides a detailed summary of greenhouse gas emissions from transportation-related activities with electricity-related emissions included in the totals.

From 1990 to 2006, transportation emissions rose by 28 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 41 percent from 1990 to 2006) 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 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 26 percent from 1990 to 2006. This rise in CO_2 emissions, combined with an increase of 66.3 Tg CO_2 Eq. in HFC emissions over the same period, led to an increase in overall emissions from transportation activities of 30 percent.

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

Gas/Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	**1,488.4**	**1,604.6**	**1,807.4**	**1,785.0**	**1,838.1**	**1,835.8**	**1,883.2**	**1,898.0**	**1,865.0**
Passenger Cars	628.4	604.7	643.5	647.8	662.6	642.1	640.0	658.4	634.5
Light-Duty Trucks	320.2	404.6	465.7	470.0	483.0	518.4	540.4	501.5	514.5
Other Trucks	219.5	264.3	336.7	336.6	350.8	346.5	358.7	386.2	395.5

Buses	7.9	8.8	10.7	9.9	9.5	10.3	14.5	11.6	11.9
Aircraft[a]	180.0	174.6	196.4	186.6	178.0	174.7	177.0	181.2	170.6
Ships and Boats	46.1	55.2	60.8	43.0	60.6	53.3	61.0	65.8	43.6
Locomotives	36.6	41.1	44.4	44.8	44.4	46.0	48.5	49.1	50.2
Other[b]	49.7	51.3	49.1	46.4	49.2	44.4	43.1	44.1	44.1
International Bunker Fuels[c]	*113.7*	*100.6*	*101.1*	*97.6*	*89.1*	*83.7*	*99.8*	*102.1*	*125.7*
CH_4	**4.5**	**4.1**	**3.2**	**3.1**	**2.7**	**2.5**	**2.4**	**2.3**	**2.1**
Passenger Cars	2.6	2.1	1.6	1.5	1.4	1.3	1.2	1.1	1.0
Light-Duty Trucks	1.4	1.4	1.1	1.1	0.9	0.8	0.7	0.7	0.7
Other Trucks and Buses	0.2	0.2	0.1	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	0.1
Ships and Boats	0.1	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	0.1
Motorcycles	+	+	+	+	+	+	+	+	+
International Bunker Fuels[c]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.2*
N_2O	**42.7**	**52.5**	**51.5**	**48.8**	**44.8**	**41.4**	**38.6**	**35.3**	**31.8**
Passenger Cars	25.4	26.9	25.2	23.8	22.5	21.0	19.5	17.8	15.6
Light-Duty Trucks	14.1	22.1	22.4	21.3	18.5	16.6	15.3	13.7	12.7
Other Trucks and Buses	0.8	1.0	1.2	1.2	1.3	1.3	1.3	1.2	1.1
Aircraft	1.7	1.7	1.9	1.8	1.7	1.7	1.7	1.7	1.6
Ships and Boats	0.4	0.4	0.5	0.3	0.5	0.4	0.5	0.5	0.4
Locomotives	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4
Motorcycles	+	+	+	+	+	+	+	+	+
International Bunker Fuels[c]	*1.0*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*	*0.9*	*0.9*	*1.1*
HFCs, PFCs, and SF_6	**+**	**19.2**	**51.3**	**55.5**	**59.1**	**62.2**	**65.3**	**66.7**	**66.3**
Mobile Air Conditioners[d]	+	16.8	41.6	44.9	47.7	50.0	52.2	53.1	52.3
Comfort Cooling	+	2.3	9.7	10.7	11.4	12.2	13.1	13.6	14.0
School and Tour Busses	+	+	0.1	0.2	0.2	0.2	0.3	0.3	0.4
Transit Buses	+	+	+	+	+	+	+	+	+
Trains	+	+	+	+	+	+	+	+	+
Refrigerated Transport	+	2.3	9.6	10.5	11.2	12.0	12.8	13.2	13.6
Total	**1,535.6**	**1,680.4**	**1,913.5**	**1,892.4**	**1,944.8**	**1,941.9**	**1,989.5**	**2,002.2**	**1,965.2**

+ 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.

Industry

The industrial end-use sector includes CO_2 emissions from fossil fuel combustion from all manufacturing facilities, in aggregate. This sector also includes emissions that are produced as a by-product of the non-energy-related industrial process activities. The variety of activities producing these non-energy-related emissions, to name a few includes fugitive CH_4 emissions from coal mining, by-product CO_2 emissions from cement manufacture, and HFC, PFC, and SF_6 by-product emissions from semiconductor manufacture. Overall, direct industry sector emissions have declined since 1990, while electricity-related emissions have risen. In theory, emissions from the industrial end-use sector should be highly correlated with economic growth and industrial output, but heating of industrial buildings and agricultural energy consumption are also affected by weather conditions. In addition, structural

changes within the U.S. economy that lead to shifts in industrial output away from energy intensive manufacturing products to less energy intensive products (e.g., from steel to computer equipment) also have a significant affect on industrial emissions.

Commercial

The commercial sector is heavily reliant on electricity for meeting energy needs, with electricity consumption for lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Energy-related emissions from the residential and commercial sectors have generally been increasing since 1990, and are often correlated with short-term fluctuations in energy consumption caused by weather conditions, rather than prevailing economic conditions. Landfills and wastewater treatment are included in this sector, with landfill emissions decreasing since 1990, while wastewater treatment emissions have increases slightly.

Residential

The residential sector is heavily reliant on electricity for meeting energy needs, with electricity consumption for lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Emissions from the residential sectors have generally been increasing since 1990, and are often correlated with short-term fluctuations in energy consumption caused by weather conditions, rather than prevailing economic conditions. In the long-term, this sector is also affected by population growth, regional migration trends, and changes in housing and building attributes (e.g., size and insulation).

Agriculture

The agricultural sector includes a variety of processes, including enteric fermentation in domestic livestock, livestock manure management, and agricultural soil management. In 2006, enteric fermentation was the largest source of CH_4 emissions in the U.S., and agricultural soil management was the largest source of N_2O emissions in the U.S. This sector also includes small amounts of CO_2 emissions from fossil fuel combustion by motorized farm equipment like tractors.

Electricity Generation

The process of generating electricity, for consumption in the above sectors, is the single largest source of greenhouse gas emissions in the United States, representing 32 percent of total U.S. emissions. Electricity generation also accounted for the largest share of CO_2 emissions from fossil fuel combustion, approximately 41 percent in 2006. Electricity was consumed primarily in the residential, commercial, and industrial end-use sectors for lighting, heating, electric motors, appliances, electronics, and air conditioning.

[BEGIN BOX]

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

In presenting the Economic Sectors in the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, EPA expands upon the standard IPCC sectors common for UNFCCC reporting. EPA believes that discussing greenhouse gas emissions relevant to U.S.-specific sectors improves communication of the report's findings.

- In the Electricity Generation economic sector, CO_2 emissions from the combustion of fossil fuels included in the EIA electric utility fuel consuming sector are apportioned to this economic sector. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA electric utility sector. Additional sources include CO_2 and N_2O from Municipal Solid Waste Combustion, as the majority of municipal solid waste is combusted in "trash-to-steam" electricity generation plants. The Electricity Generation economic sector also includes SF_6 from

Electrical Transmission and Distribution, and a portion of CO_2 from Limestone and Dolomite Use (from pollution control equipment installed in electricity generation plants).

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

- For the Industry economic sector, the CO_2 emissions from the combustion of fossil fuels included in the EIA industrial fuel consuming sector, minus the agricultural use of fuel explained below, are apportioned to this economic sector. Stationary and mobile combustion emissions of CH_4 and N_2O are also based on the EIA industrial sector, minus emissions apportioned to the Agriculture economic sector described below. Substitutes of Ozone Depleting Substitutes are apportioned based on their specific end-uses within the source category, with most emissions falling within the Industry economic sector (minus emissions from the other economic sectors). Additionally, all process-related emissions from sources with methods considered within the IPCC Industrial Process guidance have been apportioned to this economic sector. This includes the process-related emissions (i.e., emissions from the actual process to make the material, not from fuels to power the plant) from such activities as cement production, iron and steel production, and ammonia manufacture. Additionally, fugitive emissions from energy production sources, such as Natural Gas Systems, Coal Mining, and Petroleum Systems are included in the Industry economic sector. A portion of CO_2 from Limestone and Dolomite Use (from pollution control equipment installed in large industrial facilities) are also included in the Industry economic sector. Finally, all remaining CO_2 emissions from Non-Energy Uses of Fossil Fuels are assumed to be industrial in nature (besides the lubricants for transportation vehicles specified above), and are attributed to the Industry economic sector.

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

- The Residential economic sector includes the CO_2 emissions from the combustion of fossil fuels reported for the EIA residential sector. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA residential fuel consuming sector. Substitutes of Ozone Depleting Substitutes are apportioned based on their specific end-uses within the source category, with emissions from residential air-conditioning systems to this economic sector. N_2O emissions from the application of fertilizers to developed land (termed "settlements" by the IPCC) are also included in the Residential economic sector.

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

from Wastewater Treatment and Composting are included in this economic sector.

[END BOX]

[BEGIN BOX]

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

Total emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) emissions per unit of aggregate energy consumption, because energy-related activities are the largest sources of emissions; (2) emissions per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; (3) emissions per unit of electricity consumption, because the electric power industry—utilities and non-utilities combined—was the largest source of U.S. greenhouse gas emissions in 2006; (4) emissions per unit of total gross domestic product as a measure of national economic activity; or (5) emissions per capita.

Table 2-16 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. Greenhouse gas emissions in the United States have grown at an average annual rate of 0.8 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 Table 2-16).

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

Variable	1990	1995	2000	2001	2002	2003	2004	2005	2006	Growth Rate[a]
GDP[b]	100	113	138	139	141	145	150	155	159	3.0%
Electricity Consumption[c]	100	112	127	125	128	129	131	134	135	1.9%
Fossil Fuel Consumption[c]	100	107	117	115	116	116	119	119	117	1.0%
Energy Consumption[c]	100	108	116	112	115	115	118	118	117	1.0%
Population[d]	100	107	113	114	115	116	117	118	119	1.1%
Greenhouse Gas Emissions[e]	100	105	114	112	113	114	115	116	114	0.8%

[a] Average annual growth rate
[b] Gross Domestic Product in chained 2000 dollars (BEA 2007)
[c] Energy-content-weighted values (EIA 2007b)
[d] U.S. Census Bureau (2007)
[e] GWP-weighted values

Figure 2-14: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product
Source: BEA (2007), U.S. Census Bureau (2007), and emission estimates in this report.

[END BOX]

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

The reporting requirements of the UNFCCC[7] request that information be provided on indirect greenhouse gases,

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

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

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

Since 1970, the United States has published estimates of annual emissions of CO, NO_x, NMVOCs, and SO_2 (EPA 2005),[8] which are regulated under the Clean Air Act. Table 2-17 shows that fuel combustion accounts for the majority of emissions of these indirect greenhouse gases. Industrial processes—such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents—are also significant sources of CO, NO_x, and NMVOCs.

Table 2-17: Emissions of NO_x, CO, NMVOCs, and SO_2 (Gg)

Gas/Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
NO_x	**21,645**	**21,272**	**19,203**	**18,410**	**17,938**	**17,043**	**16,177**	**15,569**	**14,869**
Mobile Fossil Fuel Combustion	10,920	10,622	10,310	9,819	10,154	9,642	9,191	8,739	8,287
Stationary Fossil Fuel Combustion	9,883	9,821	8,002	7,667	6,791	6,419	6,004	5,853	5,610
Industrial Processes	591	607	626	656	534	528	524	519	515
Oil and Gas Activities	139	100	111	113	321	316	316	316	315
Municipal Solid Waste Combustion	82	88	114	114	98	97	97	97	97
Agricultural Burning	28	29	35	35	33	34	39	39	38
Solvent Use	1	3	3	3	5	5	5	5	5
Waste	0	1	2	2	2	2	2	2	2
CO	**130,461**	**109,032**	**92,777**	**89,212**	**84,609**	**80,221**	**76,342**	**72,365**	**68,372**
Mobile Fossil Fuel Combustion	119,360	97,630	83,559	79,851	75,421	71,038	67,096	63,154	59,213
Stationary Fossil Fuel Combustion	5,000	5,383	4,340	4,377	4,965	4,893	4,876	4,860	4,844
Industrial Processes	4,125	3,959	2,217	2,339	1,744	1,724	1,724	1,724	1,724
Municipal Solid Waste Combustion	978	1,073	1,670	1,672	1,439	1,437	1,437	1,437	1,437
Agricultural Burning	691	663	792	774	709	800	879	860	825
Oil and Gas Activities	302	316	146	147	323	321	321	321	322
Waste	1	2	8	8	7	7	7	7	7
Solvent Use	5	5	46	45	1	1	1	1	1
NMVOCs	**20,930**	**19,520**	**15,228**	**15,048**	**15,640**	**15,170**	**14,807**	**14,444**	**14,082**

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

Mobile Fossil Fuel Combustion	10,932	8,745	7,230	6,872	7,235	6,885	6,587	6,289	5,991
Solvent Use	5,216	5,609	4,384	4,547	3,881	3,862	3,854	3,846	3,839
Industrial Processes	2,422	2,642	1,773	1,769	2,036	1,972	1,931	1,890	1,849
Stationary Fossil Fuel Combustion	912	973	1,077	1,080	1,585	1,560	1,553	1,545	1,538
Oil and Gas Activities	554	582	389	400	545	538	533	528	523
Municipal Solid Waste Combustion	222	237	257	258	243	239	237	235	232
Waste	673	731	119	122	115	114	112	111	110
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA	NA	NA
SO_2	**20,935**	**16,891**	**14,829**	**14,452**	**13,403**	**13,631**	**13,232**	**13,114**	**12,258**
Stationary Fossil Fuel Combustion	18,407	14,724	12,848	12,461	11,613	11,956	11,625	11,573	10,784
Industrial Processes	1,307	1,117	1,031	1,047	850	804	800	797	793
Mobile Fossil Fuel Combustion	793	672	632	624	683	621	564	508	451
Oil and Gas Activities	390	335	286	289	233	226	220	213	207
Municipal Solid Waste Combustion	38	42	29	30	23	22	22	22	22
Waste	0	1	1	1	1	1	1	1	1
Solvent Use	0	1	1	1	0	0	0	0	0
Agricultural Burning	NA	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.

[BEGIN BOX]

Box 2-3: Sources and Effects of Sulfur Dioxide

Sulfur dioxide (SO_2) emitted into the atmosphere through natural and anthropogenic processes affects the earth's radiative budget through its photochemical transformation into sulfate aerosols that can (1) scatter radiation from the sun back to space, thereby reducing the radiation reaching the earth's surface; (2) affect cloud formation; and (3) affect atmospheric chemical composition (e.g., by providing surfaces for heterogeneous chemical reactions). The indirect effect of sulfur-derived aerosols on radiative forcing can be considered in two parts. The first indirect effect is the aerosols' tendency to decrease water droplet size and increase water droplet concentration in the atmosphere. The second indirect effect is the tendency of the reduction in cloud droplet size to affect precipitation by increasing cloud lifetime and thickness. Although still highly uncertain, the radiative forcing estimates from both the first and the second indirect effect are believed to be negative, as is the combined radiative forcing of the two (IPCC 2001). However, because SO_2 is short-lived and unevenly distributed in the atmosphere, its radiative forcing impacts are highly uncertain.

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

Electricity generation is the largest anthropogenic source of SO_2 emissions in the United States, accounting for 78 percent in 2006. Coal combustion contributes nearly all of those emissions (approximately 92 percent). Sulfur dioxide emissions have decreased in recent years, primarily as a result of electric power generators switching from high-sulfur to low-sulfur coal and installing flue gas desulfurization equipment.

[END BOX]

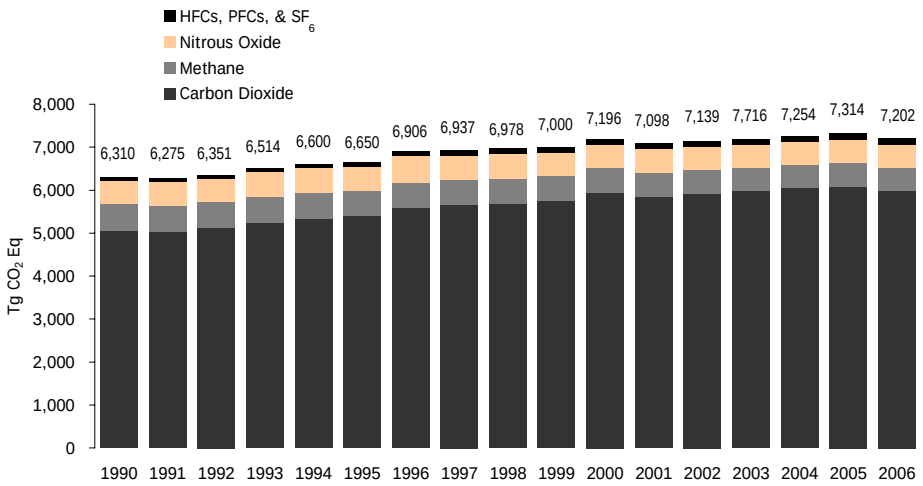

Figure 2-1: U.S. Greenhouse Gas Emissions by Gas

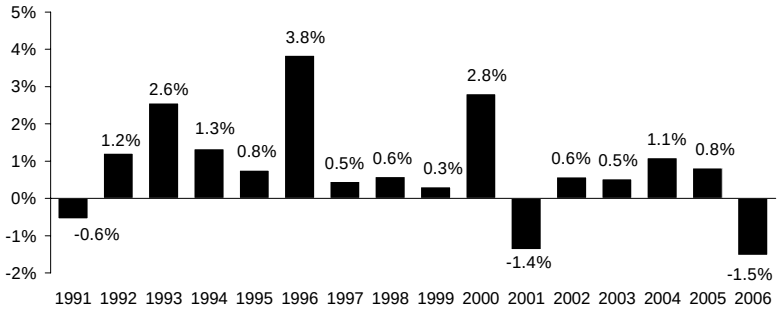

Figure 2-2: Annual Percent Change in U.S. Greenhouse Gas Emissions

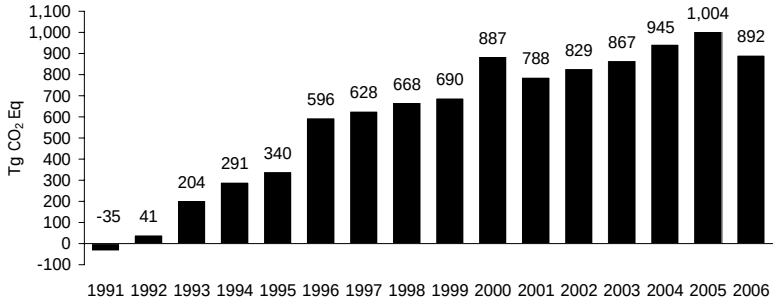

Figure 2-3: Cumulative Change in U.S. Greenhouse Gas Emissions Relative to 1990

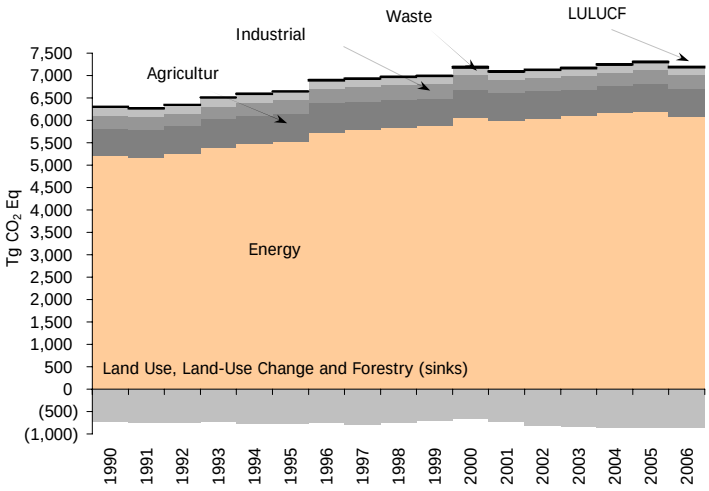

Figure 2-4: U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector

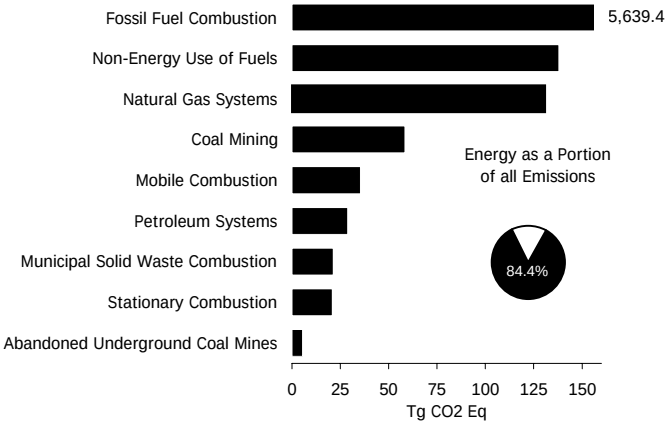

Figure 2-5: 2006 Energy Sector Greenhouse Gas Sources

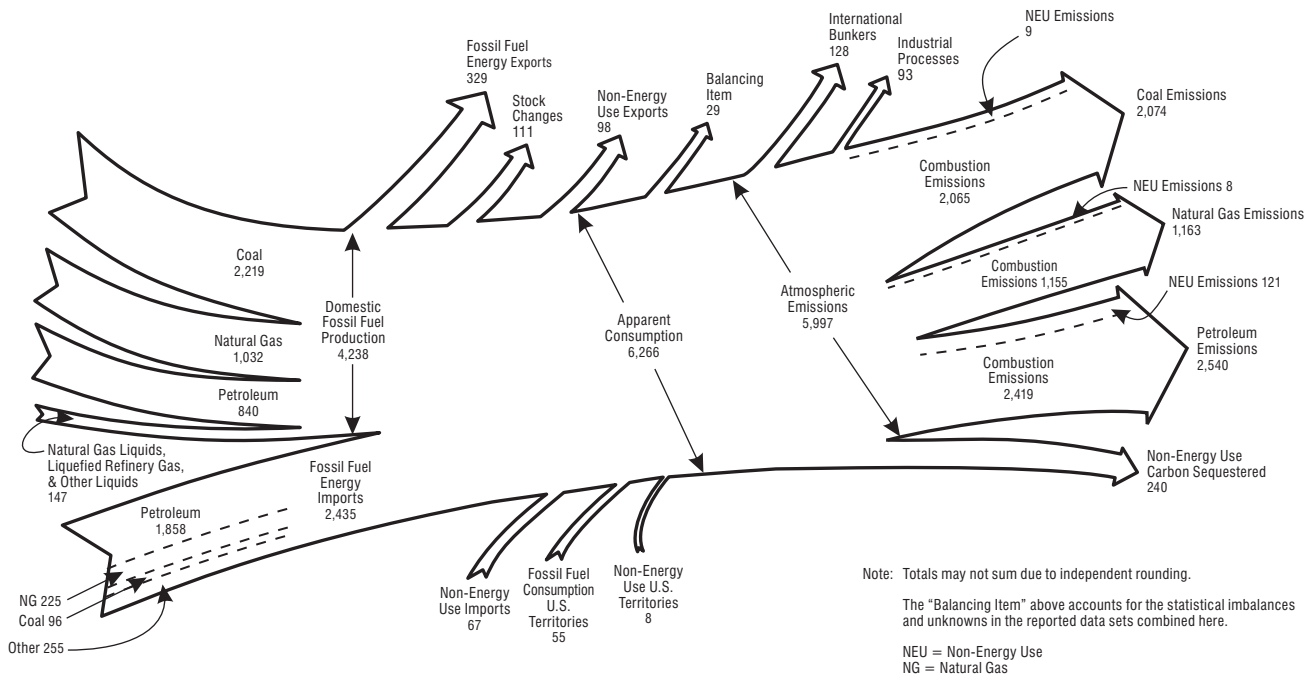

Figure 2-6 2006 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)

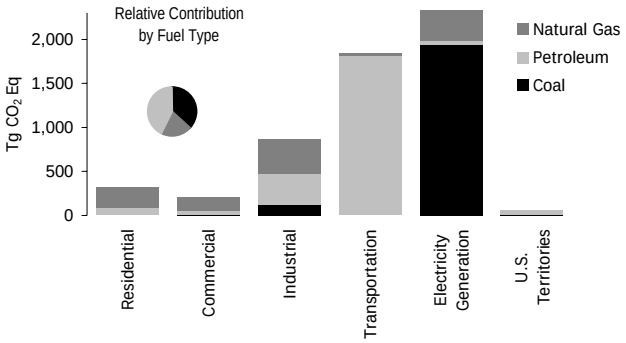

Figure 2-7: 2006 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

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

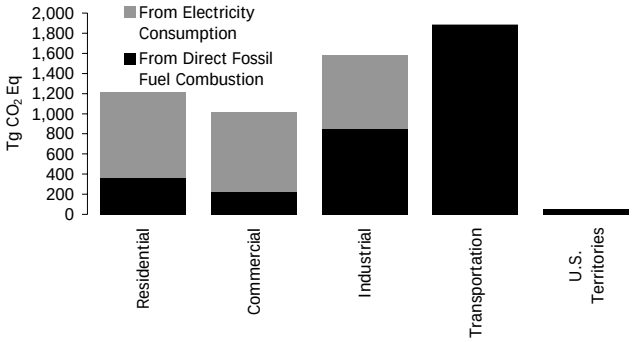

Figure 2-8: 2006 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

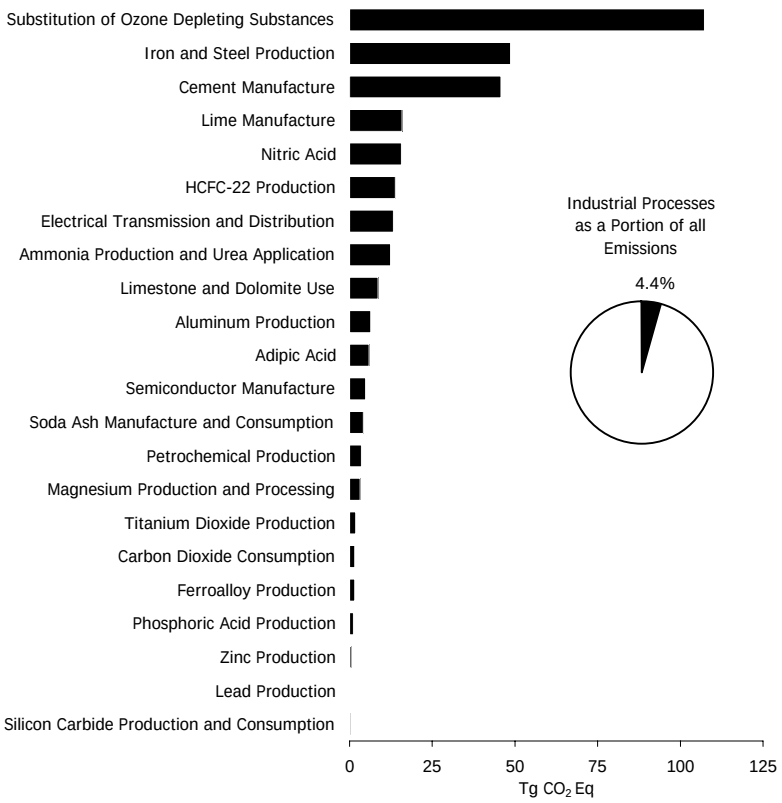

Figure 2-9: 2006 Industrial Processes Chapter Greenhouse Gas Sources

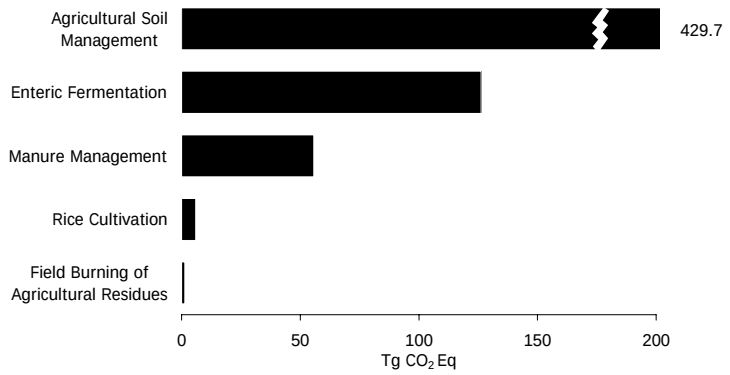

Figure 2-10: 2006 Agriculture Chapter Greenhouse Gas Sources

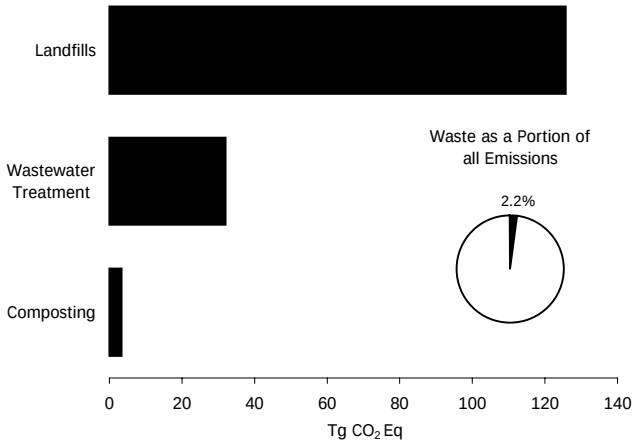

Figure 2-11: 2006 Waste Chapter Greenhouse Gas Sources

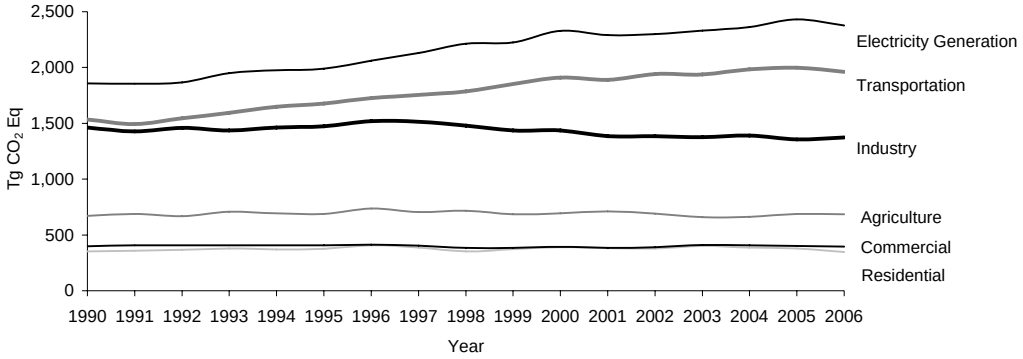

Figure 2-12: Emissions Allocated to Economic Sectors

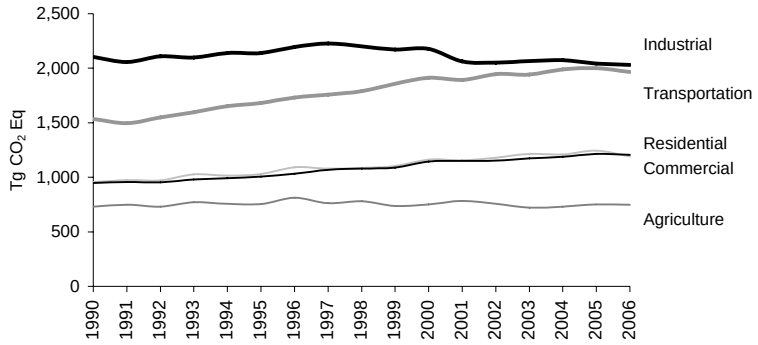

Figure 2-13: Emissions with Electricity Distributed to Economic Sectors

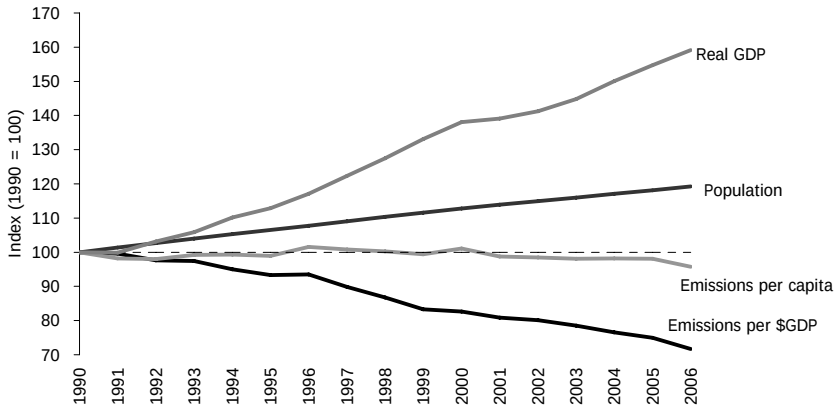

Figure 2-14: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product

3. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 84 percent of total emissions on a carbon (C) equivalent basis in 2006. This included 97, 37, and 9 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 81 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 (3 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 28,193 Tg of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2005, of which the United States accounted for about 20 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.

Figure 3-1: 2006 Energy Chapter Greenhouse Gas Sources

Figure 3-2: 2006 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)

Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of fugitive CH_4 from natural gas systems, petroleum systems, and coal mining. 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 separately within the Land Use, Land-Use Change, and Forestry chapter. Emissions of other greenhouse gases from the combustion of biomass 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 6,078.4 Tg CO_2 Eq. in 2006, an increase of 17 percent since 1990.

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	2006

[1] Global CO_2 emissions from fossil fuel combustion were taken from Energy Information Administration *International Energy Annual 2005* <http://www.eia.doe.gov/emeu/iea/carbon.html> EIA (2007).

CO_2	**4,886.4**	**5,215.5**	**5,765.7**	**5,686.4**	**5,749.1**	**5,816.5**	**5,898.0**	**5,941.0**	**5,827.1**
Fossil Fuel Combustion	4,724.1	5,032.4	5,577.1	5,507.4	5,564.8	5,636.9	5,700.5	5,751.5	5,639.4
Electricity Generation	1,809.6	1,939.3	2,282.3	2,244.3	2,253.7	2,283.1	2,314.9	2,380.2	2,328.2
Transportation	1,473.5	1,590.2	1,791.9	1,770.3	1,823.8	1,821.4	1,868.5	1,883.1	1,850.1
Industrial	849.9	880.6	863.2	855.0	857.3	858.8	861.0	850.9	866.1
Residential	344.4	359.9	374.3	365.4	362.3	385.0	370.8	360.9	328.7
Commercial	218.5	227.5	229.2	223.3	223.7	237.6	231.9	223.2	211.4
U.S. Territories	28.3	35.0	36.2	49.0	44.0	51.0	53.5	53.2	54.9
Non-Energy Use of Fuels	117.2	133.2	141.4	131.9	135.9	131.8	148.9	139.1	138.0
Natural Gas Systems	33.7	33.8	29.4	28.8	29.6	28.4	28.1	29.5	28.5
Municipal Solid Waste Combustion	10.9	15.7	17.5	18.0	18.5	19.1	20.1	20.7	20.9
Petroleum Systems	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
*Wood Biomass and Ethanol Consumption**	*219.3*	*236.8*	*227.3*	*203.2*	*204.4*	*209.5*	*224.8*	*227.4*	*234.7*
*International Bunker Fuels**	*113.7*	*100.6*	*101.1*	*97.6*	*89.1*	*83.7*	*99.8*	*102.1*	*125.7*
CH_4	**260.8**	**246.8**	**234.5**	**232.0**	**226.9**	**224.6**	**217.5**	**202.4**	**203.3**
Natural Gas Systems	124.7	128.1	126.5	125.3	124.9	123.3	114.0	102.5	102.4
Coal Mining	84.1	67.1	60.4	60.3	56.8	56.9	59.8	57.1	58.5
Petroleum Systems	33.9	32.0	30.3	30.2	29.9	29.2	28.7	28.3	28.4
Stationary Combustion	7.4	7.2	6.7	6.2	6.2	6.4	6.6	6.5	6.2
Abandoned Underground Coal Mines	6.0	8.2	7.4	6.7	6.2	6.0	5.8	5.6	5.4
Mobile Combustion	4.7	4.3	3.4	3.3	3.0	2.8	2.7	2.5	2.4
*International Bunker Fuels**	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.2*
N_2O	**56.8**	**67.3**	**67.5**	**64.4**	**60.4**	**57.3**	**54.8**	**51.7**	**48.0**
Mobile Combustion	43.5	53.4	52.5	49.9	45.9	42.5	39.8	36.5	33.1
Stationary Combustion	12.8	13.4	14.6	14.1	14.0	14.4	14.6	14.8	14.5
Municipal Solid Waste Combustion	0.5	0.5	0.4	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*	*1.1*
Total	**5,204.0**	**5,529.6**	**6,067.8**	**5,982.8**	**6,036.3**	**6,098.4**	**6,170.2**	**6,195.0**	**6,078.4**

* 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	2006
CO_2	**4,886,370**	**5,215,509**	**5,765,732**	**5,686,382**	**5,749,059**	**5,816,532**	**5,897,962**	**5,940,995**	**5,827,068**
Fossil Fuel Combustion	4,724,146	5,032,416	5,577,072	5,507,406	5,564,795	5,636,941	5,700,510	5,751,515	5,639,368
Non-Energy Use of Fuels	117,170	133,234	141,427	131,887	135,857	131,772	148,931	139,057	137,980
Natural Gas Systems	33,729	33,806	29,390	28,793	29,629	28,445	28,122	29,462	28,504
Municipal Solid Waste Combustion	10,950	15,712	17,518	17,971	18,458	19,058	20,097	20,673	20,922
Petroleum Systems	376	341	325	325	320	316	302	287	293
*Wood Biomass and Ethanol Consumption**	*219,341*	*236,775*	*227,276*	*203,163*	*204,351*	*209,537*	*224,825*	*227,366*	*234,726*
*International Bunker Fuels**	*113,683*	*100,627*	*101,125*	*97,563*	*89,101*	*83,690*	*99,828*	*102,110*	*125,659*

CH_4	**12,418**	**11,754**	**11,168**	**11,049**	**10,804**	**10,695**	**10,355**	**9,638**	**9,680**
Natural Gas Systems	5,937	6,098	6,024	5,968	5,946	5,874	5,426	4,880	4,877
Coal Mining	4,003	3,193	2,874	2,874	2,707	2,709	2,846	2,717	2,784
Petroleum Systems	1,612	1,524	1,442	1,436	1,422	1,390	1,368	1,346	1,354
Stationary Combustion	354	342	317	295	295	307	312	309	296
Abandoned Underground Coal Mines	288	392	350	319	293	284	276	265	257
Mobile Combustion	224	205	162	157	141	132	127	120	112
*International Bunker Fuels**	*8*	*6*	*6*	*5*	*4*	*4*	*5*	*5*	*7*
N_2O	**183**	**217**	**218**	**208**	**195**	**185**	**177**	**167**	**155**
Mobile Combustion	140	172	169	161	148	137	128	118	107
Stationary Combustion	41	43	47	46	45	46	47	48	47
Municipal Solid Waste Combustion	2	1	1	1	1	1	1	1	1
*International Bunker Fuels**	*3*	*3*	*3*	*3*	*3*	*2*	*3*	*3*	4

* 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.

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

CO_2 emissions from fossil fuel combustion in 2006 decreased by 1.9 percent from the previous year. This decrease is primarily a result of the restraint on fuel consumption caused by rising fuel prices, primarily in the transportation sector, an increase in the cost of electricity, and decreases in the cost of natural gas. Additionally, warmer winter conditions in 2006 decreased the demand for heating fuels. In 2006, CO_2 emissions from fossil fuel combustion were 5,639.4 Tg CO_2 Eq., or 19 percent above emissions in 1990 (see Table 3-3).[2]

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	2006
Coal	**1,698.9**	**1,805.4**	**2,053.2**	**1,996.3**	**2,002.8**	**2,043.1**	**2,058.4**	**2,094.1**	**2,065.3**
Residential	2.9	1.7	1.0	1.0	1.1	1.2	1.2	0.9	0.6
Commercial	11.8	11.1	8.2	8.4	8.4	7.9	9.7	9.2	6.2
Industrial	152.3	143.0	133.5	133.5	123.4	124.0	126.2	122.0	122.0
Transportation	NE	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	1,932.4
U.S. Territories	0.6	0.9	0.9	1.0	1.7	3.8	3.6	3.7	4.1
Natural Gas	**1,011.5**	**1,172.0**	**1,220.5**	**1,175.3**	**1,227.6**	**1,200.3**	**1,180.1**	**1,173.9**	**1,155.1**
Residential	239.8	264.4	270.6	260.3	265.0	277.5	264.5	262.7	237.5

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

Commercial	143.1	165.4	172.7	165.1	171.0	176.7	170.0	163.2	154.1
Industrial	416.3	474.4	460.0	425.0	447.2	433.0	415.5	394.5	389.3
Transportation	36.1	38.4	35.7	34.1	37.2	33.4	32.0	33.2	33.2
Electricity Generation	176.2	229.5	280.9	289.6	306.0	278.3	296.8	319.1	339.6
U.S. Territories	NO	NO	0.7	1.2	1.2	1.4	1.3	1.3	1.4
Petroleum	**2,013.3**	**2,054.7**	**2,303.0**	**2,335.5**	**2,334.0**	**2,393.2**	**2,461.6**	**2,483.1**	**2,418.6**
Residential	101.6	93.8	102.7	104.0	96.1	106.4	105.0	97.4	90.7
Commercial	63.6	51.1	48.4	49.8	44.3	53.0	52.2	50.8	51.1
Industrial	281.3	263.2	269.7	296.5	286.7	301.8	319.3	334.5	354.8
Transportation	1,437.4	1,551.8	1,756.2	1,736.3	1,786.5	1,788.0	1,836.5	1,849.9	1,816.9
Electricity Generation	101.8	60.7	91.5	102.0	79.1	98.1	100.1	102.3	55.7
U.S. Territories	27.6	34.0	34.6	46.8	41.1	45.8	48.6	48.2	49.4
Geothermal*	**0.40**	**0.34**	**0.36**	**0.35**	**0.37**	**0.37**	**0.38**	**0.38**	**0.38**
Total	**4,724.1**	**5,032.4**	**5,577.1**	**5,507.4**	**5,564.8**	**5,636.9**	**5,700.5**	**5,751.5**	**5,639.4**

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.

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).

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.

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	2002 to 2003		2003 to 2004		2004 to 2005		2005 to 2006	
Electricity Generation	Coal	38.0	2.0%	11.4	0.6%	40.8	2.1%	-26.0	-1.3%
Electricity Generation	Natural Gas	-27.6	-9.0%	18.5	6.6%	22.3	7.5%	20.5	6.4%
Electricity Generation	Petroleum	19.0	24.0%	2.0	2.0%	2.2	2.2%	-46.6	-45.5%
Transportation [a]	Petroleum	1.5	0.1%	48.5	2.7%	13.5	0.7%	-33.0	-1.8%
Residential	Natural Gas	12.5	4.7%	-12.9	-4.7%	-1.9	-0.7%	-25.2	-9.6%
Commercial	Natural Gas	5.7	3.3%	-6.7	-3.8%	-6.8	-4.0%	-9.1	-5.6%

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

Industrial	Coal	0.6	0.5%	2.3	1.8%	-4.3	-3.4%	0.1	0.1%
Industrial	Natural Gas	-14.2	-3.2%	-17.5	-4.0%	-21.0	-5.1%	-5.2	-1.3%
All Sectors [b]	**All Fuels [b]**	**72.1**	**1.3%**	**63.6**	**1.1%**	**51.0**	**0.9%**	**-112.1**	**-1.9%**

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

In the United States, 82 percent of the energy consumed in 2006 was produced through the combustion of fossil fuels such as coal, natural gas, and petroleum (see Figure 3-3 and Figure 3-4). The remaining portion was supplied by nuclear electric power (8 percent) and by a variety of renewable energy sources (9 percent), primarily hydroelectric power and biofuels (EIA 2007a). Specifically, petroleum supplied the largest share of domestic energy demands, accounting for an average of 43 percent of total fossil fuel based energy consumption in 2006. Coal and natural gas 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 2007a).

Figure 3-3: 2006 U.S. Energy Consumption by Energy Source

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

Figure 3-5: 2006 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process, the C stored in the fuels is oxidized and emitted as CO_2 and smaller amounts of other gases, 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.

[BEGIN BOX]

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

In 2006, weather conditions became warmer in the winter and slightly cooler in the summer, compared to 2005. The winter was significantly warmer than usual, with heating degree days in the United States 12 percent below

[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.

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 10 percent above normal (see Figure 3-7) (EIA 2007f),[5] however the demand for electricity only increased slightly due to the cooler summer conditions compared to 2005.

Figure 3-6: Annual Deviations from Normal Heating Degree Days for the United States (1950–2006)

Figure 3-7: Annual Deviations from Normal Cooling Degree Days for the United States (1950–2006)

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 2006 remained high at just under 90 percent. Electricity output by hydroelectric power plants increased in 2006 by approximately 7 percent. Electricity generated by nuclear plants in 2006 provided almost 3 times as much of the energy consumed in the United States as hydroelectric plants (EIA 2007a). 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 (1974–2006)

[END BOX]

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.

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

[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 2007a).

provided in Table 3-5, and explained in detail later in the chapter.

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

Vehicle Mode	1990	1995	2000	2001	2002	2003	2004	2005	2006
Aviation	45.7	50.2	59.9	58.7	61.1	58.8	64.9	67.5	71.1
Marine	68.0	50.4	41.3	38.9	28.0	24.9	34.9	34.6	54.5
Total	**113.7**	**100.6**	**101.1**	**97.6**	**89.1**	**83.7**	**99.8**	**102.1**	**125.7**

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

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.

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	2006
Transportation	**1,476.5**	**1,593.3**	**1,795.3**	**1,774.0**	**1,827.2**	**1,825.7**	**1,873.0**	**1,887.8**	**1,855.1**
Combustion	1,473.5	1,590.2	1,791.9	1,770.3	1,823.8	1,821.4	1,868.5	1,883.1	1,850.1
Electricity	3.0	3.0	3.4	3.6	3.4	4.2	4.5	4.7	4.9
Industrial	**1,532.5**	**1,593.6**	**1,648.0**	**1,586.4**	**1,574.9**	**1,594.8**	**1,600.0**	**1,583.1**	**1,571.0**
Combustion	849.9	880.6	863.2	855.0	857.3	858.8	861.0	850.9	866.1
Electricity	682.5	713.1	784.7	731.4	717.7	736.1	739.0	732.3	704.9
Residential	**933.7**	**998.8**	**1,131.9**	**1,123.5**	**1,147.4**	**1,180.4**	**1,175.6**	**1,208.8**	**1,154.1**
Combustion	344.4	359.9	374.3	365.4	362.3	385.0	370.8	360.9	328.7
Electricity	589.4	639.0	757.6	758.1	785.1	795.4	804.9	847.9	825.4
Commercial	**753.1**	**811.7**	**965.8**	**974.5**	**971.2**	**984.9**	**998.4**	**1,018.6**	**1,004.3**
Combustion	218.5	227.5	229.2	223.3	223.7	237.6	231.9	223.2	211.4
Electricity	534.7	584.2	736.6	751.1	747.5	747.3	766.5	795.4	792.9
U.S. Territories	**28.3**	**35.0**	**36.2**	**49.0**	**44.0**	**51.0**	**53.5**	**53.2**	**54.9**
Total	**4,724.1**	**5,032.4**	**5,577.1**	**5,507.4**	**5,564.8**	**5,636.9**	**5,700.5**	**5,751.5**	**5,639.4**
Electricity Generation	**1,809.6**	**1,939.3**	**2,282.3**	**2,244.3**	**2,253.7**	**2,283.1**	**2,314.9**	**2,380.2**	**2,328.2**

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.

Figure 3-9: 2006 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

Transportation End-Use Sector

The transportation end-use sector accounted for 1,855.1 Tg CO_2 in 2006, representing 33 percent of total CO_2

emissions from fossil fuel combustion; the largest share of any end-use economic sector[7]. Within the transportation sector, light duty vehicles (including passenger cars and light-duty trucks) accounted for almost 62 percent of CO_2 emissions, medium- and heavy-duty trucks 21 percent, commercial aircraft 7.6 percent, and other sources just over 9 percent. (See Table 3-7 for a detailed breakdown of CO_2 emissions by mode and fuel type.)

Transportation CO_2 emissions increased by 21 percent (378.5 Tg) between 1990 and 2006, an annualized increase of 1.5 percent. From 2005 to 2006 transportation CO_2 emissions decreased by 1.7 percent. Almost all of the energy consumed by the transportation sector is petroleum-based, including motor gasoline, diesel fuel, jet fuel, and residual oil. Transportation sources also produce CH_4 and N_2O; these emissions are included on page XX in the "Mobile Combustion" Section. Annex 3.2 presents total emissions from all transportation and mobile sources, including CO_2, N_2O, CH_4, and HFCs.

Carbon dioxide emissions from passenger cars and light-duty trucks totaled 1,148.4 Tg in 2006, an increase of 21 percent (200.2 Tg) from 1990. The increase in light-duty CO_2 emissions can be explained by the growth in vehicle travel, which substantially outweighed improvements in vehicle fuel economy. Vehicle miles traveled (VMT) increased 40 percent from 1990 to 2006; average vehicle fuel economy increased from 16.4 miles per gallon (mpg) in 1990 to 20.4 mpg in 2006, primarily reflecting the retirement of older vehicles. Among new vehicles sold annually, average fuel economy gradually declined from 1990 to 2006 (Figure 3-10), reflecting substantial growth in sales of light-duty trucks relative to passenger cars (Figure 3-11). Average new vehicle fuel economy improved in 2005 and 2006 as the market share of passenger cars increased in response to rising fuel prices.

Figure 3-10: Sales-Weighted Fuel Economy of New Passenger Cars and Light-Duty Trucks, 1990–2006

Figure 3-11: Sales of New Passenger Cars and Light-Duty Trucks, 1990–2006

Medium- and heavy-duty truck[8] CO_2 emissions increased by almost 81 percent (176.0 Tg) from 1990 to 2006, representing the largest emissions rate increase of any major transportation mode. Fuel economy for the medium- and heavy-duty truck fleet was relatively constant over this period, while VMT increased by 52 percent. CO_2 from the domestic operation of commercial aircraft increased by 2.7 percent (3.7 Tg) from 1990 to 2006, well below the growth in travel activity (passenger miles traveled grew by 69 percent from 1990 to 2005, the most recent year of available data). The operational efficiency of commercial aircraft improved substantially because of a growing percentage of seats occupied per flight and steady improvements in the fuel efficiency of new aircraft. Across all categories of aviation[9], CO_2 emissions decreased by approximately 5.2 percent (9.3 Tg CO_2) between 1990 and 2006. This decline reflects a 53 percent decrease in emissions from domestic military operations, which more than offset a small increase in domestic commercial and general aviation emissions. For further information on all greenhouse gas emissions from transportation sources, please refer to Table A-108 in Annex 3.2.

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

Fuel/Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005	2006
Gasoline	**982.8**	**1,038.9**	**1,135.7**	**1,145.4**	**1,172.3**	**1,176.5**	**1,194.8**	**1181.2**	**1,170.0**

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

[8] Includes "medium- and heavy-duty 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.

Passenger Cars	621.0	597.0	639.9	644.2	658.9	638.0	635.8	654.2	630.4
Light-Duty Trucks	308.9	389.9	446.0	449.4	461.3	491.5	511.6	476.0	488.0
Medium- and Heavy-Duty Trucks[b]	38.7	35.8	36.0	35.0	35.5	30.6	30.9	34.7	35.2
Buses	0.3	0.4	0.4	0.4	0.3	0.3	0.4	0.4	0.4
Motorcycles	1.7	1.8	1.8	1.7	1.7	1.6	1.7	1.6	1.9
Boats (Recreational)	12.1	14.0	11.6	14.6	14.6	14.5	14.4	14.3	14.1
Distillate Fuel Oil (Diesel)	**261.2**	**315.9**	**394.7**	**396.3**	**410.0**	**415.7**	**440.1**	**455.0**	**464.8**
Passenger Cars	7.5	7.5	3.5	3.6	3.7	4.1	4.2	4.1	4.0
Light-Duty Trucks	10.8	14.2	19.5	20.3	21.4	26.5	28.3	25.1	26.0
Medium- and Heavy-Duty Trucks[b]	179.9	228.0	300.3	301.1	314.8	315.3	327.1	350.8	359.6
Buses	7.6	8.4	9.9	9.1	8.6	9.3	13.2	10.4	10.7
Rail	33.6	38.1	41.0	41.2	41.0	41.8	44.0	44.4	45.3
Boats (Recreational)	1.8	2.2	2.7	2.8	2.8	2.9	3.0	3.1	3.2
Ships & Boats	8.4	8.3	11.5	13.0	12.7	9.7	13.2	9.8	8.6
Ships (Bunkers)	11.6	9.2	6.3	5.3	5.1	6.0	7.1	7.2	7.3
Jet Fuel[c]	**222.6**	**222.1**	**253.8**	**242.8**	**236.8**	**231.5**	**239.8**	**246.3**	**239.5**
Commercial Aircraft	136.7	143.1	164.2	152.9	146.1	143.9	142.9	150.4	140.4
Military Aircraft	33.9	23.5	20.5	22.5	20.4	19.9	20.4	16.9	15.8
General Aviation Aircraft	6.3	5.3	9.2	8.8	9.1	8.8	11.5	11.4	12.1
Aircraft (Bunkers)	45.7	50.2	59.9	58.7	61.1	58.8	64.9	67.5	71.1
Aviation Gasoline	**3.1**	**2.7**	**2.5**	**2.4**	**2.3**	**2.1**	**2.2**	**2.4**	**2.3**
General Aviation Aircraft	3.1	2.7	2.5	2.4	2.3	2.1	2.2	2.4	2.3
Residual Fuel Oil	**80.1**	**71.7**	**69.9**	**46.1**	**53.3**	**45.0**	**58.3**	**66.0**	**64.9**
Ships & Boats[d]	23.7	30.5	34.9	12.6	30.5	26.2	30.4	38.6	17.8
Ships (Bunkers)[d]	56.4	41.2	35.0	33.6	22.8	18.8	27.9	27.4	47.2
Natural Gas	**36.1**	**38.4**	**35.7**	**34.1**	**37.2**	**33.4**	**32.0**	**33.2**	**33.2**
Passenger Cars	+	0.1	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+
Buses	+	0.1	0.4	0.5	0.6	0.7	0.8	0.8	0.8
Pipeline	36.1	38.2	35.2	33.6	36.6	32.7	31.2	32.3	32.4
LPG	**1.4**	**1.1**	**0.7**	**0.8**	**0.8**	**1.0**	**1.1**	**1.1**	**1.1**
Light-Duty Trucks	0.5	0.5	0.3	0.3	0.3	0.4	0.4	0.4	0.4
Medium- and Heavy-Duty Trucks[b]	0.8	0.5	0.4	0.5	0.5	0.6	0.7	0.6	0.6
Buses	+	+	+	+	+	+	+	+	+
Electricity	**3.0**	**3.0**	**3.4**	**3.6**	**3.4**	**4.2**	**4.5**	**4.7**	**4.9**
Rail	3.0	3.0	3.4	3.6	3.4	4.2	4.5	4.7	4.9
Total (Including Bunkers)[e]	**1,590.2**	**1,693.9**	**1,896.4**	**1,871.5**	**1,916.3**	**1,909.4**	**1,972.8**	**1,989.9**	**1,980.7**
Total (Excluding Bunkers)[e]	**1,476.5**	**1,593.3**	**1,795.3**	**1,774.0**	**1,827.2**	**1,825.7**	**1,873.0**	**1,887.8**	**1,855.1**

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/mining equipment; it also does not include emissions associated with electricity consumption by pipelines or lubricants used in transportation.

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

[c] 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.

Industrial End-Use Sector

The industrial end-use sector accounted for 28 percent of CO_2 emissions from fossil fuel combustion. On average, 55 percent of these emissions resulted from the direct consumption of fossil fuels for steam and process heat production. The remaining 45 percent was associated with their consumption of electricity for uses such as motors, electric furnaces, ovens, and lighting.

The industrial end-use sector, per the underlying energy consumption data from EIA, includes activities such as manufacturing, construction, mining, and agriculture. The largest of these activities in terms of energy consumption is manufacturing, of which six industries—Petroleum Refineries, Chemicals, Primary Metals, Paper, Food, and Nonmetallic Mineral Products—represent the vast majority of the energy use (EIA 2007a and EIA 2005).

In theory, emissions from the industrial end-use sector should be highly correlated with economic growth and industrial output, but heating of industrial buildings and agricultural energy consumption are also affected by weather conditions.[10] 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 2005 to 2006, total industrial production and manufacturing output increased by 3.9 and 4.9 percent, respectively (FRB 2006). Over this period, output increased for Petroleum Refineries, Chemicals, Primary Metals, Food, and Nonmetallic Mineral Products, but decreased slightly for Paper (see Figure 3-12).

Figure 3-12: Industrial Production Indices (Index 2002=100)

Despite the growth in industrial output (62 percent) and the overall U.S. economy (59 percent) from 1990 to 2006, CO_2 emissions from the industrial end-use sector increased by only 3.0 percent over that time. 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 2006, CO_2 emissions from fossil fuel combustion and electricity use within the industrial end-use sectors were 1,571.0 Tg CO_2 Eq., or 0.8 percent below 2005 emissions.

Residential and Commercial End-Use Sectors

The residential and commercial end-use sectors accounted for an average 20 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 72 and 79 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 cooking needs. Coal consumption was a minor component of energy use in both of these end-use sectors. In 2006, CO_2 emissions from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 1,154.1 Tg CO_2 Eq. and 1,004.3 Tg CO_2 Eq., respectively.

[10] 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.

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 72 and 73 percent of the direct (not including electricity) fossil fuel emissions from the residential and commercial sectors, respectively. In 2006, natural gas emissions decreased by 10 percent and 6 percent, respectively, in each of these sectors. The decrease in emissions in both sectors is a result of warmer conditions in the United States.

Electricity sales to the residential and commercial end-use sectors in 2006 decreased less than 1 percent in the residential sector and increased by 2 percent in the commercial sector. The trend in the commercial sector can largely be attributed to the growing economy (2.9 percent), which led to increased demand for electricity. Increased consumption due to the growing economy was somewhat offset by decreased air conditioning-related electricity consumption in the residential sector with the cooler summer compared to 2005, and increases in electricity prices. Electricity-related emissions in both the residential and commercial sectors decreased due to decreased consumption; total emissions from the residential sector decreased by 8.9 percent in 2006, with emissions from the commercial sector 5.3 percent lower than in 2005.

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 2006. 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 3-13).

Figure 3-13: Electricity Generation Retail Sales by End-Use Sector

The electric power industry includes all power producers, consisting of both regulated utilities and nonutilities (e.g. independent power producers, qualifying cogenerators, and other small power producers). For the underlying energy data used in this chapter, the Energy Information Administration (EIA) 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 of electricity,[11] while the other sectors consist of those producers that indicate their primary business is other than the production of electricity.

In 2006, the amount of electricity generated (in kWh) increased by 0.1 percent. This growth is due to the growing economy, expanding industrial production, and warmer summer conditions. However, CO_2 emissions decreased by 2.2 percent, as a smaller share of electricity was generated by coal and a greater share generated by natural gas. Coal and natural gas consumption for electricity generation decreased by 1.3 percent and increased by 6.4 percent, respectively, in 2006, and nuclear power increased by less than 1 percent. As a result of the decrease in coal consumption, C intensity from direct fossil fuel combustion decreased slightly overall in 2006 (see Table 3-8). Coal is consumed primarily by the electric power sector in the United States, which accounted for 94 percent of total coal

[11] 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).

consumption for energy purposes in 2006. The amount of electricity generated from renewables increased by 8.1 percent in 2006.

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 published supplemental tables on petroleum product detail (EIA 2007b). The United States does not include territories in its national energy statistics, so fuel consumption data for territories were collected separately from Grillot (2007).[12]

   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.[13]

   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).[14]

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 AISI (1995 through 2007), Gambogi (2007), Coffeyville Resources Nitrogen Fertilizers, LLC (2007), Corathers (2007), U.S. Census Bureau (2007), EIA (2007h), EIA (2001), Smith, G. (2007), USGS (1998 through 2002), USGS (1995), USGS (1991a through 2006a), USGS (1991b through 2006b), USGS (1991 through 2005), and USGS (1995 through 2006).[15]

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

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[12] 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 55 Tg CO_2 Eq. in 2006.

[13] 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.

[14] 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.

[15] 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.

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 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.[16] 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 (2007b) and data for synthetic natural gas were collected from EIA (2007e), and data for CO_2 exports were collected from the Dakota Gasification Company (2006), Fitzpatrick (2002), Erickson (2003), EIA (2006), and EIA (2007e).

4. *Adjust Sectoral Allocation of Distillate Fuel Oil and Motor Gasoline*. EPA had conducted a separate bottom-up analysis of transportation fuel consumption based on FHWA Vehicle Miles Traveled (VMT) that indicated that the amount of distillate and motor gasoline consumption allocated to the transportation sector in the EIA statistics should be adjusted. Therefore, for these estimates, the transportation sector's distillate fuel and motor gasoline consumption was adjusted 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. Similarly, as the total motor gasoline consumption estimate is considered to be accurate at the national level, the motor gasoline consumption totals for commercial and industrial sectors were adjusted downward proportionately. The data sources used in the bottom-up analysis of transportation fuel consumption include AAR (2007), Benson (2002 through 2004), DOE (1993 through 2005), EIA (2007a), 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 (2007b).

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).[17] 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 2007) supplied data on military jet fuel and marine fuel use. Commercial jet fuel use was obtained from BEA (1991 through 2007) and DOT (1991 through 2007); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2007). 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 2006* (EIA 2007c) and EIA's *Monthly Energy Review* and published supplemental tables on petroleum product detail EIA (EIA 2007b). They are presented in Annexes 2.1 and 2.2.

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

[17] 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 2005).

   - For non-highway vehicles, activity data were obtained from AAR (2007), APTA (2007 and 2006), BEA (1991 through 2007), Benson (2002 through 2004), DOE (1993 through 2005), DESC (2007), DOC (1991 through 2007), DOT (1991 through 2007), EIA (2007a), EIA (2007d), EIA (2007g), EIA (2002), EIA (1991 through 2005), EPA (2004), FAA (2005), and Gaffney (2007).

   - For jet fuel used by aircraft, CO_2 emissions were calculated directly based on reported consumption of fuel as reported by EIA, and allocated to commercial aircraft using flight-specific fuel consumption data from the Federal Aviation Administration's (FAA) System for assessing Aviation's Global Emission (SAGE) model.[18] 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 (2007a) and USAF (1998).[19]

[BEGIN BOX]

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

Fossil fuels are the dominant source of energy in the United States, and CO_2 is 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.[20]

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

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[18] 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/>.

[19] 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.

[20] 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.

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.[21] 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.[22] 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.

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**	**2006**
Residential [a]	57.5		56.8		56.8	57.0	56.6	56.8	57.0	56.7	56.8
Commercial [a]	59.3		57.9		57.2	57.4	57.0	57.3	57.6	57.6	57.5
Industrial [a]	63.8		62.7		62.7	63.5	62.8	63.2	63.6	64.0	64.3
Transportation [a]	71.0		71.0		71.0	71.0	71.0	71.0	71.1	71.1	71.1
Electricity Generation [b]	86.7		86.0		85.6	85.2	85.0	85.7	85.4	85.0	84.6
U.S. Territories [c]	74.1		74.1		73.2	73.6	73.7	74.0	74.6	74.6	74.6
All Sectors [c]	**72.7**		**72.2**		**72.7**	**72.7**	**72.5**	**72.8**	**72.9**	**73.1**	**73.0**

[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.[23] 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

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

[22] 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.

[23] 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.

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	2006
Transportation [a]	70.8	70.6	70.6	70.5	70.5	70.4	70.3	70.2	70.0
Other End-Use Sectors [a, b]	57.5	56.4	57.8	58.4	57.6	58.1	58.0	58.2	57.5
Electricity Generation [c]	59.0	57.9	59.9	60.2	59.2	59.8	59.6	59.9	58.8
All Sectors [d]	**61.1**	**60.3**	**61.4**	**61.8**	**61.3**	**61.5**	**61.5**	**61.7**	**61.1**

[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 sixteen-year period of 1990 through 2006, 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 3-14). Due to a general shift from a manufacturing-based economy to a service-based economy, as well as overall increases in efficiency, energy consumption and energy-related CO_2 emissions per dollar of gross domestic product (GDP) have both declined since 1990 (BEA 2007).

Figure 3-14: U.S. Energy Consumption and Energy-Related CO2 Emissions Per Capita and Per Dollar GDP

C intensity estimates were developed using nuclear and renewable energy data from EIA (2007a) and fossil fuel consumption data as discussed above and presented in Annex 2.1.

[END BOX]

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 2006. 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 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.[24] 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.[25]

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

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[24] 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.

[25] 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.

[26] 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.

Carlo Sampling.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-10. Fossil fuel combustion CO_2 emissions in 2006 were estimated to be between 5,544.3 and 5,946.2 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 2 percent below to 5 percent above the 2006 emission estimate of 5,639.4 Tg CO_2 Eq.

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	2006 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]	**2,065.3**	**1,996.8**	**2,262.1**	**-3%**	**+10%**
Residential	0.6	0.5	0.7	-6%	+15%
Commercial	6.2	5.9	7.1	-5%	+15%
Industrial	122.0	117.3	142.4	-4%	+17%
Transportation	NE	NE	NE	NA	NA
Electricity Generation	1,932.4	1,856.4	2,119.9	-4%	+10%
U.S. Territories	4.1	3.6	4.9	-12%	+19%
Natural Gas [b]	**1,155.1**	**1,164.8**	**1,231.2**	**+1%**	**+7%**
Residential	237.5	230.8	254.2	-3%	+7%
Commercial	154.1	149.7	164.9	-3%	+7%
Industrial	389.3	399.5	440.0	+3%	+13%
Transportation	33.2	32.3	35.5	-3%	+7%
Electricity Generation	339.6	329.6	356.9	-3%	+5%
U.S. Territories	1.4	1.2	1.6	-12%	+17%
Petroleum [b]	**2,418.6**	**2,284.3**	**2,556.2**	**-6%**	**+6%**
Residential	90.7	85.9	95.1	-5%	+5%
Commercial	51.1	48.7	53.1	-5%	+4%
Industrial	354.8	308.6	411.7	-13%	+16%
Transportation	1,816.9	1,695.0	1933.7	-7%	+6%
Electric Utilities	55.7	53.3	59.7	-4%	+7%
U.S. Territories	49.4	45.6	54.9	-8%	+11%
Total (excluding Geothermal) [b]	**5,639.0**	**5,543.9**	**5,945.8**	**-2%**	**+5%**
Geothermal	**0.4**	**NE**	**NE**	**NE**	**NE**
Total (including Geothermal) [b,c]	**5,639.4**	**5,544.3**	**5,946.2**	**-2%**	**+5%**

NA (Not Applicable)
NE (Not Estimated)
[a] Range of emission estimates predicted by Monte Carlo 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.

QA/QC and Verification

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

Recalculations Discussion

The Energy Information Administration (EIA 2007b) updated energy consumption data for all years. These revisions primarily impacted the emission estimates for 2005. Overall, these changes resulted in an average annual increase of 0.8 Tg CO_2 Eq. (less than 0.1 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2005.

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.

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 62 percent of the total C consumed for non-energy purposes was stored in products, and not released to the atmosphere; the remaining 38 percent was emitted.

There are several areas in which non-energy uses of fossil fuels are closely related to other parts of the inventory. For example, some of the NEU products release CO_2 at the end of their commercial life when they are combusted after disposal; these emissions are reported separately within the Energy chapter in the 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 2006 from the non-energy uses of fossil fuels were 138.0 Tg CO_2 Eq., which constituted approximately 2 percent of overall fossil fuel emissions, approximately the same proportion as in 1990. In 2006, the consumption of fuels for non-energy uses (after the adjustments described above) was 5,417.8 TBtu, an increase of 21 percent since 1990 (see Table 3-12). About 65.4 Tg of the C (239.6 Tg CO_2 Eq.) in these fuels was stored, while the remaining 37.6 Tg C (138.0 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).

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

Year	**1990**		**1995**		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Potential Emissions	312.6		346.8		385.5	364.8	368.4	356.3	394.9	382.2	377.6
C Stored	195.5		213.5		244.1	232.9	232.6	224.5	246.0	243.1	239.6
Emissions as a % of Potential	37%		38%		37%	36%	37%	37%	38%	36%	37%
Emissions	**117.2**		**133.2**		**141.4**	**131.9**	**135.9**	**131.8**	**148.9**	**139.1**	**138.0**

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 (2007) (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.[27] 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 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.

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

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
Industry	**4,221.2**	**4,771.8**	**5,261.1**	**5,044.4**	**5,032.4**	**4,865.3**	**5,308.4**	**5,210.0**	**5,160.5**
Industrial Coking Coal	0.0	43.9	62.8	25.6	46.5	72.1	214.7	109.7	85.9
Industrial Other Coal	8.2	11.3	12.4	11.3	12.0	11.9	11.9	11.9	12.4
Natural Gas to Chemical Plants, Other Uses	276.0	330.4	421.1	407.8	364.6	352.0	360.2	390.3	403.2
Asphalt & Road Oil	1,170.2	1,178.2	1,275.7	1,256.9	1,239.9	1,219.5	1,303.8	1,323.2	1,225.6
LPG	1,119.0	1,484.7	1,604.6	1,539.0	1,565.4	1,437.8	1,436.7	1,442.0	1,491.8
Lubricants	186.3	177.8	189.9	174.0	171.9	159.0	161.0	160.2	130.6
Pentanes Plus	77.3	285.3	228.7	199.8	166.1	158.3	156.5	146.0	105.1
Naphtha (<401 ° F)	325.7	350.6	592.8	489.4	564.2	573.4	687.9	678.6	592.9
Other Oil (>401 ° F)	677.2	612.7	554.3	525.9	456.2	501.0	547.8	518.7	573.4
Still Gas	21.3	40.1	12.6	35.8	57.8	59.0	63.5	67.7	122.3
Petroleum Coke	81.0	44.1	47.8	128.1	110.2	76.9	161.3	145.0	178.7
Special Naphtha	100.9	66.9	94.4	77.9	99.5	75.7	47.2	60.9	68.7
Distillate Fuel Oil	7.0	8.0	11.7	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	25.2
Miscellaneous Products	137.8	97.1	119.2	124.9	134.2	126.0	113.4	112.8	133.2
Transportation	**176.0**	**167.9**	**179.4**	**164.3**	**162.4**	**150.1**	**152.1**	**151.3**	**147.0**
Lubricants	176.0	167.9	179.4	164.3	162.4	150.1	152.1	151.3	147.0
U.S. Territories	**86.7**	**90.8**	**165.5**	**80.3**	**138.6**	**127.9**	**110.8**	**107.6**	**110.3**

[27] 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.

Lubricants	0.7	2.0	16.4	+	1.5	9.3	5.1	5.2	5.4
Other Petroleum (Misc. Prod.)	86.0	88.8	149.1	80.3	137.2	118.6	105.7	102.4	104.9
Total	**4,483.9**	**5,030.6**	**5,605.9**	**5,289.0**	**5,333.4**	**5,143.4**	**5,571.3**	**5,468.9**	**5,417.8**

+ Does not exceed 0.05 TBtu
Note: To avoid double-counting, coal coke, petroleum coke, natural gas consumption, and other oils are adjusted for industrial process consumption reported in the Industrial Processes sector. Natural gas, LPG, Pentanes Plus, Naphthas, Special Naphtha, and Other Oils are adjusted to account for exports of chemical intermediates derived from these fuels. For residual oil (not shown in the table), all non-energy use is assumed to be consumed in C black production, which is also reported in the Industrial Processes chapter.
Note: Totals may not sum due to independent rounding.

Table 3-13: 2006 Adjusted Non-Energy Use Fossil Fuel Consumption, Storage, and Emissions

Sector/Fuel Type	Adjusted Non-Energy Use[a] (TBtu)	Carbon Content Coefficient (Tg C/QBtu)	Potential Carbon (Tg C)	Storage Factor	Carbon Stored (Tg C)	Carbon Emissions (Tg C)	Carbon Emissions (Tg CO_2 Eq.)
Industry	**5,160.5**	**-**	**97.8**	**-**	**64.9**	**32.9**	**120.8**
Industrial Coking Coal	85.9	31.00	2.7	0.10	0.3	2.4	8.8
Industrial Other Coal	12.4	25.63	0.3	0.62	0.2	0.1	0.4
Natural Gas to Chemical Plants	403.2	14.47	5.8	0.62	3.6	2.2	8.2
Asphalt & Road Oil	1,225.6	20.62	25.3	1.00	25.3	0.0	0.0
LPG	1,491.8	16.78	25.0	0.62	15.4	9.6	35.3
Lubricants	130.6	20.24	2.6	0.09	0.2	2.4	8.8
Pentanes Plus	105.1	18.24	1.9	0.62	1.2	0.7	2.7
Naphtha (<401° F)	592.9	18.14	10.8	0.62	6.6	4.1	15.2
Other Oil (>401° F)	573.4	19.95	11.4	0.62	7.0	4.4	16.1
Still Gas	122.3	17.51	2.1	0.62	1.3	0.8	3.0
Petroleum Coke	178.7	27.85	5.0	0.50	2.5	2.5	9.1
Special Naphtha	68.7	19.86	1.4	0.62	0.8	0.5	1.9
Distillate Fuel Oil	11.7	19.95	0.2	0.50	0.1	0.1	0.4
Waxes	25.2	19.81	0.5	0.58	0.3	0.2	0.8
Miscellaneous Products	133.2	20.33	2.7	0.00	0.0	2.7	9.9
Transportation	**147.0**	**-**	**3.0**	**-**	**0.3**	**2.7**	**9.9**
Lubricants	147.0	20.24	3.0	0.09	0.3	2.7	9.9
U.S. Territories	**110.3**	**-**	**2.2**	**-**	**0.2**	**2.0**	**7.3**
Lubricants	5.4	20.24	0.1	0.09	0.0	0.1	0.4
Other Petroleum (Misc. Prod.)	104.9	20.00	2.1	0.10	0.2	1.89	6.9
Total	**5,417.8**		**103.0**		**65.4**	**37.6**	**138.0**

+ Does not exceed 0.05 TBtu
- Not applicable.
[a] To avoid double counting, exports have been deducted.
Note: Totals may not sum due to independent rounding.

Lastly, emissions were estimated by subtracting the C stored from the potential emissions (see Table 3-11). 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 and Emissions Trends Report* (EPA 2006a), *Toxics Release Inventory, 1998*

(2000a), *Biennial Reporting System* (EPA 2004a, 2006b, 2007), 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, 2007); 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 through 2007); the *Material Safety Data Sheets* (Miller 1999); the Chemical Manufacturer's Association (CMA 1999); and the American Chemistry Council (ACC 2005 through 2007) 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 2006 was estimated to be between 110.2 and 150.3 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 20 percent below to 9 percent above the 2006 emission estimate of 138.0 Tg CO_2 Eq. The uncertainty in the emission estimates is a function of uncertainty in both the quantity of fuel used for non-energy purposes and the storage factor.

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

Source	Gas	2006 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	83.0	66.4	99.5	-20%	+20%
Asphalt	CO_2	0.0	0.1	0.7	NA	NA
Lubricants	CO_2	19.1	15.7	22.1	-17%	+16%
Waxes	CO_2	0.8	0.6	1.2	-23%	+59%
Other	CO_2	35.2	16.5	38.3	-53%	+9%
Total	**CO_2**	**138.0**	**110.2**	**150.3**	**-20%**	**+9%**

[a] Range of emission estimates predicted by Monte Carlo 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	2006 Storage Factor (%)	Uncertainty Range Relative to Emission Estimate[a] (%)		(%, Relative)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	62%	59%	64%	-4%	+3%
Asphalt	CO_2	100%	99%	100%	-1%	+0%
Lubricants	CO_2	9%	4%	18%	-58%	+89%
Waxes	CO_2	58%	44%	69%	-24%	+19%
Other	CO_2	24%	20%	64%	-17%	+162%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval, as a percentage of the inventory value (also expressed in percent terms).

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 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 and for imports and exports. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology for estimating the fate of C (in terms of storage and emissions) across the various end-uses of fossil C. Emission and storage totals for the different subcategories were compared, and trends across the time series were analyzed to determine whether any corrective actions were needed. Corrective actions were taken to rectify minor errors and to improve the transparency of the calculations, facilitating future QA/QC.

For petrochemical import and export data, special attention was paid to NAICS numbers and titles to verify that none had changed or been removed. Import and export totals were compared for 2006 as well as their trends across the time series.

Planned Improvements

There are several improvements planned for the future:

- Future updates in line with the 2006 IPCC Guidelines. These changes could 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.[28] 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 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. CH_4 emissions from stationary combustion are primarily a function of the CH_4 content of the fuel and combustion efficiency.

Emissions of CH_4 decreased 16 percent overall since 1990 to 6.2 Tg CO_2 Eq. (297 Gg) in 2006. This decrease in CH_4 emissions was primarily due to lower wood consumption in the residential sector. Conversely, N_2O emissions rose 13 percent since 1990 to 14.5 Tg CO_2 Eq. (47 Gg) in 2006. The largest source of N_2O emissions was coal combustion by electricity generators, which alone accounted for 66 percent of total N_2O emissions from stationary combustion in 2006. Overall, however, stationary combustion is a small source of CH_4 and N_2O in the United States.

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

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006
Electric Power	**0.6**	**0.6**	**0.7**	**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	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	0.1
Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Industrial	**1.5**	**1.6**	**1.6**	**1.5**	**1.4**	**1.4**	**1.5**	**1.5**	**1.5**
Coal	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Fuel Oil	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Natural gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1
Wood	0.9	1.0	1.0	0.9	0.8	0.8	0.9	0.9	0.9
Commercial/Institutional	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.8**
Coal	+	+	+	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1
Natural gas	0.3	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	0.4
Residential	**4.4**	**4.0**	**3.4**	**3.1**	**3.1**	**3.3**	**3.3**	**3.3**	**3.1**
Coal	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+

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

Fuel Oil	0.3	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	0.4
Wood	3.5	3.1	2.5	2.2	2.3	2.4	2.5	2.5	2.3
U.S. Territories	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+	+	+
Fuel Oil	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	+	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+	+
Total	**7.4**	**7.2**	**6.7**	**6.2**	**6.2**	**6.4**	**6.6**	**6.5**	**6.2**

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

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

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006
Electric Power	**8.1**	**8.6**	**10.0**	**9.7**	**9.7**	**10.0**	**10.0**	**10.3**	**10.1**
Coal	7.6	8.1	9.4	9.1	9.2	9.4	9.5	9.7	9.5
Fuel Oil	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.1
Natural Gas	0.1	0.1	0.2	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	0.2
Industrial	**3.2**	**3.4**	**3.3**	**3.1**	**3.0**	**3.0**	**3.1**	**3.1**	**3.2**
Coal	0.8	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6
Fuel Oil	0.5	0.5	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	0.2
Wood	1.7	1.9	1.9	1.7	1.6	1.6	1.7	1.7	1.7
Commercial/Institutional	**0.4**	**0.4**	**0.3**	**0.3**	**0.3**	**0.4**	**0.4**	**0.3**	**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	0.1
Natural Gas	0.1	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	0.1
Residential	**1.1**	**1.0**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.8**
Coal	+	+	+	+	+	+	+	+	+
Fuel Oil	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.2
Natural Gas	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.1
Wood	0.7	0.6	0.5	0.4	0.4	0.5	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**	**0.1**
Coal	+	+	+	+	+	+	+	+	+
Fuel Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	+	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+	+
Total	**12.8**	**13.4**	**14.6**	**14.1**	**14.0**	**14.4**	**14.6**	**14.8**	**14.5**

+ 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	2006
Electric Power	**27**	**27**	**33**	**32**	**32**	**34**	**34**	**35**	**34**
Coal	16	18	20	20	20	20	20	21	21
Fuel Oil	4	2	3	4	3	4	4	4	2
Natural Gas	3	4	5	5	5	5	5	6	6
Wood	4	4	4	4	4	5	5	5	5
Industrial	**74**	**78**	**77**	**71**	**69**	**68**	**72**	**71**	**72**
Coal	16	15	14	14	13	13	14	13	13
Fuel Oil	9	7	7	8	8	8	9	9	10

Natural Gas	7	8	8	8	8	8	7	7	7
Wood	41	47	47	41	40	39	42	41	42
Commercial/Institutional	**41**	**44**	**43**	**42**	**42**	**44**	**43**	**42**	**40**
Coal	1	1	1	1	1	1	1	1	1
Fuel Oil	9	7	7	7	6	7	7	7	7
Natural Gas	13	15	15	15	15	16	15	15	14
Wood	19	21	20	19	20	20	20	20	18
Residential	**210**	**190**	**162**	**147**	**149**	**158**	**160**	**157**	**147**
Coal	9	5	3	3	4	4	4	3	2
Fuel Oil	14	13	15	15	14	15	15	14	13
Natural Gas	21	24	24	23	24	25	24	24	21
Wood	165	148	120	105	108	114	117	117	111
U.S. Territories	**2**	**2**	**2**	**3**	**3**	**3**	**3**	**3**	**3**
Coal	+	+	+	+	+	+	+	+	+
Fuel Oil	2	2	2	3	3	3	3	3	3
Natural Gas	+	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+	+
Total	**354**	**342**	**317**	**295**	**295**	**307**	**312**	**309**	**297**

+ 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	2006
Electric Power	**26**	**28**	**32**	**31**	**31**	**32**	**32**	**33**	**32**
Coal	24	26	30	29	30	30	31	31	31
Fuel Oil	1	+	1	1	1	1	1	1	+
Natural Gas	+	+	1	1	1	+	1	1	1
Wood	+	+	1	+	1	1	1	1	1
Industrial	**10**	**11**	**11**	**10**	**10**	**10**	**10**	**10**	**10**
Coal	2	2	2	2	2	2	2	2	2
Fuel Oil	2	1	1	2	2	2	2	2	2
Natural Gas	1	1	1	1	1	1	1	1	1
Wood	5	6	6	5	5	5	6	6	6
Commercial/Institutional	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Coal	+	+	+	+	+	+	+	+	+
Fuel Oil	1	+	+	+	+	+	+	+	+
Natural Gas	+	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+	+
Residential	**4**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Coal	+	+	+	+	+	+	+	+	+
Fuel Oil	1	1	1	1	1	1	1	1	1
Natural Gas	+	+	+	+	+	+	+	+	+
Wood	2	2	2	1	1	2	2	2	1
U.S. Territories	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Coal	+	+	+	+	+	+	+	+	+
Fuel Oil	+	+	+	+	+	+	+	+	+
Natural Gas	+	+	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+	+	+
Total	**41**	**43**	**47**	**46**	**45**	**46**	**47**	**48**	**47**

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

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, electricity generation, and U.S. territories. For the CH_4 and N_2O estimates, fuel consumption data for coal, natural gas, fuel oil for the United States were obtained from EIA's *Monthly Energy Review* and unpublished supplemental tables on petroleum product detail (EIA 2007a). Wood consumption data for the United States was obtained from EIA's *Annual Energy Review* (EIA 2007b). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were provided separately by Grillot (2007).[29] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[30] 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 *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). U.S. territories' emission factors were estimated using the U.S. emission factors for the primary sector in which each fuel was combusted.

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.

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.[31] For these variables, the uncertainty

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[29] 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.

[30] 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.

[31] 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.

ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[32] 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 2006 (*including* biomass) were estimated to be between 4.3 and 13.4 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 31 percent below to 116 percent above the 2006 emission estimate of 6.2 Tg CO_2 Eq.[33] Stationary combustion N_2O emissions in 2006 (*including* biomass) were estimated to be between 7.0 and 37.2 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 47 percent below to 180 percent above the 2006 emissions estimate of 13.3 Tg CO_2 Eq.

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

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Stationary Combustion	CH_4	6.2	4.3	13.4	-31%	+116%
Stationary Combustion	N_2O	14.5	11.0	42.2	-24%	+190%

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

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

QA/QC and Verification

A source-specific QA/QC plan for stationary combustion was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CH_4, N_2O, and the indirect greenhouse gases from stationary combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated.

Recalculations Discussion

Historical CH_4 and N_2O emissions from stationary sources (excluding CO_2) were revised due to several changes. One of the most significant changes was implementing stationary combustion emission factors updated in IPCC (2006). As a result, N_2O emission factors for coal consumption in all sectors, and CH_4 emission factors for industrial petroleum and natural gas were revised. Slight changes to emission estimates for sectors are also due to revised data from EIA (2007a). This revision is explained in greater detail in the section on CO_2 Emissions from

[32] 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.

[33] 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.

Fossil Fuel Combustion within this sector. Wood consumption data from EIA (2007b) were revised for the residential, industrial, and electric power sectors. The combination of the methodological and historical data changes resulted in an average annual decrease of 0.6 Tg CO_2 Eq. (8.3 percent) in CH_4 emissions from stationary combustion and an average annual increase of 0.6 Tg CO_2 Eq. (4.9 percent) in N_2O emissions from stationary combustion for the period 1990 through 2005.

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, as well as indirect greenhouse gases including NO_x, CO, and NMVOCs. Mobile combustion includes sources identified in the U.S. inventory as transportation with the exception of pipelines; mobile sources also include non-transportation activities such as construction and mining equipment and agricultural equipment. Annex 3.2 includes a summary of all emissions from both transportation and mobile sources.

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. CO emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. These emissions occur especially in idle, low speed, and cold start conditions. 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).

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.[34]

Mobile combustion was responsible for a small portion of national CH_4 emissions (0.4 percent) but was the second largest source of U.S. N_2O emissions (7 percent). From 1990 to 2006, mobile source CH_4 emissions declined by 50 percent, to 2.4 Tg CO_2 Eq. (112 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 24 percent, to 33.1 Tg CO_2 Eq (107 Gg). Earlier generation control technologies initially resulted in higher N_2O emissions, causing a 26 percent increase in N_2O emissions from mobile sources between 1990 and 1998. Improvements in later-generation emission control technologies have reduced N_2O output, resulting in a 40 percent decrease in mobile source N_2O emissions from 1998 to 2006 (see Figure 3-15). Overall, CH_4 and N_2O emissions were predominantly from gasoline-fueled passenger cars and light-duty trucks.

Figure 3-15: Mobile Source CH_4 and N_2O Emissions

[34] See Annex 3.2 for a complete time series of emission estimates for 1990 through 2006.

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	2006
Gasoline Highway	**4.2**	**3.8**	**2.8**	**2.7**	**2.4**	**2.2**	**2.0**	**1.9**	**1.7**
Passenger Cars	2.6	2.1	1.6	1.5	1.4	1.3	1.2	1.1	1.0
Light-Duty Trucks	1.4	1.4	1.1	1.1	0.9	0.8	0.7	0.7	0.7
Medium- and Heavy-Duty Trucks and Buses	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Motorcycles	+	+	+	+		+	+	+	+
Diesel Highway	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Passenger Cars	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks and Buses	+	+	+	+	+	+	+	+	+
Alternative Fuel Highway	**+**	**+**	**+**	**+**	**+**	**+**	**0.1**	**0.1**	**0.1**
Non-Highway	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**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	0.1
Rail	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Agricultural Equipment	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Construction/Mining Equipment	+	0.1	0.1	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	0.1
Other[b]	+	+	+	+	0.1	0.1	0.1	0.1	0.1
Total	**4.7**	**4.3**	**3.4**	**3.3**	**3.0**	**2.8**	**2.7**	**2.5**	**2.4**

+ 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.

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	2006
Gasoline Highway	**40.1**	**49.8**	**48.4**	**45.9**	**41.8**	**38.4**	**35.6**	**32.1**	**29.0**
Passenger Cars	25.4	26.9	25.2	23.8	22.5	21.0	19.5	17.7	15.6
Light-Duty Trucks	14.1	22.1	22.4	21.2	18.5	16.5	15.3	13.6	12.6
Medium- and Heavy-Duty Trucks and Buses	0.6	0.7	0.9	0.9	0.9	0.9	0.8	0.8	0.7
Motorcycles	+	+	+	+	+	+	+	+	+
Diesel Highway	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Passenger Cars	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks and Buses	0.2	0.2	0.3	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**	**0.2**	**0.2**	**0.2**	**0.2**
Non-Highway	**3.2**	**3.3**	**3.7**	**3.6**	**3.6**	**3.6**	**3.7**	**3.8**	**3.6**
Ships and Boats	0.4	0.4	0.5	0.3	0.5	0.4	0.5	0.5	0.4
Rail	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4
Agricultural Equipment	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4
Construction/Mining Equipment	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5
Aircraft	1.7	1.7	1.9	1.8	1.7	1.7	1.7	1.7	1.6
Other*	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4
Total	**43.5**	**53.4**	**52.5**	**49.9**	**45.9**	**42.5**	**39.8**	**36.5**	**33.1**

+ 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	2006
Gasoline Highway	**201**	**180**	**134**	**129**	**112**	**103**	**96**	**88**	**82**
Passenger Cars	125	101	77	72	66	61	56	52	47
Light-Duty Trucks	65	69	50	52	41	38	35	32	31
Medium- and Heavy-Duty Trucks and Buses	10	9	5	5	4	4	4	3	3
Motorcycles	1	1	1	1	1	1	1	1	1
Diesel Highway	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Passenger Cars	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks and Buses	1	1	1	1	1	1	1	1	1
Alternative Fuel Highway	**+**	**+**	**1**	**2**	**2**	**2**	**3**	**3**	**3**
Non-Highway	**22**	**24**	**26**	**25**	**26**	**26**	**27**	**28**	**27**
Ships and Boats	3	4	5	3	4	4	5	5	3
Rail	3	3	3	3	3	3	4	4	4
Agricultural Equipment	4	5	5	6	6	6	6	7	7
Construction/Mining Equipment	2	3	3	3	3	3	3	4	4
Aircraft	7	7	7	7	7	6	7	7	7
Other*	2	2	2	2	2	3	3	3	3
Total	**224**	**205**	**162**	**157**	**141**	**132**	**127**	**120**	**112**

+ 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.

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

Fuel Type/Vehicle Type	1990	1995	2000	2001	2002	2003	2004	2005	2006
Gasoline Highway	**129**	**161**	**156**	**148**	**135**	**124**	**115**	**104**	**93**
Passenger Cars	82	87	81	77	72	68	63	57	50
Light-Duty Trucks	45	71	72	69	60	53	49	44	41
Medium- and Heavy-Duty Trucks and Buses	2	2	3	3	3	3	3	2	2
Motorcycles	+	+	+	+	+	+	+	+	+
Diesel Highway	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Passenger Cars	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks and Buses	1	1	1	1	1	1	1	1	1
Alternative Fuel Highway	**+**	**+**	**+**	**+**	**+**	**1**	**1**	**1**	**1**
Non-Highway	**10**	**11**	**12**	**11**	**12**	**12**	**12**	**12**	**12**
Ships and Boats	1	1	2	1	2	1	2	2	1
Rail	1	1	1	1	1	1	1	1	1
Agricultural Equipment	1	1	1	1	1	1	1	1	1
Construction/Mining	1	1	1	1	1	2	2	2	2

Equipment									
Aircraft	6	5	6	6	6	5	6	6	5
Other*	1	1	1	1	1	1	1	1	1
Total	**140**	**172**	**169**	**161**	**148**	**137**	**128**	**118**	**107**

+ 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.

Methodology

Estimates of CH_4 and N_2O emissions from mobile combustion were calculated by multiplying emission factors by measures of activity for each fuel and vehicle type (e.g., light-duty gasoline trucks). Activity data included vehicle miles traveled (VMT) for highway (on-road) vehicles and fuel consumption for non-highway mobile sources. The activity data and emission factors used are described in the subsections that follow. A complete discussion of the methodology used to estimate CH_4 and N_2O emissions from mobile combustion and the emission factors used in the calculations is provided in Annex 3.2.

EPA (2008, 2005, 2003) provides emission estimates of NO_x, CO, and NMVOCs for eight categories of highway vehicles,[35] aircraft, and seven categories of non-highway vehicles[36] 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>.

On-Road 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 emission control technology. Emission estimates from alternative fuel vehicles (AFVs)[37] 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) 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 segments are: (1) a transient driving cycle that includes cold start and running emissions, (2) a cycle that represents running emissions only, and (3) a transient driving cycle that includes hot start and running emissions. For each test run, a bag was affixed to the tailpipe of the vehicle and the exhaust was collected; the content of this bag was then analyzed to determine quantities of gases present. The emissions characteristics of segment 2 were used to define running emissions, and subtracted from the total FTP emissions to determine start emissions. These were then recombined based upon the ratio of start to running emissions for each vehicle class from MOBILE6.2, an EPA emission factor model that predicts gram per mile emissions of CO_2, CO, HC, NOx, and PM from vehicles under

[35] 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.

[36] 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).

[37] 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.

various conditions, to approximate average driving characteristics.[38]

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 2006 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in *Highway Statistics* (FHWA 1996 through 2007). 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 2007) and information on total motor vehicle fuel consumption by fuel type from FHWA (1996 through 2007). VMT for AFVs were taken from Browning (2003). The age distributions of the U.S. vehicle fleet were obtained from EPA (2007c, 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 2007a, 2007b, 2000, 1998, and 1997) and Browning (2005). These technologies and standards are defined in Annex 3.2, and were compiled from EPA (1993, 1994a, 1994b, 1998, 1999a) and IPCC/UNEP/OECD/IEA (1997).

These emission estimates were obtained from preliminary data (EPA 2008), 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-Road Vehicles

To estimate emissions from non-road vehicles, fuel consumption data were employed as a measure of activity, and multiplied by fuel-specific emission factors (in grams of N_2O and CH_4 per kilogram of fuel consumed).[39] Activity data were obtained from AAR (2007), APTA (2007 and 2006), BEA (1991 through 2005), Benson (2002 through 2004), DOE (1993 through 2007), DESC (2007), DOC (1991 through 2007), DOT (1991 through 2007), EIA (2007a, 2007b, 2007d, 2002), EIA (1991 through 2007), EPA (2006b), Esser (2003 through 2004), FAA (2007 and 2006), Gaffney (2007), Lou (2007), and Whorton (2006 through 2007). Emission factors for non-highway modes were taken from IPCC/UNEP/OECD/IEA (1997).

Uncertainty

This section discusses the uncertainty in 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.

Uncertainty analyses were not conducted for NO_x, CO, or NMVOC emissions. Emission factors for these gases have been extensively researched since emissions of these gases from motor vehicles are regulated in the United States, and the uncertainty in these emission estimates is believed to be relatively low. However, a much higher level of uncertainty is associated with CH_4 and N_2O emission factors, because emissions of these gases are not

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

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

regulated in the United States (and, therefore, there are not adequate emission test data), and because, unlike CO_2 emissions, the emission pathways of CH_4 and N_2O are highly complex.

Highway Vehicles

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 2006 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.

Mobile combustion emissions of CH_4 and N_2O per vehicle mile traveled vary significantly due to fuel type and composition, technology type, operating speeds and conditions, type of emission control equipment, equipment age, and operating and maintenance practices.

The primary activity data, VMT, are collected and analyzed each year by government agencies. To determine the uncertainty associated with the activity data used in the calculations of CH_4 and N_2O emissions, the agencies and the experts that supply the data were contacted. Because few of these sources were able to provide quantitative estimates of uncertainty, expert judgment was used to assess the quantitative uncertainty associated with the activity data.

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, because the testing did not yield statistically significant results within the 95 percent confidence interval, expert judgments were adopted 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 2007), and were generated though the cooperation of FHWA and state and local governments. These estimates are subject to several possible sources of error, such as unregistered vehicles, and measurement and estimation errors. These VMT were apportioned by fuel type, based on data from DOE (1993 through 2007), and then allocated to individual model years using temporal profiles of both the vehicle fleet by age and vehicle usage by model year in the United States provided by EPA (2007c) and EPA (2000). While the uncertainty associated with the total national VMT is believed to be low, the uncertainty within individual source categories was considered to be higher due to the uncertainty associated with apportioning total VMT into individual vehicle categories, by fuel type, technology type, and by equipment age. The uncertainty in the individual estimates was assumed to be inversely related to the magnitude of estimated VMT (i.e., it was assumed that smaller sources had greater percentage uncertainty and vice-versa). Another source of uncertainty in the estimates occurs due to differences in FHWA and EPA data sources. For example, FHWA data are used for defining vehicle types and for developing the estimates of VMT by vehicle type, the estimates of VMT by fuel types are calculated using EPA's definition of vehicle categories (which differ from those of the FHWA).

A total of 171 highway data input variables were simulated through Monte Carlo Simulation technique using @RISK software. Variables included VMT and emission factors for individual conventional and alternative fuel vehicle categories and technologies. In developing the uncertainty estimation model, a normal distribution was assumed for all activity-related input variables (e.g., VMT) except in the case of buses, in which a triangular distribution was used. The dependencies and other correlations among the activity data were incorporated into the model to ensure consistency in the model specification and simulation. Emission factors were assigned uniform distributions, with upper and lower bounds assigned to input variables based on 95 percent confidence intervals of laboratory test data. In cases where data did not yield statistically significant results within the 95 percent confidence interval, estimates of upper and lower bounds were determined using expert judgments. For biodiesel vehicles, because no test data were available, consistent with the assumptions underlying the ANL GREET model,

their N_2O and CH_4 emissions were assumed to be same as those for diesel vehicles of similar types. For other alternative fuel vehicles (AFVs), uncertainty estimates were developed based on conventional fuel vehicle emission factors and applicable multipliers, as described in the ICF's AFV emission factors memorandum to EPA (ICF 2006a).

The results of this analysis are reported in the section below, titled *Quantitative Estimates of Uncertainty*.

Non-Highway Vehicles

Emissions from non-highway vehicles account for 24 percent of CH_4 emissions from mobile sources and 11 percent of N_2O emissions from mobile sources in 2006. A quantitative analysis of uncertainty in the inventory estimates of emissions from non-highway vehicles has not been performed. However, sources of uncertainty for non-highway vehicles are being investigated by examining the underlying uncertainty of emission factors and fuel consumption data, and in the future, EPA will consider conducting a quantitative analysis of uncertainty for these sources.

Estimates of fuel consumption for off-highway vehicles (i.e., equipment used for agriculture, construction, lawn and garden, railroad, airport ground support, etc., as well as recreational vehicles) were generated by the EPA's NONROAD model (EPA 2006a). This model estimates fuel consumption based on estimated equipment/vehicle use (in hours) and average fuel consumed per hour of use. Since the fuel estimates are not based upon documented fuel sales or consumption, a fair degree of uncertainty accompanies these estimates.

Estimates of distillate fuel sales for ships and boats were obtained from EIA's *Fuel Oil and Kerosene Sales* (EIA 1991 through 2007). These estimates have a moderate level of uncertainty since EIA's estimates are based on survey data and reflect sales to economic sectors, which may include use by both mobile and non-mobile sources within a sector. Domestic consumption of residual fuel by ships and boats is obtained from EIA (2007b). These estimates fluctuate widely from year to year, and are believed to be highly uncertain. In addition, estimates of distillate and residual fuel sales for ships and boats are adjusted for bunker fuel consumption, which introduces an additional (and much higher) level of uncertainty.

Jet fuel and aviation gasoline consumption data are obtained from EIA (2007a) and FAA (2007). Estimates of jet fuel consumption are also adjusted downward to account for international bunker fuels, introducing a significant amount of uncertainty. Additionally, all jet fuel consumption in the transportation sector is assumed to be consumed by aircraft. Some fuel purchased by airlines is not used in aircraft but instead used to power auxiliary power units, ground equipment, and to test engines. Some jet fuel may also be used for other purposes such as blending with diesel fuel or heating oil.

In calculating CH_4 emissions from aircraft, an average emission factor is applied to total jet fuel consumption. This average emission factor takes into account the fact that CH_4 emissions occur only during the landing and take-off (LTO) cycles, with no CH_4 being emitted during the cruise cycle. However, a better approach would be to apply emission factors based on the number of LTO cycles.

Uncertainty

The results of the Tier 2 quantitative uncertainty analysis for the mobile source CH_4 and N_2O emissions from highway vehicles are summarized in Table 3-25. As noted above, an uncertainty analysis was not performed for CH_4 and N_2O emissions from non-highway vehicles. Mobile combustion CH_4 emissions (from highway vehicles) in 2006 were estimated to be between 1.7 and 1.9 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 6 percent below to 6 percent above the corresponding 2006 emission estimate of 1.8 Tg CO_2 Eq. Also at a 95 percent confidence level, mobile combustion N_2O emissions from highway vehicles in 2006 were estimated to be between 23.8 and 35.2 Tg CO_2 Eq., indicating a range of 19 percent below to 19 percent above the corresponding 2006 emission estimate of 29.5 Tg CO_2 Eq.

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

Source	Gas	2006 Emission Estimate[a] (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a],[b] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mobile Sources	CH_4	1.8	1.7	1.9	-6%	6%
Mobile Sources	N_2O	29.5	23.8	35.2	-19%	19%

[a] 2006 Emission estimates and the uncertainty range presented in this table correspond to Highway vehicles, comprising conventional and alternative fuel vehicles. Because the uncertainty associated with the emissions from non-highway vehicles were not estimated, they were excluded in the estimates reported din this table.
[b] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

This uncertainty analysis is a continuation of a multi-year process for developing quantitative uncertainty estimates for this source category using the IPCC Tier 2 approach to uncertainty analysis. As a result, as new information becomes available, uncertainty characterization of input variables may be improved and revised.

QA/QC and Verification

A source-specific QA/QC plan for mobile combustion was developed and implemented. This plan is based on the IPCC-recommended QA-QC Plan. The specific plan used for mobile combustion was updated prior to collection and analysis of this current year of data. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on the emission factor and activity data sources, as well as the methodology used for estimating emissions. These procedures included a qualitative assessment of the emissions estimates to determine whether they appear consistent with the most recent activity data and emission factors available. A comparison of historical emissions between the current Inventory and the previous Inventory was also conducted to ensure that the changes in estimates were consistent with the changes in activity data and emission factors.

Recalculations Discussion

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 methodologies used in calculating emissions in the current Inventory.

Carbon dioxide emissions from gasoline-powered on-road sources are now calculated directly using "bottom-up" fuel sales data; this methodology is similar to the bottom-up calculation of CO_2 from transportation diesel sources implemented beginning with the 1990-2004 inventory report. On-road gasoline fuel sales estimates come from FHWA's Highway Statistics (FHWA 1996 through 2007). The ethanol component of these fuel sales is subtracted to yield a fossil-only estimate, which is used to calculate CO_2 for gasoline-powered passenger cars, light-duty trucks, medium- and heavy-duty trucks, and buses. To preserve EIA's estimate of total gasoline consumption across all sectors, adjustments were made to estimated gasoline consumption by recreational boats, the commercial sector and the industrial sector. EIA estimates of transportation sector fuel consumption continue to serve as the foundation of inventory estimates for other fuel types (jet fuel, aviation gasoline, residual fuel, natural gas, LPG and natural gas). CO_2 from these fuels continues to be apportioned to individual modes using bottom-up data from BTS, FAA, and DOE's Transportation Energy Data Book.

Vehicle age distributions for 1999 to the present were revised based on new data obtained from EPA's MOVES model (EPA 2007c). Diesel fractions for light trucks and medium- and heavy-duty trucks and buses were updated based on data obtained from the Transportation Energy Data Book (DOE 1993 through 2007) for 1998 through 2003, which increased emissions from diesel vehicles and reduced emissions from gasoline vehicles. Updates were made to alternative fuel vehicle (AFV) vehicle miles traveled (VMT) numbers based on new activity data (ICF 2006a) and biodiesel was also added as a vehicle category under alternative fuel vehicles. VMT and fuel consumption estimates for highway vehicles were also revised for 2005 based on updated data from FHWA's *Highway Statistics* (FHWA 1996 through 2007).

Several changes were also made in the calculation of emissions from non-road vehicles. Similar to the previous

inventory, commercial aircraft energy consumption estimates for 2000-2005 come from the Federal Aviation Administration's (FAA) System for Assessing Aviation's Global Emissions (SAGE) database (FAA 2006). Aviation estimates were developed without the availability of 2006 data from the Federal Aviation Administration's (FAA) System for Assessing Aviation's Global Emissions (SAGE) database. Estimates for 1990-1999 were calculated using fuel consumption estimates from the Bureau of Transportation Statistics (DOT 1991 through 2007) adjusted based on the 2000-2005 data. For 2006, an estimate – similar to the method used for 1990-1999 – was derived using a combination of data from BTS and SAGE data. Class II and III railroad diesel use estimates are now obtained from the American Short Line and Regional Railroad Association, with new data for 2002, 2004, and 2006 (Whorton 2006 through 2007).

As a result of these changes, average estimates of CH_4 and N_2O emissions from mobile combustion were slightly lower relative to the previous inventory—showing a decrease of no more than 0.7 Tg CO_2 Eq. (2.0 percent) each year—for the period 1990 through 2000. Larger decreases in estimates occurred for years 2002 to 2005 when comparing the current inventory estimates with the previous inventory's estimates. The greatest decrease, 1.5 Tg CO_2 Eq. (4 percent), occurs with the 2005 N_2O estimate. Estimates for the year 2001 are the exception, as these estimates increased from the previous Inventory's estimates by 0.07 Tg CO_2 Eq. for CH_4 and 0.15 Tg CO_2 Eq. for N_2O.

Planned Improvements

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

1. Develop new emission factors for non-road sources. The current inventory estimates for non-CO2 emissions from non-road sources are based on emission factors from IPCC guidelines published in 1996. Recent data on non-road sources from Environment Canada and the California Air Resources Board will be investigated in order to assess the feasibility of developing new N_2O and CH_4 emissions factors for non-road equipment.
2. Examine the feasibility of estimating aircraft N_2O and CH_4emissions by the number of takeoffs and landings, instead of total fuel consumption. Various studies have indicated that aircraft N_2O and CH_4 emissions are more dependent on aircraft takeoffs and landings than on total aircraft fuel consumption; however, aircraft emissions are currently estimated from fuel consumption data. FAA's SAGE database contains detailed data on takeoffs and landings for each calendar year starting in 1999, and could potentially be used to conduct a Tier II analysis of aircraft emissions. This methodology will require a detailed analysis of the number of takeoffs and landings by aircraft type on domestic trips and development of procedures to develop comparable estimates for years prior to 1999. The feasibility of this approach will be explored.
3. Develop improved estimates of domestic waterborne fuel consumption. The inventory estimates for residual fuel used by ships and boats is based in part on data on bunker fuel use from the U.S. Department of Commerce. The Department of Homeland Security (DHS) maintains an electronic reporting system that automatically registers monthly sales of bunker fuel at ports, which should provide a more accurate and comprehensive estimate of residual bunker fuel use by reducing the amount of non-reporting. This system has been used to collect data since 2002, and these data could be incorporated into the development of inventory figures. The DHS figures will need to be reconciled with figures from the current sources of data and a methodology will need to be developed to produce updated estimates for prior years.
4. Develop improved estimates of domestic aviation fuel consumption. The inventory calculation of domestic jet fuel consumption is derived by first estimating international aviation bunker fuel consumption and subtracting this value from EIA's estimate of total jet fuel consumption. Aviation bunker fuel estimates involve a number of uncertainties, including the lack of specific data on the amount of total jet fuel consumption to allocate to international bunkers. As mentioned above, FAA's SAGE database contains detailed data of domestic operations of aircraft and associated fuel consumption, and could potentially be used for a direct calculation of commercial aviation fuel consumption similar to the bottom-up approaches currently used for transportation diesel sources and on-road gasoline.
5. 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 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.

6. Continue to examine the use of EPA's MOVES model in the development of the inventory estimates, including use for uncertainty analysis. Although the inventory uses some of the underlying data from MOVES, such as vehicle age distributions by model year, MOVES is not used directly in calculating mobile source emissions. As MOVES goes through additional testing and refinement, the use of MOVES will be further explored.

3.5. 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 120 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, 20 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 2006, 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 mining is released during processing, storage, and transport of the coal.

Total CH_4 emissions in 2006 were estimated to be 58.5 Tg CO_2 Eq. (2,784 Gg), a decline of 30 percent since 1990 (see Table 3-26 and Table 3-27). Of this amount, underground mines accounted for 61 percent, surface mines accounted for 24 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. Since that time, underground coal production and the associated methane emissions have remained fairly level, while surface coal production and its associated emissions have steadily increased.

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

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Underground Mining	62.3	46.7	39.4	38.2	35.5	36.0	38.1	35.2	35.9
Liberated	67.9	59.1	55.0	55.5	54.7	53.0	53.2	52.3	54.6
Recovered & Used	(5.6)	(12.4)	(15.6)	(17.2)	(19.2)	(17.0)	(15.1)	(17.1)	(18.7)
Surface Mining	12.0	11.5	12.3	13.2	12.8	12.4	12.9	13.3	14.0
Post-Mining (Underground)	7.7	6.9	6.7	6.8	6.4	6.4	6.6	6.4	6.3
Post-Mining (Surface)	2.0	1.9	2.0	2.1	2.1	2.0	2.1	2.2	2.3
Total	**84.1**	**67.1**	**60.4**	**60.3**	**56.8**	**56.9**	**59.8**	**57.1**	**58.5**

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	2006
Underground Mining	2,968	2,226	1,875	1,820	1,692	1,715	1,813	1,675	1,709
Liberated	3,234	2,816	2,619	2,641	2,605	2,522	2,534	2,491	2,599
Recovered & Used	(266)	(591)	(744)	(821)	(913)	(807)	(721)	(815)	(891)
Surface Mining	574	548	586	627	610	592	616	633	668
Post-Mining (Underground)	368	330	318	325	305	306	317	306	298

Post-Mining (Surface)	93	89	95	102	99	96	100	103	109
Total	**4,003**	**3,193**	**2,874**	**2,874**	**2,707**	**2,709**	**2,846**	**2,717**	**2,784**

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

Methodology

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

Underground mines. Total CH_4 emitted from underground mines was estimated as the sum of CH_4 liberated from ventilation systems and CH_4 liberated by means of degasification systems, minus CH_4 recovered and used. The Mine Safety and Heath Administration (MSHA) samples CH_4 emissions from ventilation systems for all mines with detectable[40] CH_4 concentrations. These mine-by-mine measurements are used to estimate CH_4 emissions from ventilation systems.

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

Finally, the amount of CH_4 recovered by degasification systems and then used (i.e., not vented) was estimated. In 2006, 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. In the case of Jim Walter Resources (JWR), the emissions avoided data was taken from the 1605b reports that the mining company has been filing with the Department of Energy (DOE) since 1991 as part of their Voluntary Reporting Program.

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 (2005), EPA (1996), and AAPG (1984). This calculation accounts for CH_4 released from the strata surrounding the coal seam. For post-mining emissions, the emission factor was assumed to be 32.5 percent of the average *in situ* CH_4 content of coals mined in the basin.

Table 3-28: Coal Production (Thousand Metric Tons)

Year	Underground	Surface	Total

[40] 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.

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
2006	325,703	728,459	1,054,162

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 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 vary if the drainage area is found to be larger or smaller than currently estimated.

Compared to underground mines, there is considerably more uncertainty associated with surface mining and post-mining emissions because of the difficulty in developing accurate emission factors from field measurements. However, since underground emissions comprise the majority of total coal mining emissions, the uncertainty associated with underground emissions is the primary factor that determines overall uncertainty. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-29. Coal mining CH_4 emissions in 2006 were estimated to be between 53.3 and 76.3 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 9 percent below to 30 percent above the 2006 emission estimate of 58.5 Tg CO_2 Eq.

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

Source	**Gas**	**2006 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Coal Mining	CH_4	58.5	53.3	76.3	-8.9%	+30.3%

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

Recalculations Discussion

In 2006, recalculations of emissions avoided at three JWR coal mines in Alabama were performed as the mining company provided copies of their 1605b reports that they had been filing with DO. These reports cover the years 1991 through 2005. The 2006 report has not yet been filed, however JWR provided the 2006 data. 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. Emission reductions were calculated for pre-drainage wells located inside the mine plan boundaries and were declared "shut-in" by the O&G Board. The total production for a well was claimed in the year that the well was shut-in and mined through.

Secondly, the gas content values assigned to each coal basin in the surface mine emissions component of the inventory were changed to reflect recent work carried out by U.S. EPA (EPA 2005). This change for the 2006 inventory also impacted the reported emissions attributed to surface mining operations (active and post mining) for all past reported years (1990 – 2005), resulting in increased emission estimates for surface and post-surface mining operations for all reported years.

Finally, the conversion factor used previously to convert from mmcf of methane to Gg of CH_4 was 52,150 (1990 – 2005). The conversion factor used in the natural gas emissions inventory is 51,921. In order to ensure consistency of emissions estimates across the inventory, the conversion factor for the active mines inventory was changed to 51,921. This change impacted all previous year's inventories for the values calculated and reported for Gg of methane emitted, and for Tg of CO_2 Eq. emitted. The difference between these factors is 0.44 percent.

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

Underground coal mines contribute the largest share of CH_4 emissions, with active underground mines the leading source of underground emissions. However, mines also continue to release CH_4 after closure. As mines mature and coal seams are mined through, mines are closed and abandoned. Many are sealed and some flood through intrusion of groundwater or surface water into the void. Shafts or portals are generally filled with gravel and capped with a concrete seal, while vent pipes and boreholes are plugged in a manner similar to oil and gas wells. Some abandoned mines are vented to the atmosphere to prevent the buildup of CH_4 that may find its way to surface structures through overburden fractures. As work stops within the mines, the CH_4 liberation decreases but it does not stop completely. Following an initial decline, abandoned mines can liberate CH_4 at a near-steady rate over an extended period of time, or, if flooded, produce gas for only a few years. The gas can migrate to the surface through the conduits described above, particularly if they have not been sealed adequately. In addition, diffuse emissions can occur when CH_4 migrates to the surface through cracks and fissures in the strata overlying the coal mine. The following factors influence abandoned mine emissions:

- Time since abandonment;
- Gas content and adsorption characteristics of coal;
- CH_4 flow capacity of the mine;
- Mine flooding;
- Presence of vent holes; and
- Mine seals.

Gross abandoned mine CH_4 emissions ranged from 6.0 to 9.1 Tg CO_2 Eq. from 1990 through 2006, varying, in general, by less than 1 to approximately 19 percent from year to year. Fluctuations were due mainly to the number of mines closed during a given year as well as the magnitude of the emissions from those mines when active. Gross abandoned mine emissions peaked in 1996 (9.1 Tg CO_2 Eq.) due to the large number of mine closures from 1994 to 1996 (70 gassy mines closed during the three-year period). In spite of this rapid rise, abandoned mine emissions have been generally on the decline since 1996. There were fewer than fifteen gassy mine closures during each of the years from 1998 through 2006, with only one closure in 2006. By 2006, gross abandoned mine emissions declined to 6.8 Tg CO_2 Eq. (see Table 3-30 and Table 3-31). Gross emissions are reduced by methane recovered and used at 20 mines, resulting in net emissions in 2006 of 5.4 Tg CO_2Eq.

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

Activity	**1990**		**1995**		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Abandoned Underground Mines	6.0		8.9		8.9	8.2	7.7	7.5	7.3	7.0	6.8
Recovered & Used	0.0		0.7		1.5	1.5	1.6	1.5	1.5	1.4	1.4
Total	**6.0**		**8.2**		**7.4**	**6.7**	**6.2**	**6.0**	**5.8**	**5.6**	**5.4**

Note: Totals may not sum due to independent rounding.

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

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Abandoned Underground Mines	288	424	422	389	368	356	347	333	322
Recovered & Used	0	32	72	70	75	72	71	68	65
Total	**288**	**392**	**350**	**319**	**293**	**284**	**276**	**265**	**257**

Note: Totals may not sum due to independent rounding.

Methodology

Estimating CH_4 emissions from an abandoned coal mine requires predicting the emissions of a mine from the time of abandonment through the inventory year of interest. The flow of CH_4 from the coal to the mine void is primarily dependent on the mine's emissions when active and the extent to which the mine is flooded or sealed. The CH_4 emission rate before abandonment reflects the gas content of the coal, rate of coal mining, and the flow capacity of the mine in much the same way as the initial rate of a water-free conventional gas well reflects the gas content of the producing formation and the flow capacity of the well. A well or a mine which produces gas from a coal seam and the surrounding strata will produce less gas through time as the reservoir of gas is depleted. Depletion of a reservoir will follow a predictable pattern depending on the interplay of a variety of natural physical conditions imposed on the reservoir. The depletion of a reservoir is commonly modeled by mathematical equations and mapped as a type curve. Type curves which are referred to as decline curves have been developed for abandoned coal mines. Existing data on abandoned mine emissions through time, although sparse, appear to fit the hyperbolic type of decline curve used in forecasting production from natural gas wells.

In order to estimate CH_4 emissions over time for a given mine, it is necessary to apply a decline function, initiated upon abandonment, to that mine. In the analysis, mines were grouped by coal basin with the assumption that they will generally have the same initial pressures, permeability and isotherm. As CH_4 leaves the system, the reservoir pressure, 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 mmcf/d
- q_i = Initial gas rate at time zero (t_o) in million cubic feet per day mmcfd)
- b = The hyperbolic exponent, dimensionless
- D_i = Initial decline rate, 1/yr
- t = Elapsed time from t_o (years)

This equation is applied to mines of various initial emission rates that have similar initial pressures, permeability and adsorption isotherms (EPA 2003).

The decline curves created to model the gas emission rate of coal mines must account for factors that decrease the rate of emission after mining activities cease, such as sealing and flooding. Based on field measurement data, it was assumed that most U.S. mines prone to flooding will become completely flooded within eight years and therefore no longer have any measurable CH_4 emissions. Based on this assumption, an average decline rate for flooding mines was established by fitting a decline curve to emissions from field measurements. An exponential equation was developed from emissions data measured at eight abandoned mines known to be filling with water located in two of the five basins. Using a least squares, curve-fitting algorithm, emissions data were matched to the exponential equation shown below. There was not enough data to establish basin-specific equations as was done with the vented, non-flooding mines (EPA 2003).

$$q = q_ie^{(-Dt)}$$

where,

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

Seals have an inhibiting effect on the rate of flow of CH_4 into the atmosphere compared to the rate that would be emitted if the mine had an open vent. The total volume emitted will be the same, but will occur over a longer period. The methodology, therefore, treats the emissions prediction from a sealed mine similar to emissions from a vented mine, but uses a lower initial rate depending on the degree of sealing. The computational fluid dynamics simulator was again used with the conceptual abandoned mine model to predict the decline curve for inhibited flow. The percent sealed is defined as 100 × (1 − (initial emissions from sealed mine / emission rate at abandonment prior to sealing)). Significant differences are seen between 50 percent, 80 percent and 95 percent closure. These decline curves were therefore used as the high, middle, and low values for emissions from sealed mines (EPA 2003).

For active coal mines, those mines producing over 100 mcfd account for 98 percent of all CH_4 emissions. This same relationship is assumed for abandoned mines. It was determined that 441 abandoned mines closing after 1972 produced emissions greater than 100 mcfd when active. Further, the status of 264 of the 441 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).

Table 3-32: Number of gassy abandoned mines occurring in U.S. basins grouped by class according to post-abandonment state

Basin	Sealed	Vented	Flooded	Total Known	Unknown	Total Mines
Central Appl.	23	25	48	96	111	207
Illinois	28	3	14	45	25	70
Northern Appl.	41	22	16	79	32	111
Warrior Basin	0	0	14	14	0	14
Western Basins	25	3	2	30	9	39
Total	**117**	**53**	**94**	**264**	**177**	**441**

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

During the 1970s, 78 percent of CH_4 emissions from coal mining came from seventeen counties in seven states. In addition, mine closure dates were obtained for two states, Colorado and Illinois, for the hundred year period extending from 1900 through 1999. The data were used to establish a frequency of mine closure histogram (by decade) and applied to the other five states with gassy mine closures. As a result, basin-specific decline curve equations were applied to 145 gassy coal mines estimated to have closed between 1920 and 1971 in the United States, representing 78 percent of the emissions. State-specific, initial emission rates were used based on average coal mine CH_4 emissions rates during the 1970s (EPA 2003).

Abandoned mines emission estimates are based on all closed mines known to have active mine CH_4 ventilation emission rates greater than 100 mcfd at the time of abandonment. For example, for 1990 the analysis included 145 mines closed before 1972 and 258 mines closed between 1972 and 1990. Initial emission rates based on MSHA reports, time of abandonment, and basin-specific decline curves influenced by a number of factors were used to calculate annual emissions for each mine in the database. Coal mine degasification data are not available for years prior to 1990, thus the initial emission rates used reflect ventilation emissions only for pre-1990 closures. CH_4 degasification amounts were added to the quantity of CH_4 ventilated for the total CH_4 liberation rate for fifteen mines that closed between 1992 and 2006. Since the sample of gassy mines (with active mine emissions greater

than 100 mcfd) is assumed to account for 78 percent of the pre-1971 and 98 percent of the post-1971 abandoned mine emissions, the modeled results were multiplied by 1.22 and 1.02 to account for all U.S. abandoned mine emissions.

From 1993 through 2006, 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 3-33. Abandoned coal mines CH_4 emissions in 2006 were estimated to be between 4.5 and 6.4 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 17 percent below to 19 percent above the 2006 emission estimate of 5.4 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.

Table 3-33: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Abandoned Underground Coal Mines (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	5.4	4.5	6.4	-17%	+19%

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

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 102.4 Tg CO_2 Eq. (4,877 Gg) of CH_4 in 2006, an 18 percent decrease over 1990 emissions (see Table 3-34 and Table 3-35), and 28.5 Tg CO_2 Eq. (28,504Gg) of non-combustion CO_2 in 2006, a 15 percent decrease over 1990 emissions (see Table 3-36 and Table 3-37). Improvements in management practices and technology, along with the replacement of older equipment, have helped to stabilize emissions.

CH_4 and non-combustion CO_2 emissions from natural gas systems are generally process related, with normal operations, routine maintenance, and system upsets being the primary contributors. Emissions from normal operations include: natural gas engines and turbine uncombusted exhaust, bleed and discharge emissions from pneumatic devices, and fugitive emissions from system components. Routine maintenance emissions originate from

pipelines, equipment, and wells during repair and maintenance activities. Pressure surge relief systems and accidents can lead to system upset emissions. Below is a characterization of the four major stages of the natural gas system. Each of the stages is described and the different factors affecting CH_4 and non-combustion CO_2 emissions are discussed.

Field Production. In this initial stage, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, gathering pipelines, and well-site gas treatment facilities such as dehydrators and separators. Fugitive emissions and emissions from pneumatic devices account for the majority of CH_4 emissions. Flaring emissions account for the majority of the non-combustion CO_2 emissions. Emissions from field production accounted for approximately 27 percent of CH_4 emissions and about 25 percent of non-combustion CO_2 emissions from natural gas systems in 2006.

Processing. In this stage, natural gas liquids and various other constituents from the raw gas are removed, resulting in "pipeline quality" gas, which is injected into the transmission system. Fugitive CH_4 emissions from compressors, including compressor seals, are the primary emission source from this stage. The majority of non-combustion CO_2 emissions come from acid gas removal units, which are designed to remove CO_2 from natural gas. Processing plants account for about 12 percent of CH_4 emissions and approximately 74 percent of non-combustion CO_2 emissions from natural gas systems.

Transmission and Storage. Natural gas transmission involves high pressure, large diameter pipelines that transport gas long distances from field production and processing areas to distribution systems or large volume customers such as power plants or chemical plants. Compressor station facilities, which contain large reciprocating and turbine compressors, are used to move the gas throughout the United States transmission system. Fugitive CH_4 emissions from these compressor stations and from metering and regulating stations account for the majority of the emissions from this stage. Pneumatic devices and engine uncombusted exhaust are also sources of CH_4 emissions from transmission facilities.

Natural gas is also injected and stored in underground formations, or liquefied and stored in above ground tanks, during periods of low demand (e.g., summer), and withdrawn, processed, and distributed during periods of high demand (e.g., winter). Compressors and dehydrators are the primary contributors to emissions from these storage facilities. CH_4 emissions from the transmission and storage sector account for approximately 37 percent of emissions from natural gas systems, while CO_2 emissions from transmission and storage account for less than 1 percent of the non-combustion CO_2 emissions from natural gas systems.

Distribution. Distribution pipelines take the high-pressure gas from the transmission system at "city gate" stations, reduce the pressure and distribute the gas through primarily underground mains and service lines to individual end users. There were over 1,250,000 miles of distribution mains in 2006, an increase from just over 947,000 miles in 1990 (OPS 2007b). Distribution system emissions, which account for approximately 24 percent of CH_4 emissions from natural gas systems and less than 1 percent of non-combustion CO_2 emissions, result mainly from fugitive emissions from gate stations and pipelines.[41] 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 2006 were 20 percent lower than 1990 levels.

Table 3-34. CH_4 Emissions from Natural Gas Systems (Tg CO_2 Eq.)*

Stage	**1990**		**1995**		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Field Production	32.7		37.2		38.8	41.5	42.5	40.1	32.9	25.0	27.6
Processing	14.9		14.9		14.6	14.7	14.2	13.6	13.4	11.8	11.9
Transmission and Storage	46.3		45.8		43.8	40.7	42.4	42.8	40.9	38.5	38.2
Distribution	30.8		30.1		29.3	28.5	25.8	26.9	26.8	27.2	24.7

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

Total	**124.7**		**128.1**		**126.5**	**125.3**	**124.9**	**123.3**	**114.0**	**102.5**	**102.4**

*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. CH_4 Emissions from Natural Gas Systems (Gg)*

Stage	1990		1995		2000	2001	2002	2003	2004	2005	2006
Field Production	1,555		1,774		1,849	1,976	2,024	1,909	1,566	1,190	1,317
Processing	707		711		693	699	675	646	639	560	568
Transmission and Storage	2,206		2,181		2,087	1,936	2,019	2,039	1,947	1,834	1,817
Distribution	1,468		1,432		1,395	1,356	1,228	1,279	1,275	1,296	1,176
Total	**5,937**		**6,098**		**6,024**	**5,968**	**5,946**	**5,874**	**5,426**	**4,880**	**4,877**

*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 3-36. Non-combustion CO_2 Emissions from Natural Gas Systems (Tg CO_2 Eq.)

Stage	1990		1995		2000	2001	2002	2003	2004	2005	2006
Field Production	5.9		9.1		6.0	6.3	6.5	6.3	6.2	7.6	7.2
Processing	27.8		24.6		23.3	22.4	23.1	22.0	21.8	21.7	21.2
Transmission and Storage	0.1		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**	**28.1**	**29.5**	**28.5**

Note: Totals may not sum due to independent rounding.

Table 3-37. Non-combustion CO_2 Emissions from Natural Gas Systems (Gg)

Stage	1990		1995		2000	2001	2002	2003	2004	2005	2006
Field Production	5,876		9,083		5,956	6,307	6,463	6,342	6,242	7,627	7,203
Processing	27,752		24,621		23,333	22,387	23,066	22,002	21,780	21,736	21,204
Transmission and Storage	58		60		60	59	61	61	61	60	59
Distribution	42		42		41	40	40	40	40	39	37
Total	**33,729**		**33,806**		**29,390**	**28,793**	**29,629**	**28,445**	**28,122**	**29,462**	**28,504**

Note: Totals may not sum due to independent rounding.

Methodology

The primary basis for estimates of CH_4 and non-combustion-related CO_2 emissions from the U.S. natural gas industry is a detailed study by the Gas Research Institute and EPA (EPA/GRI 1996). The EPA/GRI study developed over 80 CH_4 emission 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-combustion CO_2 emissions. However, the CH_4 emission factors were adjusted for CO_2 content when estimating fugitive and vented non-combustion 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-combustion CO_2 emissions from natural gas systems.

Activity factor data were taken from the following sources: American Gas Association (AGA 1991 through 1998); Minerals and Management Service (MMS 2007a-e); Monthly Energy Review (EIA 2007f); Natural Gas Liquids Reserves Report (EIA 2005); Natural Gas Monthly (EIA 2007b,c,e); the Natural Gas STAR Program annual emissions savings (EPA 2007); Oil and Gas Journal (OGJ 1997 through 2007); Office of Pipeline Safety (OPS

2007a-b) and other Energy Information Administration publications (EIA 2001, 2004, 2007a,d); World Oil Magazine (2007a-b). Data for estimating emissions from hydrocarbon production tanks is incorporated (EPA 1999). Coalbed CH_4 well activity factors were taken from the Wyoming Oil and Gas Conservation Commission (Wyoming 2007) and the Alabama State Oil and Gas Board (Alabama 2007). Other state well data was taken from: American Association of Petroleum Geologists (AAPG 2004); Brookhaven College (Brookhaven 2004); Kansas Geological Survey (Kansas 2007); Montana Board of Oil and Gas Conservation (Montana 2007); Oklahoma Geological Survey (Oklahoma 2007); Morgan Stanley (Morgan Stanley 2005); Rocky Mountain Production Report (Lippman (2003); New Mexico Oil Conservation Division (New Mexico 2007a,b); Texas Railroad Commission (Texas 2007a-d); Utah Division of Oil, Gas and Mining (Utah 2007). Emission factors were taken from EPA/GRI (1996). GTI's Unconventional Natural Gas and Gas Composition Databases (GTI 2001) were used to adapt the CH_4 emission factors into non-combustion related CO_2 emission factors. 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-combustion 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 is summarized in Table 3-38. Natural gas systems CH_4 emissions in 2006 were estimated to be between 79.1 and 148.4 Tg CO_2 Eq. at a 95 percent confidence level. Natural gas systems non-combustion CO_2 emissions in 2006 were estimated to be between 22.0 and 41.3 Tg CO_2 Eq. at 95 percent confidence level.

Table 3-38: Tier 2 Quantitative Uncertainty Estimates for CH_4 and Non-combustion CO_2 Emissions from Natural Gas Systems (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	102.4	79.1	148.4	-23%	+45%
Natural Gas Systems[b]	CO_2	28.5	22.0	41.3	-23%	+45%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.
[b] An uncertainty analysis for the non-combustion 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-combustion CO_2 emissions.

Recalculations Discussion

The offshore gas platform count is driven by the percentage of total platforms that are located on gas fields as identified by MMS. This percentage can be calculated from MMS (2007a,b,e) for years 2003 onward. For year 1992, the estimate was provided by MMS by direct communication. The oil platform count for years 1990, 1991, and 1993 through 2002 are driven by a linear projection based on known platform counts in 1992 and 2003. A miscalculation in year 2003 was re-estimated, which caused the entire time series prior to year 2003 (except 1992) to change. The effects of this recalculation are most significant in 1990, with an absolute difference of 31 Gg; less significant changes occurred in all subsequent years.

The second recalculation is a result of changing several base year (1992) activity factor and emissions factor data to the exact values from the EPA/GRI 1996 report. These changes were small and the effects were an increase of less than 1 percent in 1992 CH_4 emissions.

A third recalculation is the result of updating previous years' activity and Natural Gas STAR reduction values with revised data. This is especially evident in 2005, where the revised reductions data reports an additional 443 Gg of reductions totaled from all four sectors; decreasing total 2005 emission estimates by nearly 9.5 percent.

QA/QC and Verification Discussion

A tier 2 QA/QC analysis was undertaken to examine why emissions from small reciprocating compressors are lower in the production sector than in other sectors of the natural gas industry. The emission factor for these compressors is based on EPA/GRI 1996. Background information from EPA/GRI 1996, along with information from the Natural Gas STAR program was analyzed and it was determined that the emission factor for small compressors in the eastern United States (U.S. East) was significantly lower than the emission factor developed for the western area of the country (U.S. West). Details of the emission factor development revealed that the U.S. East emission factor in EPA/GRI 1996 does not include fugitives from compressor seals and pressure relief valves. Experience from the Natural Gas STAR Program demonstrates that seal leakage from rod packing is the largest source of fugitive emissions from reciprocating compressors. To account for compressor seal leakage, the U.S. West emission factor was used for the entire United States for 1990 through 2006. These updated emission factors are an interim improvement and further research is underway to compare these updated emissions factors with recent vendor data.

Planned Improvements

Currently, activity factors for most sources in the natural gas inventory are dependent on EPA/GRI 1996 estimates of activity data in base year 1992. The activity factors for all years other than the base year are estimated from the base year activity data and are driven by an appropriate activity driver. However, in some instances activity data are directly available from published sources and there is no need to derive the current year activity data through the use of drivers. Research is underway to determine the feasibility of using published activity data, where available, and whether this would impact any of the emission factors currently used.

Separately, work has been initiated to update select emission factors from the earlier study. Where relevant, these emission factors will be incorporated into the inventory when they become available.

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 emissions are released to the atmosphere as fugitive emissions, vented emissions, emissions from operational upsets, and emissions from fuel combustion. Fugitive and vented CO_2 emissions from petroleum systems are primarily associated with crude oil production and are negligible in the transportation and refining operations. Combusted CO_2 emissions are already accounted for in the Fossil Fuels Combustion calculations previously discussed, and hence have not been taken into account in this inventory. Total CH_4 and CO_2 emissions from petroleum systems in 2006 were 28.4 Tg CO_2 Eq. (1,354 Gg CH_4) and 0.3 Tg CO_2 (293 Gg) respectively. Since 1990, CH_4 emissions have declined by 16 percent, due to industry efforts to reduce emissions and a decline in domestic oil production (see Table 3-39, Table 3-40, Table 3-41, and Table 3-42). CO_2 emissions have also declined by 22 percent since 1990 due to similar reasons.

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 over 91 percent of the emissions from the production sector, unburned CH_4 combustion emissions account for 5.2 percent, fugitive emissions are 3.4 percent, and process upset emissions, slightly over one-tenth of a percent. The most dominant sources of emissions, in the order of magnitude, are shallow water offshore oil platforms, natural-gas-powered pneumatic devices (low bleed and high bleed), field storage tanks, gas engines, chemical injection pumps and deep water offshore platforms. These seven sources alone emit over 95 percent of the production field operations emissions. Offshore platform

emissions are a combination of fugitive, vented, and unburned fuel combustion emissions from all equipment housed on oil platforms producing oil and associated gas. Emissions from high and low-bleed pneumatics occur when pressurized gas that is used for control devices is bled to the atmosphere as they cycle open and closed to modulate the system. Emissions from 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 gas engines are due to unburned CH_4 that vents with the exhaust. Emissions from chemical injection pumps are due to the 25 percent that use associated gas to drive pneumatic pumps. The remaining five percent of the emissions are distributed among 26 additional activities within the four categories: vented, fugitive, combustion and process upset emissions. For more detailed, source-level, data on methane emissions in production field operations refer to Annex 3.5.

Vented CO_2 associated with natural gas emissions from field operations account for 99 percent of the total CO_2 emissions, while fugitive and process upsets together account for 1 percent of the emissions. The most dominant sources of vented emissions are field storage tanks, pneumatic devices (high bleed and low bleed), shallow water offshore oil platforms, and chemical injection pumps. These five sources together account for 98.5 percent of the non-combustion CO_2 emissions while the remaining 1.5 percent of the emissions is distributed among 24 additional activities within the three categories: vented, fugitive and process upsets.

Crude Oil Transportation. Crude oil transportation activities account for less than one half of one percent of total CH_4 emissions from the oil industry. Venting from tanks and marine vessel loading operations accounts for 64 percent of CH_4 emissions from crude oil transportation. Fugitive emissions, almost entirely from floating roof tanks, account for 19 percent. The remaining 17 percent is distributed among six additional sources within these two categories. Emissions from pump engine drivers and heaters were not estimated due to lack of data.

Crude Oil Refining. Crude oil refining processes and systems account for 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.

Table 3-39: CH_4 Emissions from Petroleum Systems (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Production Field Operations	**33.2**	**31.3**	**29.6**	**29.5**	**29.2**	**28.5**	**28.0**	**27.6**	**27.7**
Pneumatic device venting	10.3	9.7	9.0	8.9	8.9	8.7	8.6	8.3	8.4
Tank venting	3.8	3.4	3.2	3.2	3.2	3.1	3.0	2.8	2.9
Combustion & process upsets	1.9	1.7	1.6	1.6	1.6	1.5	1.5	1.5	1.5
Misc. venting & fugitives	16.8	16.0	15.3	15.3	15.1	14.7	14.5	14.5	14.5
Wellhead fugitives	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4
Crude Oil Transportation	**0.1**	**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**	**0.6**
Total	**33.9**	**32.0**	**30.3**	**30.2**	**29.9**	**29.2**	**28.7**	**28.3**	**28.4**

Note: Totals may not sum due to independent rounding.

Table 3-40: CH_4 Emissions from Petroleum Systems (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Production Field Operations	**1,581**	**1,493**	**1,409**	**1,404**	**1,390**	**1,357**	**1,335**	**1,314**	**1,321**
Pneumatic device venting	489	463	428	425	424	412	408	397	399
Tank venting	179	161	154	154	151	150	142	135	138
Combustion & process upsets	88	82	76	75	75	73	72	71	72
Misc. venting & fugitives	799	762	728	727	717	701	692	691	693
Wellhead fugitives	26	25	22	22	23	22	21	20	20

Crude Oil Transportation	**7**	**6**	**5**	**5**	**5**	**5**	**5**	**5**	**5**
Refining	**25**	**25**	**28**	**27**	**27**	**27**	**28**	**28**	**28**
Total	**1,612**	**1,524**	**1,442**	**1,436**	**1,422**	**1,390**	**1,368**	**1,346**	**1,354**

Note: Totals may not sum due to independent rounding.

Table 3-41: CO_2 Emissions from Petroleum Systems (Tg CO2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Production Field Operations	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Pneumatic device venting	+	+	+	+	+	+	+	+	+
Tank venting	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3
Misc. venting & fugitives	+	+	+	+	+	+	+	+	+
Wellhead fugitives	+	+	+	+	+	+	+	+	+
Total	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**

+ Does not exceed 0.05 Tg CO_2 Eq.

Table 3-42: CO_2 Emissions from Petroleum Systems (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Production Field Operations	**376**	**341**	**325**	**325**	**320**	**316**	**302**	**287**	**293**
Pneumatic device venting	27	26	24	24	24	23	23	22	22
Tank venting	328	296	283	283	278	276	262	248	253
Misc. venting & fugitives	18	18	17	17	16	16	16	16	16
Wellhead fugitives	1	1	1	1	1	1	1	1	1
Total	**376**	**341**	**325**	**325**	**320**	**316**	**302**	**287**	**293**

Note: Totals may not sum due to independent rounding.

Methodology

The methodology for estimating CH_4 emissions from petroleum systems is a bottom-up approach, based on comprehensive studies of CH_4 emissions from U.S. petroleum systems (EPA 1996, EPA 1999). These studies combined emission estimates from 64 activities occurring in petroleum systems from the oil wellhead through crude oil refining, including 33 activities for crude oil production field operations, 11 for crude oil transportation activities, and 20 for refining operations. Annex 3.5 provides greater detail on the emission estimates for these 64 activities. The estimates of CH_4 emissions from petroleum systems do not include emissions downstream of oil refineries because these emissions are 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) and EPA (2005). 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 and field storage tanks. For offshore oil production, two emission factors were calculated using data collected over a one-year period for all federal offshore platforms (EPA 2005, MMS 2004). One emission factor is for oil platforms in shallow water, and one emission factor is for oil platforms in deep water. Emission factors are held constant for the period 1990 through 2006. 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 2007a-c). For oil storage tanks, the emissions factor was calculated from API TankCalc data as the total emissions per barrel of crude charge (EPA 1999).

The methodology for estimating CO_2 emissions from petroleum systems combines vented, fugitive and process upset emissions sources from 29 activities for crude oil production field operations. Emissions are estimated for each activity by multiplying emission factors by their corresponding activity factors. The emission factors for CO_2 are estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and

methane content in produced associated gas. The only exceptions to this methodology are the emission factors for crude oil storage tanks which are obtained from API TankCalc simulation runs.

Activity factors for years 1990 through 2006 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 2006 based on EPA (1999). Lastly, the previous year's data were used when data for the current year were unavailable. The CH_4 and CO_2 sources in the production sector share common activity factors. 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 2006, 1990 through 2007, 1995 through 2007a-b), *Methane Emissions from the Natural Gas Industry* by the Gas Research Institute and EPA (EPA/GRI 1996a-d), *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999), consensus of industry peer review panels, MMS reports (MMS 2001, 2007a-c), analysis of MMS data (EPA 2005, MMS 2004), the *Oil & Gas Journal* (OGJ 2007a,b), the Interstate Oil and Gas Compact Commission (IOGCC 2007), and the United States Army Corps of Engineers (1995-2005).

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 the seven major sources, which account for 93.0 percent of the total emissions, the uncertainty surrounding these seven sources has been estimated most rigorously, and serves as the basis for determining the overall uncertainty of petroleum systems emission estimates.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-43 Petroleum systems CH_4 emissions in 2006 were estimated to be between 20.5 and 69.3 Tg CO_2 Eq., while CO_2 emissions were estimated to be between 0.2 and 0.7 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 28 percent below to 144 percent above the 2006 emission estimates of 28.4 and 0.3 Tg CO_2 Eq. for CH_4 and CO_2, respectively.

Table 3-43: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petroleum Systems (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	28.4	20.5	69.3	-28%	+144%
Petroleum Systems	CO_2	0.3	0.2	0.7	-28%	+144%

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

Recalculations Discussion

Estimates of vented, fugitive, and process upset CO_2 emissions from the production sector were incorporated into the petroleum systems inventory for 1990-2006. CO_2 emissions were estimated using the methane emission sources' activity factors and drivers for the corresponding CO_2 emission sources. The emission factors for CO_2 were estimated by multiplying the methane emission factors by a conversion factor, which is the ratio of CO_2 content divided by methane content in produced associated gas. The only exceptions to this methodology are the emission factors for crude oil storage tanks, which were estimated from API TankCalc simulation runs. CO_2 emissions from the production sector account for 293 Gg of CO_2 in the year 2006. CO_2 emissions from the transportation and refining sectors are assumed to be negligible. Combustion emissions are already accounted for in the Fossils Fuels Combustion inventory.

In addition, two types of activity factor and seven types of activity driver revisions were made in the 2006 Petroleum Systems emissions inventory. All revisions but one were due to updating previous years' data with revised data from existing data sources. The one exception to the general revisions was the recalculation of an activity driver for oil platforms. Offshore oil platform count is driven by the percentage of total platforms that are located on oil fields as identified by MMS. This percentage can be calculated from MMS (2007a-c) for years 2003 onward. For year 1992, the estimate was provided by MMS by direct communication. The oil platform counts for years 1990, 1991, and 1993 through 2002 are driven by a linear projection based on known platform counts in 1992 and 2003. A miscalculation in year 2003 was re-estimated, causing the entire time series prior to year 2003 (except 1992) to change.

Overall changes resulted in a decrease in total emissions of approximately 0.22 Tg CO_2 Eq. (0.8 percent) for year 2005. For 1990 and 1991, total emissions decreased by 2 percent or less; while between 1993 and 2004 the total emission estimates increased by up to 13 percent from the previous year's inventory estimates. This increase is largely due to the recalculation of the oil platform activity driver.

[BEGIN BOX]

Box 3-3. Carbon Dioxide Transport, Injection, and Geological Storage

Carbon dioxide is produced, captured, transported, and used for Enhanced Oil Recovery (EOR) as well as commercial and non-EOR industrial applications. This CO_2 is produced from both naturally-occurring CO_2 reservoirs and from industrial sources such as natural gas processing plants and ammonia plants. In the current Inventory, emissions from naturally-produced CO_2 are estimated based on the application.

In the current Inventory report, the CO_2 that is used in non-EOR industrial and commercial applications (e.g., food processing, chemical production) is assumed to be emitted to the atmosphere during its industrial use. These emissions are discussed in the Carbon Dioxide Consumption section. The naturally-occurring CO_2 used in EOR operations is assumed to be fully sequestered. Additionally, all anthropogenic CO_2 emitted from natural gas processing and ammonia plants is assumed to be emitted to the atmosphere, regardless of whether the CO_2 is captured or not. These emissions are currently included in the Natural Gas Systems and the Ammonia Manufacture 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. However, IPCC (2006) notes that if a national regulatory process exists, emissions information available through that process may support development of CO_2 emissions estimates for geologic storage.

In October 2007, the U.S. EPA announced plans to develop regulations for geologic sequestration of CO_2 under the EPA Underground Injection Control Program. Given that the regulatory process is in its early phases, and site-specific emissions estimates are not yet available, emissions estimates from CO_2 capture, transport, injection and geologic storage are not yet included in national totals. Preliminary estimates indicate that the amount of CO_2 captured from industrial and natural sites, as well as fugitive emissions from pipelines is 39.0 Tg CO_2 (39,041 Gg CO_2) (see Table 3-44). Site-specific monitoring and reporting data for CO_2 injection sites (i.e., EOR operations) were not readily available, therefore, these estimates assume all CO_2 is emitted.

Table 3-44: Emissions of CO_2 from EOR Operations and Pipelines (Tg CO_2 Eq.)

Year	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Acid Gas Removal Plants	4.8	3.7	2.3	2.9	2.9	3.0	3.7	6.0	7.0
Naturally Occurring CO_2	15.1	22.7	23.1	23.4	23.0	24.4	27.0	28.2	31.4
Ammonia Production Plants	0.0	0.7	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	0.0
Total	**20.0**	**26.9**	**26.1**	**27.0**	**26.6**	**28.1**	**31.4**	**34.9**	**39.0**

Table 3-45: Emissions of CO_2 from EOR Operations and Pipelines (Gg)

Year	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Acid Gas Removal Plants	4,832	3,672	2,264	2,894	2,943	2,993	3,719	5,992	6,997
Naturally Occurring CO_2	15,129	22,547	23,149	23,442	22,967	24,395	27,002	28,192	31,359
Ammonia Production Plants	0	676	676	676	676	676	676	676	676
Pipelines Transporting CO_2	8	8	8	8	8	8	7	7	8
Total	**19,969**	**26,904**	**26,098**	**27,020**	**26,595**	**28,073**	**31,405**	**34,868**	**39,041**

[END BOX]

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 municipal solid wastes 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).

Over 31 million metric tons of municipal solid wastes were combusted in the United States in 2006 (EPA 2007). CO_2 emissions from combustion of municipal solid wastes rose 91 percent since 1990, to an estimated 20.9 Tg CO_2 Eq. (20,922 Gg) in 2006, as the volume of synthetic fibers and other fossil C-containing materials in MSW increased (see Table 3-46 and Table 3-47). 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 2006, and have not changed significantly since 1990.

Table 3-46: 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	2006
CO_2	**10.9**	**15.7**	**17.5**	**18.0**	**18.5**	**19.1**	**20.1**	**20.7**	**20.9**
Plastics	8.0	10.3	11.8	12.1	12.3	12.7	13.4	13.7	13.7
Synthetic Rubber in Tires	0.2	0.8	0.9	0.9	1.0	1.0	1.1	1.2	1.2
Carbon Black in Tires	0.2	1.1	1.2	1.2	1.2	1.3	1.4	1.6	1.6
Synthetic Rubber in MSW	1.3	1.6	1.6	1.7	1.8	1.8	1.9	1.9	1.9
Synthetic Fibers	1.2	1.8	2.0	2.1	2.2	2.3	2.3	2.4	2.5
N_2O	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total	**11.4**	**16.2**	**17.9**	**18.4**	**18.9**	**19.5**	**20.5**	**21.1**	**21.3**

Table 3-47: CO_2 and N_2O Emissions from Municipal Solid Waste Combustion (Gg)

Gas/Waste Product	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	**10,950**	**15,712**	**17,518**	**17,971**	**18,458**	**19,058**	**20,097**	**20,673**	**20,922**
Plastics	7,976	10,347	11,791	12,094	12,316	12,657	13,356	13,662	13,746
Synthetic Rubber in Tires	191	841	893	895	952	1,010	1,108	1,207	1,207
Carbon Black in Tires	249	1,099	1,167	1,170	1,245	1,320	1,449	1,579	1,579
Synthetic Rubber in MSW	1,334	1,596	1,640	1,721	1,760	1,815	1,871	1,873	1,902
Synthetic Fibers	1,200	1,830	2,027	2,090	2,185	2,257	2,312	2,352	2,489
N_2O	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

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 municipal solid wastes were categorized into seven plastic resin types, each material having a discrete C content. Similarly, synthetic rubber is categorized into three product types, and synthetic fibers were categorized into four product types, each having a discrete C content. Scrap tires contain several types of synthetic rubber, as well as carbon black. Each type of synthetic rubber has a discrete C content, and carbon black is 100 percent C. Emissions of CO_2 were calculated based on the 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 municipal solid wastes and its portion combusted were taken from the *Characterization of Municipal Solid Waste in the United States* (EPA 2000b, 2002, 2003, 2005a, 2006b, 2007) 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 through 2003, 2006). For 2006, synthetic rubber data is set equal to 2005 due to a lack of more recently available data.

Average C contents for the "Other" plastics category, synthetic rubber in municipal solid wastes, 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 municipal solid waste combustion categories for CO_2 emissions) was reported in EPA's life cycle analysis of greenhouse gas emissions and sinks from management of solid waste (EPA 2006a).

Combustion of municipal solid waste also results in emissions of N_2O. These emissions were calculated as a function of the total estimated mass of municipal solid waste combusted and an emission factor. The N_2O emission estimates are based on different data sources than the CO_2 emission estimates. As noted above, N_2O emissions are a function of total waste combusted in each year; for 1990 through 2004, these data were derived from the information published in *BioCycle* (Simmons et al. 2006). Data on total waste combusted was not available for 2005 and 2006, so the values for 2005 and 2006 were assumed to equal the most recent value available (2004). Table 3-48 provides data on municipal solid waste generation and percentage combustion for the total waste stream. The emission factor of N_2O emissions per quantity of municipal solid waste combusted is an average of values from IPCC's *Good Practice Guidance* (2000).

Table 3-48: 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]
2006	351,86,2474[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 municipal solid waste 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 3-49. Municipal solid waste combustion CO_2 emissions in 2006 were estimated to be between 16.8 and 23.7 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 20 percent below to 13 percent above the 2006 emission estimate of 20.9 Tg CO_2 Eq. Also at a 95 percent confidence level, municipal solid waste combustion N_2O emissions in 2006 were estimated to be between 0.1 and 1.1 Tg CO_2 Eq. This indicates a range of 66 percent below to 184 percent above the 2006 emission estimate of 0.4 Tg CO_2 Eq.

Table 3-49: Tier 2 Quantitative Uncertainty Estimates for CO_2 and N_2O from Municipal Solid Waste Combustion (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	16.8	23.7	-20%	13%
Municipal Solid Waste Combustion	N_2O	0.4	0.1	1.1	-66%	184%

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

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.

Planned Improvements

Additional data sources for calculating an N_2O emission factor for U.S. MSW combustion will be investigated for future drafts. In addition, the use of new techniques using radiocarbon dating to directly measure biogenic C content of MSW combustion flue gas will also be investigated.

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 2006 are reported in Table 3-50.

Table 3-50: NO_x, CO, and NMVOC Emissions from Energy-Related Activities (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
NO_x	**21,024**	**20,631**	**18,537**	**17,714**	**17,364**	**16,474**	**15,607**	**15,005**	**14,309**
Mobile Combustion	10,920	10,622	10,310	9,819	10,154	9,642	9,191	8,739	8,287
Stationary Combustion	9,883	9,821	8,002	7,667	6,791	6,419	6,004	5,853	5,610
Oil and Gas Activities	139	100	111	113	321	316	316	316	315
Municipal Solid Waste Combustion	82	88	114	114	98	97	97	97	97
*International Bunker Fuels**	*1,985*	*1,540*	*1,334*	*1,266*	*988*	*900*	*1,190*	*1,190*	*1,731*
CO	**125,640**	**104,402**	**89,715**	**86,046**	**82,148**	**77,689**	**73,731**	**69,773**	**65,815**
Mobile Combustion	119,360	97,630	83,559	79,851	75,421	71,038	67,096	63,154	59,213
Stationary Combustion	5,000	5,383	4,340	4,377	4,965	4,893	4,876	4,860	4,844
Municipal Solid Waste Combustion	302	316	146	147	323	321	321	321	322
Oil and Gas Activities	978	1,073	1,670	1,672	1,439	1,437	1,437	1,437	1,437

*International Bunker Fuels**	*115*	*113*	*124*	*120*	*118*	*112*	*128*	*133*	*150*
NMVOCs	**12,620**	**10,538**	**8,953**	**8,610**	**9,608**	**9,223**	**8,910**	**8,597**	**8,284**
Mobile Combustion	10,932	8,745	7,230	6,872	7,235	6,885	6,587	6,289	5,991
Stationary Combustion	912	973	1,077	1,080	1,585	1,560	1,553	1,545	1,538
Oil and Gas Activities	554	582	389	400	545	538	533	528	523
Municipal Solid Waste Combustion	222	237	257	258	243	239	237	235	232
*International Bunker Fuels**	*59*	*48*	*44*	*42*	*35*	*32*	*41*	*41*	*56*

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

Methodology

These emission estimates were obtained from preliminary data (EPA 2008), 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 Intergovernmental Negotiating Committee in establishing the Framework Convention on Climate Change.[42] 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).[43]

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.[44] Emissions from ground transport activities—by road vehicles and trains—even when crossing

[42] 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).

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

[44] Most emission related international aviation and marine regulations are under the rubric of the International Civil Aviation

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.[45]

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 occur 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 2006 from the combustion of international bunker fuels from both aviation and marine activities were 126.9 Tg CO_2 Eq., or 11 percent above emissions in 1990 (see Table 3-51 and Table 3-52). Although emissions from international flights departing from the United States have increased significantly (56 percent), emissions from international shipping voyages departing the United States have decreased by 20 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.

Table 3-51: 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	2006
CO_2	**113.7**	**100.6**	**101.1**	**97.6**	**89.1**	**83.7**	**99.8**	**102.1**	**125.7**
Aviation	45.7	50.2	59.9	58.7	61.1	58.8	64.9	67.5	71.1
Marine	68.0	50.4	41.3	38.9	28.0	24.9	34.9	34.6	54.5
CH_4	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.2**
Aviation	+	+	+	+	+	+	+	+	+
Marine	0.1	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**	**1.1**
Aviation	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.7	0.7
Marine	0.5	0.4	0.3	0.3	0.2	0.2	0.3	0.3	0.4
Total	**114.8**	**101.6**	**102.2**	**98.6**	**90.0**	**84.5**	**100.8**	**103.2**	**126.9**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Table 3-52: CO_2, CH_4 and N_2O Emissions from International Bunker Fuels (Gg)

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).

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

Gas/Mode	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	**113,683**	**100,627**	**101,125**	**97,563**	**89,101**	**83,690**	**99,828**	**102,110**	**125,659**
Aviation	45,731	50,202	59,853	58,696	61,120	58,806	64,891	67,517	71,141
Marine	67,952	50,425	41,272	38,866	27,981	24,884	34,937	34,593	54,519
CH_4	**8**	**6**	**6**	**5**	**4**	**4**	**5**	**5**	**7**
Aviation	1	1	2	2	2	2	2	2	2
Marine	7	5	4	4	3	2	3	3	5
N_2O	**3**	**3**	**3**	**3**	**3**	**2**	**3**	**3**	**4**
Aviation	1	2	2	2	2	2	2	2	2
Marine	2	1	1	1	1	1	1	1	1

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

Methodology

Emissions of CO_2 were estimated by applying C content and fraction oxidized factors to fuel consumption activity data. This approach is analogous to that described under CO_2 from Fossil Fuel Combustion. C content and fraction oxidized factors for jet fuel, distillate fuel oil, and residual fuel oil were taken directly from EIA and are presented in Annex 2.1, Annex 2.2, and Annex 3.7 of this Inventory. Density conversions were taken from Chevron (2000), ASTM (1989), and USAF (1998). Heat content for distillate fuel oil and residual fuel oil were taken from EIA (2007) and USAF (1998), and heat content for jet fuel was taken from EIA (2007). A complete description of the methodology and a listing of the various factors employed can be found in Annex 2.1. See Annex 3.7 for a specific discussion on the methodology used for estimating emissions from international bunker fuel use by the U.S. military.

Emission estimates for CH_4 and N_2O were calculated by multiplying emission factors by measures of fuel consumption by fuel type and mode. Emission factors used in the calculations of CH_4 and N_2O emissions were obtained from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). For aircraft emissions, the following values, in units of grams of pollutant per kilogram of fuel consumed (g/kg), were employed: 0.09 for CH_4 and 0.1 for N_2O For marine vessels consuming either distillate diesel or residual fuel oil the following values (g/MJ), were employed: 0.32 for CH_4 and 0.08 for N_2O. Activity data for aviation included solely jet fuel consumption statistics, while the marine mode included both distillate diesel and residual fuel oil.

Activity data on aircraft fuel consumption 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 2007). 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 3-53. 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 2007). Activity data on distillate diesel consumption by military vessels departing from U.S. ports were provided by DESC (2007). The total amount of fuel provided to naval vessels was reduced by 13 percent to account for fuel used while the vessels were not-underway (i.e., in port). Data on the percentage of steaming hours underway versus not-underway were provided by the U.S. Navy. These fuel consumption estimates are presented in Table 3-53.

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

Nationality	1990	1995	2000	2001	2002	2003	2004	2005	2006
U.S. and Foreign Carriers	1,954	2,221	2,737	2,619	2,495	2,418	2,466	2,760	2,914
Foreign Carriers	2,051	2,544	3,162	3,113	3,537	3,377	3,953	3,975	4,272
U.S. Military	862	581	480	524	482	473	498	462	400
Total	**4,867**	**5,347**	**6,380**	**6,255**	**6,515**	**6,268**	**6,917**	**7,198**	**7,586**

Note: Totals may not sum due to independent rounding.

Table 3-54: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006
Residual Fuel Oil	4,781	3,495	2,967	2,846	1,937	1,597	2,363	2,320	3,999
Distillate Diesel Fuel & Other	617	573	290	204	158	137	167	241	310
U.S. Military Naval Fuels	522	334	329	318	348	459	530	471	414
Total	**5,920**	**4,402**	**3,586**	**3,368**	**2,443**	**2,193**	**3,059**	**3,032**	**4,723**

Note: Totals may not sum due to independent rounding.

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.[46] 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 2007) 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 for the BEA (1991 through 2007) 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.[47]

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

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

[47] 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.

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.[48]

There is also concern as to the reliability of the existing DOC (1991 through 2007) 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.

Recalculations Discussion

Historical activity data for aviation was revised for both U.S. and foreign carriers. These historical data changes resulted in changes to the emission estimates for 1990 through 2005, which averaged to an annual increase in emissions from international bunker fuels of 0.6 Tg CO_2 Eq. (0.6 percent) in CO_2 emissions, an annual increase of less than 0.1 Tg CO_2 Eq. (0.4 percent) in CH_4 emissions, and annual increase of less than 0.1 Tg CO_2 Eq. (0.6

[48] 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.

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 2006, total CO_2 emissions from the burning of woody biomass in the industrial, residential, commercial, and electricity generation sectors were approximately 204.4 Tg CO_2 Eq. (204,435 Gg) (see Table 3-55 and Table 3-56). As the largest consumer of woody biomass, the industrial sector was responsible for 67 percent of the CO_2 emissions from this source. The residential sector was the second largest emitter, constituting 20 percent of the total, while the commercial and electricity generation sectors accounted for the remainder.

Table 3-55: 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	2006
Industrial	135.3	155.1	153.6	135.4	131.1	128.0	138.5	136.3	137.9
Residential	59.8	53.6	43.3	38.2	39.2	41.2	42.3	42.3	40.2
Commercial	6.8	7.5	7.4	6.9	7.1	7.4	7.3	7.2	6.7
Electricity Generation	13.3	12.9	13.9	13.0	15.5	17.3	17.0	19.1	19.6
Total	**215.2**	**229.1**	**218.1**	**193.5**	**192.8**	**193.8**	**205.1**	**204.8**	**204.4**

Note: Totals may not sum due to independent rounding.

Table 3-56: CO_2 Emissions from Wood Consumption by End-Use Sector (Gg)

End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005	2006
Industrial	135,348	155,075	153,559	135,415	131,079	127,970	138,522	136,269	137,929
Residential	59,808	53,621	43,309	38,153	39,184	41,247	42,278	42,278	40,215
Commercial	6,779	7,463	7,370	6,887	7,080	7,366	7,252	7,191	6,685
Electricity Generation	13,252	12,932	13,851	13,034	15,487	17,250	17,034	19,704	19,606
Total	**215,186**	**229,091**	**218,088**	**193,489**	**192,830**	**193,833**	**205,086**	**204,812**	**204,435**

Note: Totals may not sum due to independent rounding.

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 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 2006, the United States consumed an estimated 459 trillion Btu of ethanol, and as a result, produced approximately 30.3 Tg CO_2 Eq. (30,291 Gg) (see Table 3-57 and) of CO_2 emissions. Ethanol production and consumption has grown steadily every year since 1990, with the exception of 1996 due to short corn supplies and high prices in that year.

Table 3-57: CO_2 Emissions from Ethanol Consumption (Tg CO_2 Eq.)

End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005	2006
Transportation	4.1	7.6	9.1	9.5	11.3	15.4	19.3	22.0	29.6

Industrial	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.5	0.6
Commercial	+	+	+	+	+	0.1	0.1	0.1	0.1
Total	**4.2**	**7.7**	**9.2**	**9.7**	**11.5**	**15.7**	**19.7**	**22.6**	**30.3**

+ Does not exceed 0.05 Tg CO_2 Eq.

Table 3-58: CO_2 Emissions from Ethanol Consumption (Gg)

End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005	2006
Transportation	4,066	7,570	9,078	9,479	11,280	15,353	19,267	22,014	29,566
Industrial	55	104	85	172	209	296	418	478	641
Commercial	33	9	25	22	31	55	55	62	84
Total	**4,155**	**7,683**	**9,188**	**9,673**	**11,520**	**15,704**	**19,740**	**22,554**	**30,291**

Methodology

Woody biomass emissions were estimated by applying two EIA gross heat contents (Lindstrom 2006) to U.S. consumption data (EIA 2007) (see Table 3-59), 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 2007) (see Table 3-60).

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

End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005	2006
Industrial	1,442	1,652	1,636	1,443	1,396	1,363	1,476	1,452	1,469
Residential	580	520	420	370	380	400	410	410	390
Commercial	66	72	71	67	69	71	70	70	65
Electricity Generation	129	125	134	126	150	167	165	185	190
Total	**2,216**	**2,370**	**2,262**	**2,006**	**1,995**	**2,002**	**2,121**	**2,116**	**2,114**

Table 3-60: Ethanol Consumption (Trillion Btu)

End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005	2006
Transportation	61.7	114.8	137.7	143.7	171.0	232.8	292.1	333.8	448.3
Industrial	0.8	1.6	1.3	2.6	3.2	4.5	6.3	7.2	9.7
Commercial	0.5	0.1	0.4	0.3	0.5	0.8	0.8	0.9	1.3
Total	**63.0**	**116.5**	**139.3**	**146.7**	**174.7**	**238.1**	**299.3**	**342.0**	**459.3**

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

Residential wood consumption values were revised in 1997, 1999, and 2000 based on updated information from EIA's Annual Energy Review (EIA 2007). EIA (2007) also reported minor changes in wood consumption for all sectors in 2005. This adjustment of historical data for wood biomass consumption resulted in an average annual increase in emissions from wood biomass consumption of 1.1 Tg CO_2 Eq. (0.6 percent) from 1990 through 2005. Industrial and commercial sector ethanol consumption is now estimated in EIA (2007), which slightly decreased estimates for ethanol consumed in the transportation sector in all years. As a result of these adjustments, average annual emissions from ethanol consumption in the transportation sector decreased by 0.2 Tg CO_2 Eq. (1.8 percent).

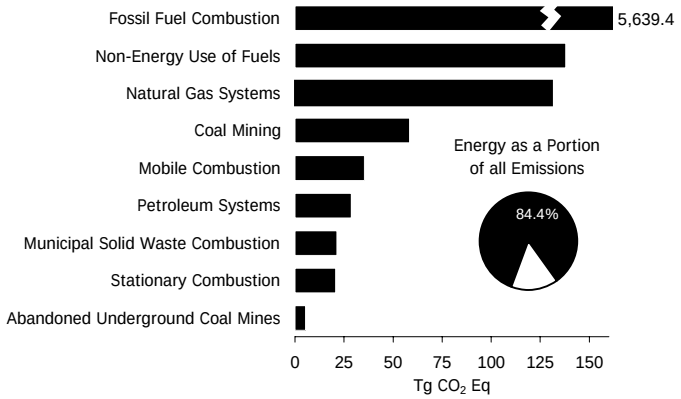

Figure 3-1: 2006 Energy Sector Greenhouse Gas Sources

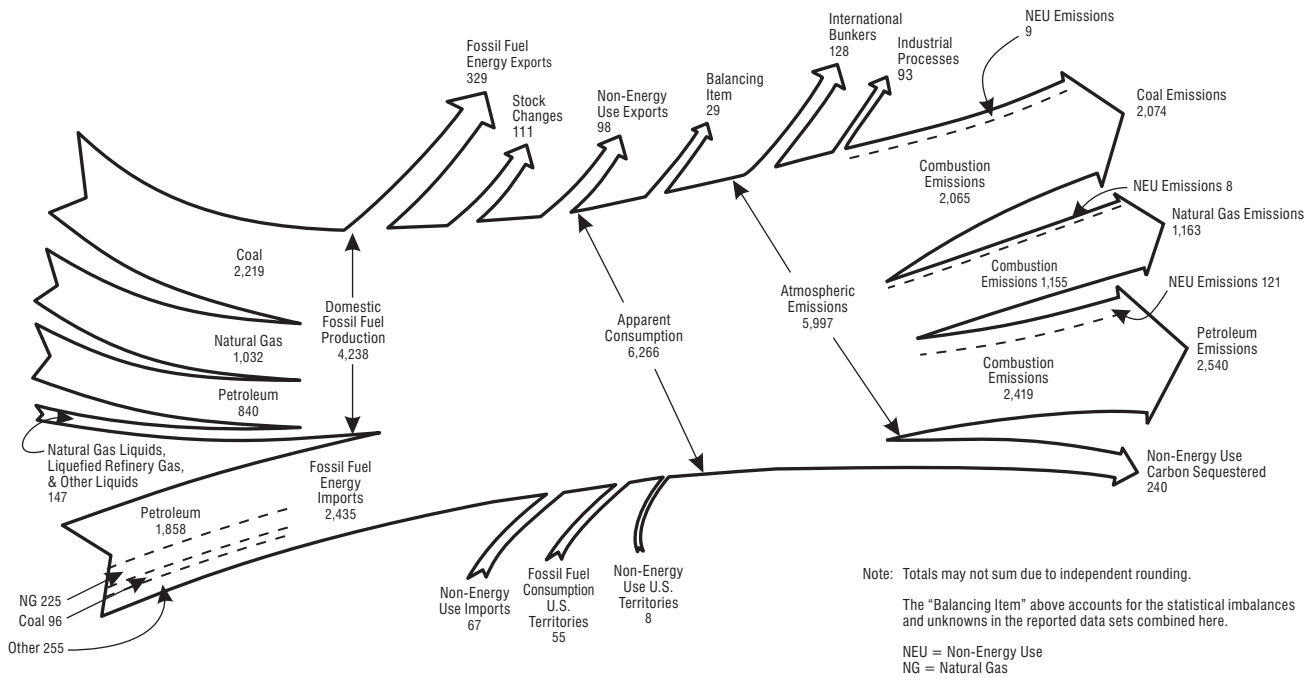

Figure 3-2 2006 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)

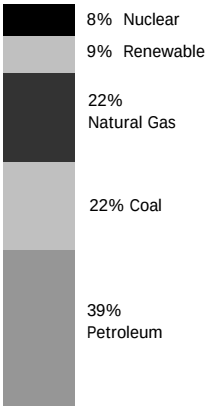

Figure 3-3: 2006 U.S. Energy Consumption by Energy Source

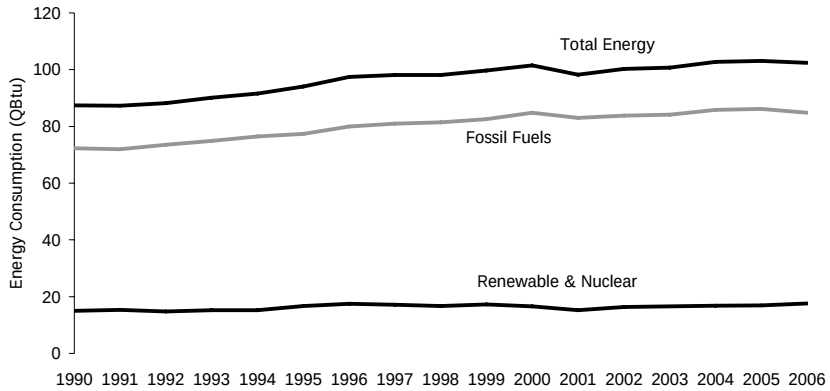

Figure 3-4: U.S. Energy Consumption (Quadrillion Btu)
Note: Expressed as gross calorific values

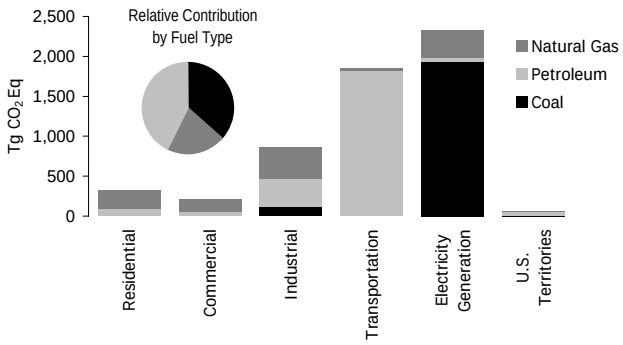

Figure 3-5: 2006 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type
Note: The electricity generation sector also includes emissions of less than 0.01 Tg CO_2 Eq. from geothermal-based electricity generation

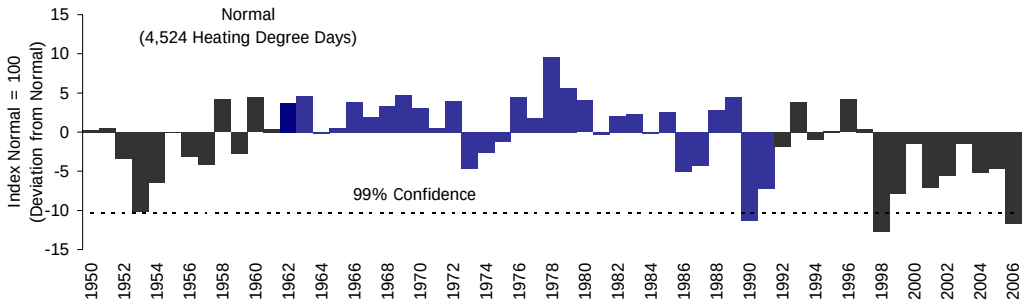

Figure 3-6. Annual Deviations from Normal Heating Degree Days for the United States (1950-2006)
Note: Climatological normal data are highlighted.
Statistical confidence interval for "normal" climatology period of 1961 through 1990.

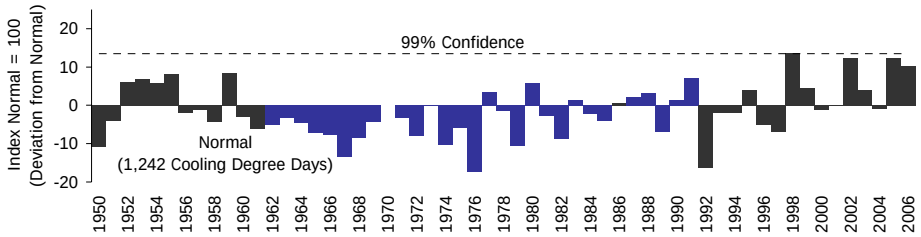

Figure 3-7: Annual Deviations from Normal Cooling Degree Days for the United States (1950-2006)
Note: Climatological normal data are highlighted.
Statistical confidence interval for "normal" climatology period of 1961 through 1990.

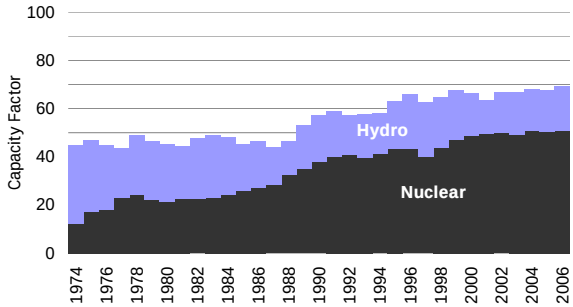

Figure 3-8: Aggregate Nuclear and Hydroelectric Power Plant Capacity Factors in the United States (1974-2006)

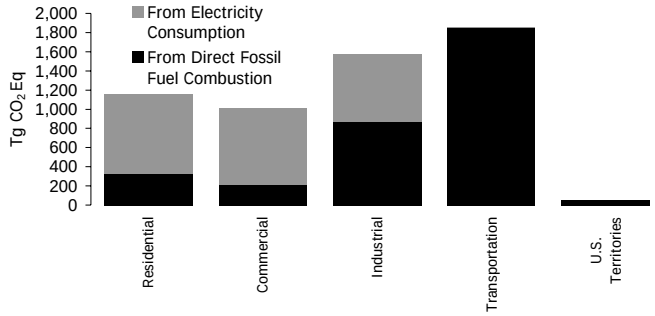

Figure 3-9: 2006 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

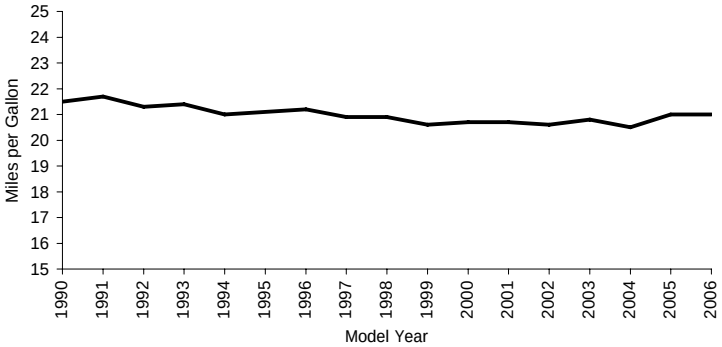

Figure 3-10: Sales-Weighted Fuel Economy of Passenger Cars and Light-Duty Trucks, 1990-2006

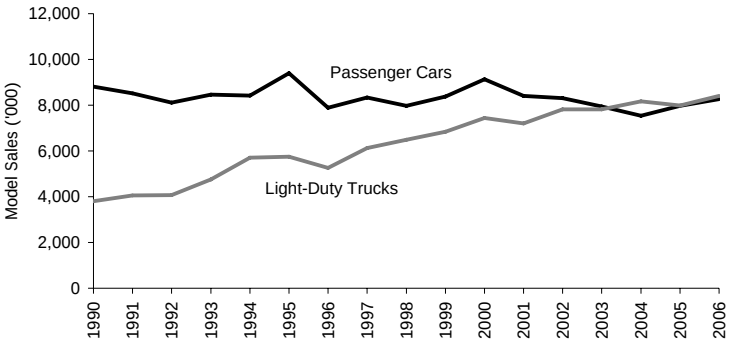

Figure 3-11: Sales of Passenger Cars and Light-Duty Trucks, 1990-2006

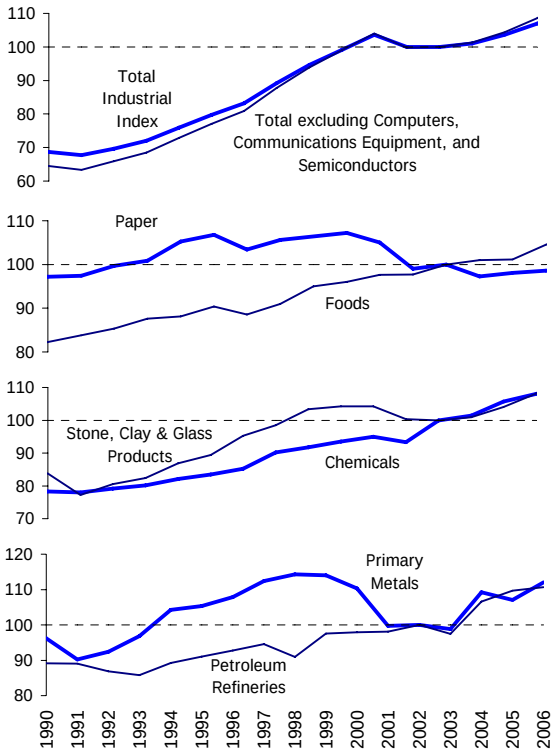

Figure 3-12: Industrial Production Indexes (Index 2002=100)

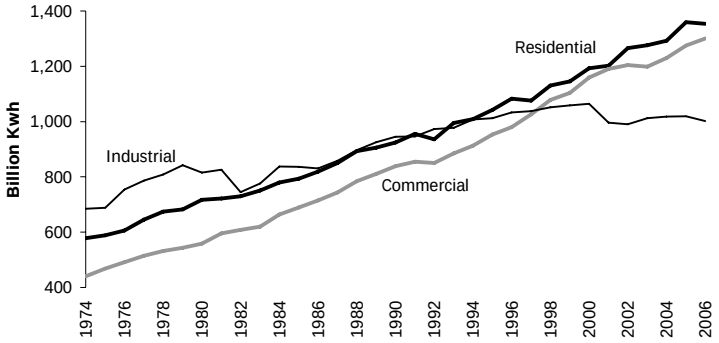

Figure 3-13: Electric Generation Retail Sales by End-Use Sector
Note: The transportation end-use sector consumes minor quanties of electricity.

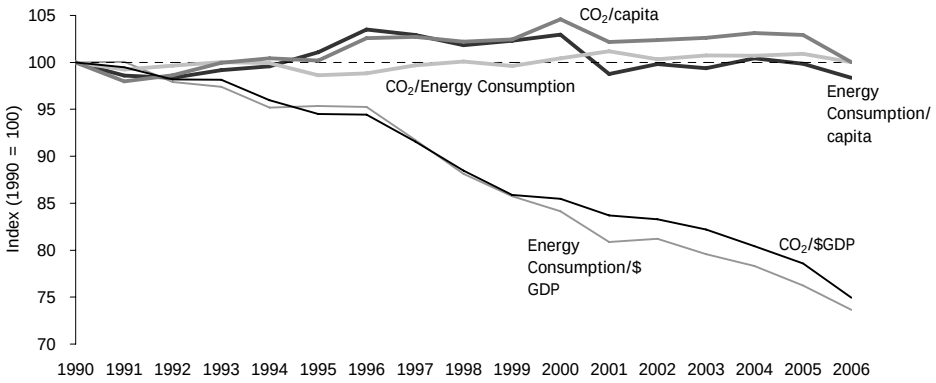

Figure 3-14: U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP

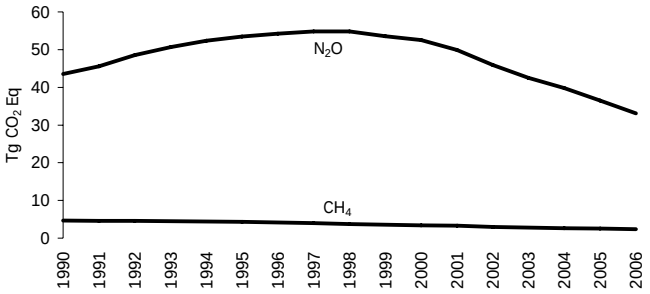

Figure 3-15: Mobile Source CH_4 and N_2O Emissions

4. Industrial Processes

Greenhouse gas emissions are produced as the by-products of various non-energy-related industrial activities. That is, these emissions are produced from an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically transformed from one state to another. This transformation can result in the release of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), or nitrous oxide (N_2O). The processes addressed in this chapter include iron and steel production, cement manufacture, lime manufacture, ammonia manufacture and urea consumption, limestone and dolomite use (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash manufacture and use, aluminum production, titanium dioxide production, CO_2 consumption, ferroalloy production, phosphoric acid production, zinc production, lead production, petrochemical production, silicon carbide production and consumption, nitric acid production, and adipic acid production (see Figure 4-1).

Figure 4-1: 2006 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 2006, industrial processes generated emissions of 316.3 teragrams of CO_2 equivalent (Tg CO_2 Eq.), or 4 percent of total U.S. greenhouse gas emissions. CO_2 emissions from all industrial processes were 148.0 Tg CO_2 Eq. (146,701 Gg) in 2006, 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. (94 Gg) in 2006, which was less than 1 percent of U.S. CH_4 emissions. N_2O emissions from adipic acid and nitric acid production were 21.6 Tg CO_2 Eq. (70 Gg) in 2006, or 4 percent of total U.S. N_2O emissions. In 2006, combined emissions of HFCs, PFCs and SF_6 totaled 144.7 Tg CO_2 Eq. Overall, emissions from industrial processes increased by 6.5 percent from 1990 to 2006 despite decreases in emissions from several industrial processes, such as iron and steel, aluminum production, 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 gigagrams (Gg) are provided in Table 4-2.

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

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	**173.7**	**170.2**	**165.0**	**150.6**	**149.6**	**146.3**	**150.4**	**144.5**	**148.0**
Iron and Steel Production	84.9	73.3	65.1	57.9	54.6	53.4	51.3	45.2	47.7
Cement Manufacture	33.3	36.8	41.2	41.4	42.9	43.1	45.6	45.9	45.7
Lime Manufacture	12.0	14.0	14.9	14.3	13.7	14.5	15.2	15.1	15.8

Ammonia Manufacture & Urea Consumption	16.9	17.8	16.4	13.3	14.2	12.5	13.2	12.8	12.4
Limestone and Dolomite Use	5.5	7.4	6.0	5.7	5.9	4.7	6.7	7.4	8.6
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.1	4.1	4.1	4.2	4.2	4.2
Aluminum Production	6.8	5.7	6.1	4.4	4.5	4.5	4.2	4.2	3.9
Petrochemical Production	2.2	2.8	3.0	2.8	2.9	2.8	2.9	2.8	2.6
Titanium Dioxide Production	1.2	1.5	1.8	1.7	1.8	1.8	2.1	1.8	1.9
Carbon Dioxide Consumption	1.4	1.4	1.4	0.8	1.0	1.3	1.2	1.3	1.6
Ferroalloy Production	2.2	2.0	1.9	1.5	1.3	1.3	1.4	1.4	1.5
Phosphoric Acid Production	1.5	1.5	1.4	1.3	1.3	1.4	1.4	1.4	1.2
Zinc Production	0.9	1.0	1.1	1.0	0.9	0.5	0.5	0.5	0.5
Lead Production	0.3	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	0.2
CH_4	**2.2**	**2.4**	**2.5**	**2.2**	**2.1**	**2.1**	**2.2**	**2.0**	**2.0**
Petrochemical Production	0.9	1.1	1.2	1.1	1.1	1.1	1.2	1.1	1.0
Iron and Steel Production	1.3	1.3	1.2	1.1	1.0	1.0	1.0	1.0	0.9
Ferroalloy Production	+	+	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+	+	+
N_2O	**32.3**	**36.2**	**24.8**	**20.2**	**22.4**	**21.7**	**21.2**	**21.7**	**21.6**
Nitric Acid Production	17.0	18.9	18.6	15.1	16.4	15.4	15.2	15.8	15.6
Adipic Acid Production	15.3	17.3	6.2	5.1	6.1	6.3	5.9	5.9	5.9
HFCs	**35.5**	**56.4**	**100.0**	**96.3**	**103.0**	**102.3**	**112.4**	**119.1**	**121.3**
Substitution of Ozone Depleting Substances	0.3	29.1	70.0	76.3	83.0	89.8	96.6	102.3	107.3
HCFC-22 Production	35.0	27.0	29.8	19.8	19.8	12.3	15.6	16.5	13.8
Semiconductor Manufacturing HFCs	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.3
PFCs	**20.8**	**15.6**	**13.5**	**7.0**	**8.7**	**7.1**	**6.1**	**6.2**	**6.1**
Semiconductor Manufacturing PFCs	2.2	3.8	4.9	3.5	3.5	3.3	3.3	3.2	3.6
Aluminum Production	18.5	11.8	8.6	3.5	5.2	3.8	2.8	3.0	2.5
SF_6	**32.7**	**28.0**	**19.2**	**18.7**	**18.0**	**18.1**	**18.0**	**18.3**	**17.4**
Electrical Transmission and Distribution	26.7	21.5	15.1	15.0	14.4	13.9	14.0	14.0	13.2
Magnesium Production and Processing	5.4	5.6	3.0	2.9	2.9	3.4	3.2	3.3	3.2
Semiconductor Manufacturing SF6	0.5	0.9	1.1	0.7	0.7	0.8	0.8	1.0	1.0
Total	**297.1**	**308.9**	**324.9**	**294.9**	**303.9**	**297.7**	**310.3**	**311.8**	**316.3**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.
[a] Small amounts of PFC emissions also result from this source.

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

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	**173,702**	**170,204**	**164,959**	**150,623**	**149,617**	**146,345**	**150,378**	**144,532**	**148,025**
Iron and Steel Production	84,904	73,333	65,115	57,927	54,595	53,370	51,309	45,235	47,679
Cement Manufacture	33,278	36,847	41,190	41,357	42,898	43,082	45,603	45,910	45,739
Lime Manufacture	12,004	14,019	14,872	14,261	13,652	14,458	15,154	15,131	15,825
Ammonia Manufacture & Urea Consumption	16,889	17,796	16,402	13,305	14,194	12,488	13,241	12,817	12,376
Limestone and Dolomite Use	5,533	7,359	5,960	5,733	5,885	4,720	6,702	7,397	8,615

Soda Ash Manufacture and Consumption	4,141	4,304	4,181	4,147	4,139	4,111	4,205	4,228	4,162
Aluminum Production	6,831	5,659	6,086	4,381	4,490	4,503	4,231	4,207	3,923
Petrochemical Production	2,221	2,750	3,004	2,787	2,857	2,777	2,895	2,804	2,573
Titanium Dioxide Production	1,195	1,526	1,752	1,697	1,824	1,839	2,064	1,755	1,876
Carbon Dioxide Consumption	1,416	1,422	1,421	829	989	1,311	1,198	1,321	1,579
Ferroalloy Production	2,152	2,036	1,893	1,459	1,349	1,305	1,419	1,392	1,505
Phosphoric Acid Production	1,529	1,513	1,382	1,264	1,338	1,382	1,395	1,383	1,167
Zinc Production	949	1,013	1,140	986	937	507	477	465	529
Lead Production	285	298	311	291	286	289	262	267	270
Silicon Carbide Production and Consumption	375	329	248	199	183	202	224	219	207
CH_4	**106**	**116**	**117**	**103**	**101**	**101**	**106**	**97**	**94**
Petrochemical Production	41	52	58	51	52	51	55	51	48
Iron and Steel Production	63	62	58	51	48	49	50	45	45
Ferroalloy Production	1	1	1	+	+	+	+	+	+
Silicon Carbide Production and Consumption	1	1	1	+	+	+	+	+	+
N_2O	**104**	**117**	**80**	**65**	**72**	**70**	**68**	**70**	**70**
Nitric Acid Production	55	61	60	49	53	50	49	51	50
Adipic Acid Production	49	56	20	16	20	20	19	19	19
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M	M	M
HCFC-22 Production	3	2	3	2	2	1	1	1	1
Semiconductor Manufacturing HFCs	+	+	+	+	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Semiconductor Manufacturing PFCs	M	M	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M	M	M
SF_6	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Electrical Transmission and Distribution	1	1	1	1	1	1	1	1	1
Magnesium Production and Processing	+	+	+	+	+	+	+	+	+
Semiconductor Manufacturing SF6	+	+	+	+	+	+	+	+	+

+ Does not exceed 0.5 Gg
M (Mixture of gases)
Note: Totals may not sum due to independent rounding.
[a] Small amounts of PFC emissions also result from this source.

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 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 2006 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. 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 or crude 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 CO2 emissions and fugitive CH4 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 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 used 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 2006 were 47.7 Tg CO_2 Eq. (47,679 Gg) and 0.9 Tg CO_2 Eq. (45 Gg), respectively (see Table 4-3 and Table 4-4), totaling 48.6 Tg CO_2 Eq. Emissions increased in 2006 after declining steadily from 1990 to 2005 due to restructuring of the industry, technological improvements, and increased scrap utilization. In 2006, domestic production of pig iron increased by 1.8 percent and coal coke production decreased by 1.9 percent. Overall, domestic pig iron and coke production have declined since the 1990s. Pig iron production in 2006 was 21 percent lower than in 2000 and 23 percent below 1990 levels. Coke production in 2006 was 21 percent lower than in 2000 and 41 percent below 1990 levels. Overall, emissions from iron and steel productions have declined by 44 percent (37.6 Tg CO_2 Eq.) from 1990 to 2006.

Table 4-3: CO_2 and CH_4 Emissions from Iron and Steel Production (Tg CO_2 Eq.)

Year	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
CO_2	84.9	73.3	65.1	57.9	54.6	53.4	51.3	45.2	47.7
CH_4	1.3	1.3	1.2	1.1	1.0	1.0	1.0	1.0	0.9
Total	**86.2**	**74.6**	**66.3**	**59.0**	**55.6**	**54.4**	**52.4**	**46.2**	**48.6**

Table 4-4: CO_2 and CH_4 Emissions from Iron and Steel Production (Gg)

Year	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
CO_2	84,904	73,333	65,115	57,927	54,595	53,370	51,309	45,235	47,679
CH_4	63	62	58	51	48	49	50	45	45

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 reuse 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 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 4-5) to annual domestic production data for coal coke, sinter, and pig iron.

Table 4-5: 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 through 2004a) and January through March (EIA 2006c, 2007). Data on total coke consumed for pig iron production were taken from the American Iron and Steel Institute (AISI), *Annual Statistical Report* (AISI 2001 through 2007). Scrap steel consumption data for 1990 through 2005 were obtained from *Annual Statistical Report* (AISI 1995, 2001 through 2006) (see Table 4-6). Because scrap steel consumption data were unavailable for 2006, 2005 data were used. 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 through 2007). 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 2007). 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 2005 was obtained from the USGS *Iron Ore Yearbook* (USGS 1994 through 2005). Iron ore consumption for 2006 was obtained from the USGS Minerals Commodity Specialist (Jorgenson 2007). 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 C anodes used during EAF steel and aluminum production were obtained from *Energy and Environmental Profile of the U.S. Aluminum Industry* (DOE 1997).

Table 4-6: 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	2006
CO_2									
Coal Consumption at Coke Plants	35,269	29,948	26,254	23,655	21,461	21,998	21,473	21,259	20,827
Coke Consumption for Pig Iron	25,043	22,288	19,307	17,236	15,959	15,482	15,068	13,848	14,729
Basic Oxygen Furnace Steel Production	56,216	56,721	53,965	47,359	45,463	45,874	47,714	42,705	42,119
Electric Arc Furnace Steel Production	33,510	38,472	47,860	42,774	46,125	47,804	51,969	52,194	56,071
CH_4									
Coke Production	25,054	21,545	18,877	17,191	15,221	15,579	15,340	15,167	14,882
Iron Ore Consumption for Sinter	12,239	12,575	10,784	9,234	9,018	8,984	8,047	8,313	7,085
Domestic Pig Iron Production for Steel	49,062	50,233	47,888	42,134	40,226	40,644	42,292	37,222	37,903

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 4-7. Iron and Steel CO_2 emissions were estimated to be between 39.6 and 55.8 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 17 percent below and 17 percent above the emission estimate of 47.7 Tg CO_2 Eq. Iron and Steel CH_4 emissions were estimated to be between 0.9 Tg CO_2 Eq. 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 0.9 Tg CO_2 Eq.

Table 4-7: 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	2006 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	47.7	39.6	55.8	-17%	+17%
Iron and Steel Production	CH_4	0.9	0.9	1.0	-8%	+8%

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

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- and flux-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.

4.2. 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 is manufactured in 37 states and Puerto Rico. CO_2 emitted from the chemical process of cement production is the second 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 1,450°C (2,400°F) to form lime (i.e., calcium oxide or CaO) and CO_2 in a process known as calcination or calcining. A very small amount of carbonates other than $CaCO_3$ and non-carbonates are 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 potentially other materials (e.g., slag) and used to make portland cement.[2]

In 2006, U.S. clinker production—including Puerto Rico—totaled 88,453 thousand metric tons (van Oss 2007). The resulting emissions of CO_2 from 2006 cement production were estimated to be 45.7 Tg CO_2 Eq. (45,739 Gg) (see Table 4-8).

Table 4-8: 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

[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.

[2] Approximately six percent of total clinker production is used to produce masonry cement, which is produced using plasticizers (e.g., ground limestone, lime) and portland cement. CO_2 emissions that result from the production of lime used to create masonry cement are included in the Lime Manufacture source category (van Oss 2008).

2005	45.9	45,910
2006	45.7	45,739

After falling in 1991 by two percent from 1990 levels, cement production emissions grew every year through 2005, and then decreased slightly from 2005 to 2006. Overall, from 1990 to 2006, emissions increased by 37 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) in the cement kiln. While in the kiln, limestone is broken down into CO_2 and lime with the CO_2 released to the atmosphere. The quantity of CO_2 emitted during cement production is directly proportional to the lime content of the clinker. During calcination, each mole of $CaCO_3$ (i.e., limestone) heated in the clinker kiln forms one mole of lime (CaO) and one mole of CO_2:

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

CO_2 emissions were estimated by applying an emission factor, in tons of CO_2 released per ton of clinker produced, to the total amount of clinker produced. The emission factor used in this analysis is the product of the average lime fraction for clinker of 65 percent (van Oss 2008) and a constant reflecting the mass of CO_2 released per unit of lime. This calculation yields an emission factor of 0.51 tons of CO_2 per ton of clinker produced, which was determined as follows:

$$EF_{\text{Clinker}} = 0.65\ \text{CaO} \times \left[\frac{44.01\ \text{g/mole}\,CO_2}{56.08\ \text{g/mole}\,\text{CaO}}\right] = 0.51\ \text{tons}\ CO_2/\text{ton clinker}$$

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 2006).[3]

The 1990 through 2006 activity data for clinker production (see Table 4-9) were obtained through a personal communication with Hendrik van Oss (van Oss 2007) of the USGS and through the USGS *Mineral Yearbook: Cement* (USGS 1993 through 2006). The data were compiled by USGS through questionnaires sent to domestic clinker and cement manufacturing plants.

Table 4-9: Clinker Production (Gg)

Year	Clinker
1990	64,355
1995	71,257

[3] The 2 percent CO_2 addition associated with CKD is included in the emission estimate for completeness. The cement emission estimate also includes an assumption that all raw material is limestone ($CaCO_3$) when in fact a small percentage is likely composed of non-carbonate materials. Together these assumptions may result in a small emission overestimate (van Oss 2008).

2000	79,656
2001	79,979
2002	82,959
2003	83,315
2004	88,190
2005	88,783
2006	88,453

Uncertainty

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker and in the percentage of CKD recycled inside the cement kiln. Uncertainty is also associated with the assumption that all calcium-containing raw material is $CaCO_3$ when a small percentage likely consists of other carbonate and non-carbonate raw materials. The lime content of clinker varies from 60 to 67 percent (van Oss 2008). CKD loss can range from 1.5 to 8 percent depending upon plant specifications. Additionally, some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of surface area. Because the amount of CO_2 reabsorbed is thought to be minimal, it was not estimated.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-10. Cement Manufacture CO_2 emissions were estimated to be between 39.8 and 52.0 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 45.7 Tg CO_2 Eq.

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

Source	**Gas**	**2006 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	45.7	39.8	52.0	-13%	+14%

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

4.3. 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. 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. In certain applications, lime reabsorbs CO_2 during use.

Lime production in the United States—including Puerto Rico—was reported to be 20,929 thousand metric tons in 2006 (USGS 2007). This resulted in estimated CO_2 emissions of 15.8 Tg CO_2 Eq. (or 15,825 Gg) (see Table 4-11).

Table 4-11: CO_2 Emissions from Lime Manufacture (Tg CO_2 Eq. and Gg)

Year	**Tg CO_2 Eq.**	**Gg**

1990	12.0	12,004
1995	14.0	14,019
2000	14.9	14,872
2001	14.3	14,261
2002	13.7	13,652
2003	14.5	14,458
2004	15.2	15,154
2005	15.1	15,131
2006	15.8	15,825

The contemporary lime market is distributed across five end-use categories as follows: metallurgical uses, 36 percent; environmental uses, 29 percent; chemical and industrial uses, 21 percent; construction uses, 13 percent; and refractory dolomite, 1 percent. In the construction sector, lime is used to improve durability in plaster, stucco, and mortars, as well as to stabilize soils. In 2006, the amount of lime used for construction decreased slightly from 2005 levels, most likely as a result of increased prices for lime and the downturn in new home construction (USGS 2007).

Lime production in 2006 slightly increased over 2005, the fourth annual increase in production after four years of decline. Overall, from 1990 to 2006, lime production has increased by 32 percent. Annual consumption for industrial and chemical, and environmental lime consumption increased by 8 percent and 7 percent, respectively (USGS 2007). The increase in environmental production for environmental uses is attributed in part to growth in demand for flue gas desulfurization technologies, particularly at incineration plants, and wastewater treatment (USGS 2007).

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) (IPCC 2006). The emission factors were calculated as follows:

For high-calcium lime:

$$[(44.01 \text{ g/mole } CO_2) \div (56.08 \text{ g/mole CaO})] \times (0.95 \text{ CaO/lime}) = 0.75 \text{ g } CO_2\text{/g lime}$$

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 $[Ca(OH)_2 \bullet Mg(OH)_2]$) (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 emission estimates were multiplied by a factor of 1.02 to account for lime kiln dust (LKD), which is produced as a by-product during the production of lime (IPCC 2006).

Lime production data (high-calcium- and dolomitic-quicklime, high-calcium- and dolomitic-hydrated, and dead-burned dolomite) for 1990 through 2006 (see Table 4-12) were obtained from USGS (1992 through 2007). Natural hydraulic lime, which is produced from CaO and hydraulic calcium silicates, is not produced in the United States

(USGS 2006). Total lime production was adjusted to account for the water content of hydrated lime by converting hydrate to oxide equivalent, based on recommendations from the IPCC *Good Practice Guidance* and is presented in Table 4-13 (USGS 1992 through 2007, IPCC 2000). The CaO and CaO•MgO contents of lime were obtained from the IPCC (IPCC 2006). Since data for the individual lime types (high calcium and dolomitic) was not provided prior to 1997, total lime production for 1990 through 1996 was calculated according to the three year distribution from 1997 to 1999.

Table 4-12: 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
2006	15,000	2,950	2,370	409	200

Table 4-13: Adjusted Lime Production[a] (Gg)

Year	High-Calcium	Dolomitic
1990	12,514	2,809
1995	14,700	3,207
2000	15,473	3,506
2001	15,137	3,105
2002	14,536	2,934
2003	15,520	2,998
2004	15,820	3,526
2005	15,781	3,535
2006	16,794	3,448

[a] Minus water content of hydrated lime

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.[4]

In some cases, lime is generated from calcium carbonate by-products at pulp mills and water treatment plants.[5] 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.[6]

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 4-14. Lime CO_2 emissions were estimated to be between 14.6 and 17.1 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 15.8 Tg CO_2 Eq.

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

Source	Gas	2006 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	15.8	14.6	17.1	-8%	+8%

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

Recalculations Discussion

Estimates of CO_2 emissions from lime manufacture were revised for all years in the timeseries to remove estimates of CO_2 recovery associated with lime use during sugar refining and precipitate calcium carbonate (PCC) production. Currently, research does not indicate that CO_2 used in these processes stems from CO_2 captured during lime production. Additional research is needed to determine if lime production plants in the US capture CO_2 as well as to determine the fates of precipitates formed during the sugar refining process. This change resulted in an average annual emission increase of 9.5 percent.

[4] 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).

[5] 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.

[6] Based on comments submitted by and personal communication with Dr. Sergio F. Galeano, Georgia-Pacific Corporation.

4.4. Ammonia Manufacture (IPCC Source Category 2B1) and Urea Consumption

Emissions of CO_2 occur during the production of synthetic ammonia, primarily through the use of natural gas 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:

$$0.88\ CH_4 + 1.26\ Air + 1.24\ H_2O \xrightarrow{\text{(catalyst)}} 0.88\ CO_2 + N_2 + 3\ H_2$$

$$N2 + 3\ H2 \rightarrow 2\ NH3$$

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:

$$2\ NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

Urea is consumed for a variety of uses, including as a nitrogenous fertilizer, in urea-formaldehyde resins, and as a deicing agent (TIG 2002). The C in the consumed urea is assumed to be released into the environment as CO_2 during use. Therefore, the CO_2 produced by ammonia production that is subsequently used in the production of urea is still emitted during urea consumption. The majority of CO_2 emissions associated with urea consumption are those that result from its use as a fertilizer. These emissions are accounted for in the Cropland Remaining Cropland section of the Land Use, Land-Use Change, and Forestry chapter. CO_2 emissions associated with other uses of urea are accounted for in this chapter. Net emissions of CO_2 from ammonia manufacture in 2006 were 11.8 Tg CO_2 Eq. (11,832 Gg), and are summarized in Table 4-15 and Table 4-16. Emissions of CO_2 from urea consumed for non-fertilizer purposes in 2006 totaled 0.5 Tg CO_2 Eq. (543 Gg), and are summarized in Table 4-15 and Table 4-16. The decrease in ammonia manufacture in recent years is due to several factors, including market fluctuations and high natural gas prices. Ammonia manufacture relies on natural gas as both a feedstock and a fuel, and as such, domestic manufacturers are competing with imports from countries with lower gas prices. If natural gas prices remain high, it is likely that domestically manufactured ammonia will continue to decrease with increasing ammonia imports (EEA 2004).

Table 4-15: CO_2Emissions from Ammonia Manufacture and Urea Consumption (Tg CO_2 Eq.)

Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
Ammonia Manufacture	16.5	17.4	15.9	12.8	13.7	11.9	12.7	12.3	11.8

Urea Consumption[a]	0.4		0.4		0.5	0.5	0.5	0.6	0.5	0.5	0.5
Total	**16.9**		**17.8**		**16.4**	**13.3**	**14.2**	**12.5**	**13.2**	**12.8**	**12.4**

Note: Totals may not sum due to independent rounding.
[a] Urea Consumption is for non-fertilizer purposes only. Urea consumed as a fertilizer is accounted for in the Land Use, Land-Use Change, and Forestry chapter.

Table 4-16: CO_2 Emissions from Ammonia Manufacture and Urea Consumption (Gg)

Source	**1990**		**1995**		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Ammonia Manufacture	16,528		17,399		15,922	12,795	13,660	11,937	12,695	12,293	11,832
Urea Consumption[a]	361		397		480	510	534	551	546	524	543
Total	**16,889**		**17,796**		**16,402**	**13,305**	**14,194**	**12,488**	**13,241**	**12,817**	**12,376**

Note: Totals may not sum due to independent rounding.
[a] Urea Consumption is for non-fertilizer purposes only. Urea consumed as a fertilizer is accounted for in the Land Use, Land-Use Change, and Forestry chapter.

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 selected EFMA factor is based on ammonia manufacture technologies that are similar to those employed in the U.S. The CO_2 emission factor (1.2 metric tons CO_2/metric ton NH_3) is applied to the percent of total annual domestic ammonia production from natural gas feedstock. Emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter. Emissions of CO_2 from ammonia production are then adjusted to account for the use of some of the CO_2 produced from ammonia production as a raw material in the production of urea. 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. 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 consumption. Those CO_2 emissions that result from the use of urea as a fertilizer are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

Approximately 87 percent (TIG 2002) of urea consumed in the U.S. is consumed as a nitrogenous fertilizer on agricultural lands. The total amount of urea consumed is estimated based on this percent and the quantity of urea fertilizer applied to agricultural lands, which is obtained directly from the Land Use, Land-Use Change, and Forestry Chapter, and is reported in Table 4-17. CO_2 emissions associated with the remaining urea are estimated using a factor of 0.73 tons of CO_2 per ton of urea consumed. Total urea production is estimated based on the amount of urea applied plus the sum of net 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 ton CO_2/metric ton NH_3 for production of ammonia from natural gas feedstock was taken from the EFMA Best Available Techniques publication, *Production of Ammonia* (EFMA 1995). The EFMA reported an emission factor range of 1.15 to 1.30 metric ton CO_2/metric ton NH_3, with 1.2 metric ton CO_2/metric ton NH_3 as a typical value. Technologies (e.g., catalytic reforming process) associated with this factor are found to closely resemble those employed in the U.S. for use of natural gas as a feedstock. The EFMA

reference also indicates that more than 99 percent of the CH_4 feedstock to the catalytic reforming process is ultimately converted to CO_2. The emission factor of 3.57 metric ton CO_2/metric ton NH_3 for production of ammonia from petroleum coke feedstock was developed from plant-specific ammonia production data and petroleum coke feedstock utilization data for the ammonia plant located in Kansas (Bark 2004). As noted earlier, emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter. Ammonia production data (see Table 4-17) was obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007) and the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 1994, 1998 through 2007) as reported in *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports. Urea-ammonia nitrate production was obtained from Coffeyville Resources (Coffeyville 2005 through 2007). With the exception of 2006 urea export data, 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 2006 (U.S. Census Bureau 1998 through 2007), 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 4-17). Because the U.S. Census Bureau did not report urea export data for 2006, 2005 data were proxied.

Table 4-17: Ammonia Production, Urea Production, Urea Net Imports, and Urea Exports (Gg)

Year	Ammonia Production	Urea Applied as Fertilizer	Urea Imports	Urea Exports
1990	15,425	3,296	1,860	774
1995	15,788	3,623	2,936	881
2000	14,342	4,382	3,904	663
2001	11,092	4,655	4,800	792
2002	12,577	4,871	3,840	970
2003	10,279	5,025	4,973	723
2004	10,939	4,982	4,935	704
2005	10,143	4,779	5,026	579
2006	9,962	4,958	5,029	579

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, and the assumption that 87 percent of urea consumed is as fertilizer. 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. 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 4-18. Ammonia Manufacture and Urea Consumption CO_2 emissions were estimated to be between 11.1 and 13.8 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 10 percent below and 12 percent above the emission estimate of 12.4 Tg CO_2 Eq.

Table 4-18: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Manufacture and Urea Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission	Uncertainty Range Relative to Emission Estimate[a]

		Estimate (Tg CO_2 Eq.)	(Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ammonia Manufacture and Urea Consumption	CO_2	12.4	11.1	13.8	-10%	12%

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

Recalculations Discussion

Estimates of CO_2 emissions from ammonia manufacture and urea consumption were revised for all years to allocate CO_2 emissions associated with urea applied as fertilizer to the Land Use, Land-Use Change, and Forestry chapter. Revised estimates reflect a new methodology that estimates urea production and consumption based on urea consumed as fertilizer. Previous estimates of urea production are believed to have overestimated actual urea production. On average, this change resulted in a 19 percent decrease in emissions for each year in the timeseries 1990-2005; however, because CO_2 captured during ammonia manufacture to produce urea is estimated based on the amount of urea produced, emissions from ammonia manufacturing have increased.

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 and incorporating CO_2 capture and storage. Methodologies will also be updated if additional ammonia-production plants are found to use hydrocarbons other than natural gas for ammonia production.

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

Limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$)[7] 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 2006, approximately 13,192 thousand metric tons of limestone and 5,886 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 8.6 Tg CO_2 Eq. (8,615 Gg) (see Table 4-19 and Table 4-20). Emissions in 2006 increased 17 percent from the previous year and have increased 56 percent overall from 1990 through 2006.

Table 4-19: CO_2 Emissions from Limestone & Dolomite Use (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Flux Stone	3.0	4.0	2.8	2.5	2.4	2.1	4.1	3.3	5.1
Glass Making	0.2	0.5	0.4	0.1	0.1	0.3	0.4	0.4	0.7
FGD	1.4	1.7	1.8	2.6	2.8	1.9	1.9	3.0	2.1
Magnesium Production	0.1	0.0	0.1	0.1	0.0	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	0.7

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

Total	**5.5**		**7.4**		**6.0**	**5.7**	**5.9**	**4.7**	**6.7**	**7.4**	**8.6**

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 4-20: CO_2 Emissions from Limestone & Dolomite Use (Gg)

Activity	**1990**		**1995**		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Flux Stone	2,999		4,004		2,830	2,514	2,405	2,072	4,112	3,265	5,072
Limestone	2,554		3,077		1,810	1,640	1,330	904	2,023	1,398	2,291
Dolomite	446		927		1,020	874	1,075	1,168	2,088	1,867	2,781
Glass Making	217		533		368	113	61	337	350	427	747
Limestone	189		410		368	113	61	337	350	406	717
Dolomite	28		122		0	0	0	0	0	21	31
FGD	1,433		1,663		1,774	2,551	2,766	1,932	1,871	2,985	2,061
Magnesium Production	64		41		73	53	0	0	0	0	0
Other Miscellaneous Uses	819		1,119		916	501	652	380	369	721	735
Total	**5,533**		**7,359**		**5,960**	**5,733**	**5,885**	**4,720**	**6,702**	**7,397**	**8,615**

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.

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

Consumption data for 1990 through 2006 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 4-21) were obtained from the USGS *Minerals Yearbook: Crushed Stone Annual Report* (USGS 1993, 1995a-b, 1996a through 2007a). The production capacity data for 1990 through 2006 of dolomitic magnesium metal (see Table 4-22) also came from the USGS (1995c, 1996b through 2007b). 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 2006 *Minerals Yearbook: Magnesium*; therefore, it is assumed that this process continues to be non-existent in the United States (USGS 2007b). During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use. Consumption for 1990 was estimated by applying the 1991 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to 1990 total use. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to the 1992 total.

Additionally, each year the USGS withholds data on certain limestone and dolomite end-uses due to confidentiality agreements regarding company proprietary data. For the purposes of this analysis, emissive end-uses that contained withheld data were estimated using one of the following techniques: (1) the value for all the withheld data points for limestone or dolomite use was distributed evenly to all withheld end-uses; (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years; or (3) the average fraction of total

limestone or dolomite for the end-use over the entire time period.

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.[8]

Table 4-21: Limestone and Dolomite Consumption (Thousand Metric Tons)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Flux Stone	6,738	8,935	6,249	5,558	5,275	4,501	8,971	7,086	11,030
Limestone	5,804	6,995	4,114	3,727	3,023	2,055	4,599	3,176	5,208
Dolomite	933	1,941	2,135	1,831	2,252	2,466	4,373	3,910	5,822
Glass Making	489	1,189	836	258	139	765	796	966	1,693
Limestone	430	933	836	258	139	765	796	923	1,629
Dolomite	59	256	0	0	0	0	0	43	64
FGD	3,258	3,779	4,031	5,798	6,286	4,390	4,253	6,785	4,683
Other Miscellaneous Uses	1,835	2,543	2,081	1,138	1,483	863	840	1,638	1,671
Total	**12,319**	**16,445**	**13,197**	**12,751**	**13,183**	**10,520**	**14,859**	**16,475**	**19,078**

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 4-22: 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
2006	0

Note: Production capacity for 2002, 2003, 2004, 2005, and 2006 amounts to zero because the last U.S. production plant employing the dolomitic process shut down mid-2001 (USGS 2002b through 2007b).

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, among other minerals. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process and the kind of ore processed. Similarly, the quality of the limestone used for glass manufacturing will depend on the type of glass being manufactured.

The estimates below also account for uncertainty associated with activity data. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. The accuracy of

[8] This approach was recommended by USGS.

distribution by end use is also uncertain because this value is reported by the manufacturer and not the end user. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. The uncertainty of the estimates for limestone used in glass making is especially high; however, since glass making accounts for a small percent of consumption, its contribution to the overall emissions estimate is low. Lastly, much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-23. Limestone and Dolomite Use CO_2 emissions were estimated to be between 8.0 and 9.2 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 8.6 Tg CO_2 Eq.

Table 4-23: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Limestone and Dolomite Use (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	8.6	8.0	9.2	-7%	+7%

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

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 consumer products such as glass, soap and detergents, paper, textiles, and food. It is used primarily as an alkali, either in glass manufacturing or simply as a material that reacts with and neutralizes acids or acidic substances. Internationally, two types of soda ash are produced—natural and synthetic. The United States produces only natural soda ash and is second only to China in total soda ash-production. Trona is the principal ore from which natural soda ash is made.

Only two states produce natural soda ash: Wyoming and California. Of these two states, only net emissions of CO_2 from Wyoming were calculated due to specifics regarding the production processes employed in the state.[9] During

[9] 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.
A third state, Colorado, produced soda ash until the plant was idled in 2004. The lone producer of sodium bicarbonate no longer mines trona in the state. For a brief time, $NaHCO_3$ was produced using soda ash feedstocks mined in Wyoming and shipped to Colorado. Because the trona is mined in Wyoming, the production numbers given by the USGS included the feedstocks mined in Wyoming and shipped to Colorado. In this way, the sodium bicarbonate production that took place in Colorado was accounted for in the Wyoming numbers.

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 2006, CO_2 emissions from the manufacture of soda ash from trona were approximately 1.6 Tg CO_2 Eq. (1,626 Gg). Soda ash consumption in the United States generated 2.5 Tg CO_2 Eq. (2,536 Gg) in 2006. Total emissions from soda ash manufacture and consumption in 2006 were 4.2 Tg CO_2 Eq. (4,162 Gg) (see Table 4-24 and Table 4-25). Emissions have fluctuated since 1990. These fluctuations were strongly related to the behavior of the export market and the U.S. economy. Emissions in 2006 decreased by approximately 1.6 percent from the previous year, and have increased overall by approximately 0.5 percent since 1990.

Table 4-24: 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
2006	1.6	2.5	4.2

Note: Totals may not sum due to independent rounding.

Table 4-25: 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
2006	1,626	2,536	4,162

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 2006 was glass making, 50 percent; chemical production, 29 percent; soap and detergent manufacturing, 9 percent; distributors, 4 percent; flue gas desulfurization, 2 percent; water treatment, 2 percent; pulp and paper production, 1 percent; and miscellaneous, 3 percent (USGS 2007).

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 emissions from the calcination of trona can be estimated based on the following chemical reaction:

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

Based on this formula, approximately 10.27 metric tons of trona are required to generate one metric ton of CO_2, or an emission factor of 0.097 metric tons CO_2 per metric ton trona (IPCC 2006). Thus, the 16.7 million metric tons of trona mined in 2006 for soda ash production (USGS 2007) resulted in CO_2 emissions of approximately 1.6 Tg CO_2 Eq. (1,626 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 4-26) were taken from USGS (1994 through 2007). Soda ash manufacture and consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Table 4-26: 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
2006	16,700	6,110

* 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 4-27. 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.

Table 4-27: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Manufacture and Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]

		(Tg CO_2 Eq.)	(Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
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.

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 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 2006 were 1.9 Tg CO_2 Eq. (1,876 Gg), an increase of 7 percent from the previous year and an increase of 57 percent since 1990 (Table 4-28).

Table 4-28: CO_2 Emissions from Titanium Dioxide (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.2	1,195
1995	1.5	1,526
2000	1.8	1,752
2001	1.7	1,697
2002	1.8	1,824
2003	1.8	1,839
2004	2.1	2,064
2005	1.8	1,755
2006	1.9	1,876

Methodology

Emissions of CO_2 from TiO_2 production were calculated by multiplying annual TiO_2 production by chloride-process-specific emission factors.

Data were obtained for the total amount of TiO_2 produced each year. For years previous to 2004, it was assumed that TiO_2 was produced using the chloride process and the sulfate process in the same ratio as the ratio of the total 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 *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Titanium dioxide production data and the percentage of total TiO_2 production capacity that is chloride process for 1990 through 2006 (see Table 4-29) were obtained from a personal communication with Joe Gambogi, USGS Commodity Specialist, of the USGS (Gambogi 2007) 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 4-29: 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
2006	1,400

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 4-30. Titanium dioxide consumption CO_2 emissions were estimated to be between 1.7 and 2.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 13 percent above the emission estimate of 1.9 Tg CO_2 Eq.

Table 4-30: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	1.7	2.1	-12%	+13%

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

Recalculations Discussion

Estimates of CO_2 emissions from titanium dioxide production were updated to reflect a revised chloride-process emission factor provided by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). The change in emission factor resulted in a decrease in emissions of 8.6 percent for each year in the timeseries.

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. 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.

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 U.S. 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 2006, the amount of CO_2 produced by the Mississippi and New Mexico facilities for commercial applications and subsequently emitted to the atmosphere were 1.6 Tg CO_2 Eq. (1,579 Gg) (see Table 4-31). This amount represents an increase of 17.9 percent from the previous year and an increase of 9.9 percent from emissions in 1990. This increase was due to an in increase in production at the Mississippi facility, despite the decrease in the percent of the facility's total reported production that was used for commercial applications.

Table 4-31: CO_2 Emissions from CO_2 Consumption (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.4	1,416
1995	1.4	1,422
2000	1.4	1,421
2001	0.8	829
2002	1.0	989
2003	1.3	1,311
2004	1.2	1,198
2005	1.3	1,321
2006	1.6	1,579

Methodology

CO_2 emission estimates for 1990 through 2006 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. 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 for EOR and in non-EOR applications were obtained from the Advanced Resources Institute (ARI 2007) for 1990 to 2000 and from the Annual Reports for Denbury Resources (Denbury Resources 2002 through 2007) for 2001 to 2006 (see Table 4-32). Denbury Resources reported the average CO_2 production in units of MMCF CO_2 per day for 2001 through 2006 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 Advanced Resources International, Inc. (ARI 2007).

Table 4-32: 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%	6,301	1%

1995	1,353	100%	6,862	1%
2000	1,353	100%	6,834	1%
2001	1,624	47%	6,627	1%
2002	2,010	46%	6,420	1%
2003	3,286	38%	6,213	1%
2004	4,214	27%	6,006	1%
2005	4,678	27%	5,799	1%
2006	7,615	20%	5,613	1%

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 4-33. CO_2 consumption CO_2 emissions were estimated to be between 1.3 and 2.0 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 21 percent below to 26 percent above the emission estimate of 1.6 Tg CO_2 Eq.

Table 4-33: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from CO_2 Consumption (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2006 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	1.6	1.3	2.0	-21%	26%

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

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. These changes resulted in an average annual emission increase of less than one percent for 1990 through 2005.

4.9. 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:

$$Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO$$

While most of the C contained in the process materials is released to the atmosphere as CO_2, a percentage is also released as CH_4 and other volatiles. The amount of CH_4 that is released is dependent on furnace efficiency, operation technique, and control technology.

Emissions of CO_2 from ferroalloy production in 2006 were 1.5 Tg CO_2 Eq. (1,505 Gg) (see Table 4-34 and Table 4-35), which is an eight percent increase from the previous year and a 30 percent reduction since 1990. Emissions of CH_4 from ferroalloy production in 2006 were 0.01 Tg CO_2 Eq. (0.4 Gg), which is an 11 percent increase from the previous year and a 37 percent decrease since 1990.

Table 4-34: CO_2 and CH_4 Emissions from Ferroalloy Production (Tg CO_2 Eq.)

Year	**1990**		**1995**		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
CO_2	2.2		2.0		1.9	1.5	1.3	1.3	1.4	1.4	1.5
CH_4	+		+		+	+	+	+	+	+	+
Total	**2.2**		**2.0**		**1.9**	**1.5**	**1.4**	**1.3**	**1.4**	**1.4**	**1.5**

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

Table 4-35: CO_2 and CH_4 Emissions from Ferroalloy Production (Gg)

Year	**1990**		**1995**		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
CO_2	2,152		2,036		1,893	1,459	1,349	1,305	1,419	1,392	1,505
CH_4	0.7		0.6		0.5	0.4	0.4	0.4	0.4	0.4	0.4

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 CH_4/metric ton of alloy produced). Additionally, for ferrosilicon alloys containing 56 to 95 percent silicon, an emission factor for 75 percent silicon ferrosilicon was applied for both CO_2 and CH_4 (4 metric tons CO_2/metric ton alloy produced and 1 kg CH_4/metric ton of alloy produced, respectively). The emission factors for silicon metal equaled 5 metric tons CO_2/metric ton metal produced and 1.2 kg CH_4/metric ton metal produced. It was assumed that 100 percent of the ferroalloy production was produced using petroleum coke using an electric arc furnace process (IPCC 2006), although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite C inputs. The amount of petroleum coke consumed in ferroalloy production was calculated assuming that the petroleum coke used is 90 percent C and 10 percent inert material.

Ferroalloy production data for 1990 through 2006 (see Table 4-36) were obtained from the USGS through personal communications with the USGS Silicon Commodity Specialist (Corathers 2007) and through the *Minerals Yearbook: Silicon Annual Report* (USGS 1991 through 2006). Because USGS does not provide estimates of silicon metal production for 2006, 2005 production data are used. Until 1999, the USGS reported production of ferrosilicon containing 25 to 55 percent silicon separately from production of miscellaneous alloys containing 32 to 65 percent silicon; beginning in 1999, the USGS reported these as a single category (see Table 4-36). The composition data for petroleum coke was obtained from Onder and Bagdoyan (1993).

Table 4-36: 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
2006	164,000	88,700	148,000	NA

NA (Not Available)

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.[10] 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 4-37. Ferroalloy production CO_2 emissions were estimated to be between 1.3 and 1.7 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 12 percent above the emission estimate of 1.5 Tg CO_2 Eq. Ferroalloy production CH_4 emissions were estimated to be between a range of approximately 12 percent below and 12 percent above the emission estimate of 0.01 Tg CO_2 Eq.

Table 4-37: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ferroalloy Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower	Upper	Lower	Upper

[10] Emissions and sinks of biogenic carbon are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

			Bound	Bound	Bound	Bound
Ferroalloy Production	CO_2	1.5	1.3	1.7	-12%	+12%
Ferroalloy Production	CH_4	+	+	+	-12%	+12%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
+ Does not exceed 0.05 Tg CO_2 Eq.

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.

4.10. Phosphoric Acid Production (IPCC Source Category 2B5)

Phosphoric acid (H_3PO_4) is a basic raw material in the production of phosphate-based fertilizers. Phosphate rock is mined in Florida, North Carolina, Idaho, Utah, and other areas of the United States and is used primarily as a raw material for phosphoric acid production. The production of phosphoric acid from phosphate rock produces byproduct gypsum ($CaSO_4$-$2H_2O$), referred to as phosphogypsum.

The composition of natural phosphate rock varies depending upon the location where it is mined. Natural phosphate rock mined in the United States generally contains inorganic C in the form of calcium carbonate (limestone) and also may contain organic C. The chemical composition of phosphate rock (francolite) mined in Florida is:

$$Ca_{10-x-y}\ Na_x\ Mg_y\ (PO_4)_{6-x}(CO_3)_xF_{2+0.4x}$$

The calcium carbonate component of the phosphate rock is integral to the phosphate rock chemistry. Phosphate rock can also contain organic C that is physically incorporated into the mined rock but is not an integral component of the phosphate rock chemistry. Phosphoric acid production from natural phosphate rock is a source of CO_2 emissions, due to the chemical reaction of the inorganic C (calcium carbonate) component of the phosphate rock.

The phosphoric acid production process involves chemical reaction of the calcium phosphate ($Ca_3(PO_4)_2$) component of the phosphate rock with sulfuric acid (H_2SO_4) and recirculated phosphoric acid (H_3PO_4) (EFMA 1997). The primary chemical reactions for the production of phosphoric acid from phosphate rock are:

$$Ca_3(PO_4)_2 + 4H_3PO_4 \rightarrow 3Ca(H_2PO_4)_2$$

$$3Ca(H_2PO_4)_2 + 3H_2SO_4 + 6H_2O \rightarrow 3CaSO_4\ 6H_2O + 6H_3PO_4$$

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:

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4\ 2H_2O + CO_2$$

Total marketable phosphate rock production in 2006 was 30.1 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, 2.4 million metric tons of crude phosphate rock was imported for consumption in 2006. Marketable phosphate rock production, including domestic production and imports for consumption, decreased by approximately 16 percent between 2005 and 2006. However, over the 1990 to 2006 period, production has decreased by 26 percent. Total CO_2 emissions from phosphoric acid production were 1.2 Tg CO_2 Eq. (1,167 Gg) in 2006 (see Table 4-38).

Table 4-38: 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
2006	1.2	1,167

Methodology

CO_2 emissions from production of phosphoric acid from phosphate rock are calculated by multiplying the average amount of calcium carbonate contained in the natural phosphate rock by the amount of phosphate rock that is used annually to produce phosphoric acid, accounting for domestic production and net imports for consumption.

The CO_2 emissions calculation methodology is based on the assumption that all of the inorganic C (calcium carbonate) content of the phosphate rock reacts to CO_2 in the phosphoric acid production process and is emitted with the stack gas. The methodology also assumes that none of the organic C content of the phosphate rock is converted to CO_2 and that all of the organic C content remains in the phosphoric acid product.

From 1993 to 2004, the *USGS Mineral Yearbook: Phosphate Rock* disaggregated phosphate rock mined annually in Florida and North Carolina from phosphate rock mined annually in Idaho and Utah, and reported the annual amounts of phosphate rock exported and imported for consumption (see Table 4-39). For the years 1990, 1991, 1992, 2005, and 2006 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 phosphate rock for consumption for 1990 through 2005 were obtained from *USGS Minerals Yearbook: Phosphate Rock* (USGS 1994 through 2006). Production data for 2006 were obtained from a personal communication with the USGS Minerals Commodity Specialist (Jasinski 2007). From 2004-2006, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2005, 2006, Jasinski 2007).

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 4-40).

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 2006). Carbonate content data for uncalcined phosphate rock mined in Idaho and Utah (13 percent of domestic production) were not available, and carbonate content was therefore estimated from the carbonate content data for calcined phosphate rock mined in Idaho.

Table 4-39: Phosphate Rock Domestic Production, Exports, and Imports (Gg)

Location/Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
U.S. Production[a]	49,800	43,720	37,370	32,830	34,720	36,410	36,530	36,000	30,100
FL & NC	42,494	38,100	31,900	28,100	29,800	31,300	31,600	31,140	26,037
ID & UT	7,306	5,620	5,470	4,730	4,920	5,110	4,930	4,860	4,064
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	2,420
Total U.S. Consumption	**44,011**	**42,760**	**39,001**	**35,321**	**37,358**	**38,746**	**39,030**	**38,630**	**32,520**

[a] USGS does not disaggregate production data regionally (FL & NC and ID & UT) for 1990 and 2006. Data for those years are estimated based on the remaining time series distribution.
- Assumed equal to zero.

Table 4-40: Chemical Composition of Phosphate Rock (percent by weight)

Composition	Central Florida	North Florida	North Carolina (calcined)	Idaho (calcined)	Morocco
Total Carbon (as C)	1.60	1.76	0.76	0.60	1.56
Inorganic Carbon (as C)	1.00	0.93	0.41	0.27	1.46
Organic Carbon (as C)	0.60	0.83	0.35	-	0.10
Inorganic Carbon (as CO_2)	3.67	3.43	1.50	1.00	5.00

Source: FIPR 2003
- Assumed equal to zero.

Uncertainty

Phosphate rock production data used in the emission calculations were developed by the USGS through monthly and semiannual voluntary surveys of the active phosphate rock mines during 2006. For previous years in the time series, USGS provided the data disaggregated regionally; however, for 2006 only total U.S. phosphate rock production were reported. Regional production for 2006 was estimated based on regional production data from previous years and multiplied by regionally-specific emission factors. There is uncertainty associated with the degree to which the estimated 2006 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 approximately 7 percent of domestically-produced phosphate rock is used to manufacture elemental phosphorus and other phosphorus-based chemicals, rather than phosphoric acid (USGS 2006). According to USGS, there is only one domestic producer of elemental phosphorus, in Idaho, and no data were available concerning the annual production of this single producer. Elemental phosphorus is produced by

reducing phosphate rock with coal coke, and it is therefore assumed that 100 percent of the carbonate content of the phosphate rock will be converted to CO_2 in the elemental phosphorus production process. The calculation for CO_2 emissions is based on the assumption that phosphate rock consumption, for purposes other than phosphoric acid production, results in CO_2 emissions from 100 percent of the inorganic C content in phosphate rock, but none from the organic C content.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-41. Phosphoric acid production CO_2 emissions were estimated to be between 1.0 and 1.4 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 19 percent above the emission estimate of 1.2 Tg CO_2 Eq.

Table 4-41: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	1.2	1.0	1.4	-18%	+19%

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

Planned Improvements

Currently, data sources for the carbonate content of the phosphate rock are limited. If additional data sources are found, this information will be incorporated into future estimates.

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 electrothermic 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 electrothermic 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 electrothermic 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).

In 2006, U.S. primary and secondary zinc production totaled 510,000 metric tons (Tolcin 2007). The resulting emissions of CO_2 from zinc production in 2006 were estimated to be 0.5 Tg CO_2 Eq. (529 Gg) (see Table 4-42). All 2006 CO_2 emissions result from secondary zinc production.

Table 4-42: CO_2 Emissions from Zinc Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	0.9	949
1995	1.0	1,013
2000	1.1	1,140
2001	1.0	986
2002	0.9	937
2003	0.5	507
2004	0.5	477
2005	0.5	465
2006	0.5	529

After a gradual increase in total emissions from 1990 to 2000, largely due to an increase in secondary zinc production, emissions have decreased in recent years due to the closing of an electro-thermic-process zinc plant in Monaca, PA (USGS 2004). In 2006, emissions, which are nearly half that of 1990 (44 percent), increased by 14 percent over 2005 levels despite decreases in overall production due to an increase in production from emissive secondary zinc production processes.

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:

$$EF_{\text{Waelz Kiln}} = \frac{1.19\ metric\ tons\ coke}{metric\ tons\ zinc} \times \frac{0.84\ metric\ tons\ C}{metric\ ton\ coke} \times \frac{3.67\ metric\ tons\ CO2}{metric\ ton\ C} = \frac{3.66\ metric\ tons\ CO2}{metric\ ton\ zinc}$$

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:

$$EF_{\text{EAF Dust}} = \frac{0.4\ metric\ tons\ coke}{metric\ tons\ EAF\ dust} \times \frac{0.84\ metric\ tons\ C}{metric\ ton\ coke} \times \frac{3.67\ metric\ tons\ CO2}{metric\ ton\ C} = \frac{1.23\ metric\ tons\ CO2}{metric\ ton\ EAF\ Dust}$$

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 2006 activity data for primary and secondary zinc production (see Table 4-43) were obtained through the USGS *Mineral Yearbook: Zinc* (USGS 1994 through 2006) and from the USGS Minerals Commodity Specialist (Tolcin 2007).

Table 4-43: 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	191,120	349,000
2006	113,000	397,000

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 4-44. Zinc production CO_2 emissions were estimated to be between 0.4 and 0.7 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.

Table 4-44: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	0.7	-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—both of which emit CO_2 (Sjardin 2003). Primary lead production, in the form of direct smelting, mostly occurs at plants located in Alaska and Missouri, though to a lesser extent in Idaho, Montana, and Washington. Secondary production largely involves the recycling of lead acid batteries at 18 separate smelters located in 11 states (USGS 2006). Secondary lead production has increased in the United States over the past decade while primary lead production has decreased. In 2006, secondary lead production accounted for approximately 88 percent of total lead production (Smith 2007, USGS 1995).

Primary production of lead through the direct smelting of lead concentrate produces CO_2 emissions as the lead concentrates are reduced in a furnace using metallurgical coke (Sjardin 2003). U.S. primary lead production increased by 7 percent from 2005 to 2006 and has decreased by 62 percent since 1990 (Smith 2007, USGS 1995)

Approximately 92 percent of U.S. secondary lead is produced by recycling lead acid batteries in either blast furnaces or reverberatory furnaces (USGS 2006). The remaining 8 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 half a percent from 2005 to 2006, and has increased by 25 percent since 1990.

At last reporting, the United States was the third largest mine producer of lead in the world, behind China and Australia, accounting for 13 percent of world production in 2005 (USGS 2006). In 2006, U.S. primary and secondary lead production totaled 1,313,000 metric tons (Smith 2007). The resulting emissions of CO_2 from 2006 production were estimated to be 0.3 Tg CO_2 Eq. (270 Gg) (see Table 4-45). The majority of 2006 lead production is from secondary processes, which account for 86 percent of total 2006 CO_2 emissions.

Table 4-45: 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	291
2002	0.3	286
2003	0.3	289
2004	0.3	262
2005	0.3	267
2006	0.3	270

After a gradual increase in total emissions from 1990 to 2000, total emissions have decreased by five percent since 1990, largely due to a decrease in primary production (62 percent since 1990) and a transition within the United States from primary lead production to secondary lead production, which is less emissive than primary production, although the sharp decrease leveled off in 2005 and even increased slightly in 2006 (USGS 2006, Smith 2007).

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) and the IPCC (2006) provide an emission factor of 0.25 metric tons CO_2/ton lead. For secondary lead production, Sjardin (2003) and IPCC (2006) provide 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 2005 activity data for primary and secondary lead production (see Table 4-46) were obtained through the USGS *Mineral Yearbook: Lead* (USGS 1994 through 2006). Primary and secondary lead production data for 2006 were obtained from the USGS Lead Minerals Commodity Specialist (Smith 2007)

Table 4-46: 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	1,090,000
2002	262,000	1,100,000
2003	245,000	1,140,000
2004	148,000	1,127,000
2005	143,000	1,154,000
2006	153,000	1,160,000

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 emission factor associated with battery treatment. The applicability of these emission factors to plants in the United States is uncertain. There is also a smaller level of uncertainty associated with the accuracy of primary and secondary production data provided by the USGS.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-47. 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 16 percent above the emission estimate of 0.3 Tg CO_2 Eq.

Table 4-47: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lead Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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%	+16%

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

Recalculations Discussion

Estimates of CO_2 emissions from lead production were revised for the 2001, 2002, 2004, and 2005 to reflect updated secondary production activity (USGS 2006 and Smith 2007). This change resulted in a less than 2 percent decrease in emissions for 2001 and 2002, and a less than 2 percent increase in emissions for 2004 and 2005.

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 2006 were 2.6 Tg CO_2 Eq. (2,573 Gg) and 1.0 Tg CO_2 Eq. (48 Gg), respectively (see Table 4-48 and Table 4-49), totaling 3.6 Tg CO_2 Eq. Emissions of CO_2 from C black production decreased from 2.8 Tg CO_2 Eq. (2,805 Gg) in 2005 to 2.6 Tg CO_2 Eq. (2,573 Gg) in 2006 . There has been an overall increase in CO_2 emissions from C black production of 16 percent since 1990. CH_4 emissions from petrochemical production decreased by less than 1 percent from the previous year and increased 16 percent since 1990.

Table 4-48: CO_2 and CH_4 Emissions from Petrochemical Production (Tg CO_2 Eq.)

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	2.2	2.8	3.0	2.8	2.9	2.8	2.9	2.8	2.6
CH_4	0.9	1.1	1.2	1.1	1.1	1.1	1.2	1.1	1.0
Total	**3.1**	**3.8**	**4.2**	**3.9**	**4.0**	**3.9**	**4.1**	**4.0**	**3.6**

Table 4-49: CO_2 and CH_4 Emissions from Petrochemical Production (Gg)

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	2,221	2,750	3,004	2,787	2,857	2,777	2,895	2,804	2,573
CH_4	41	52	58	51	52	51	55	51	48

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,[11] 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 4-50) were obtained from the Chemical Manufacturer's Association *Statistical Handbook* (CMA 1999). Production data for 1991 through 2006 were obtained from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2002, 2003, 2005 through 2007) and the International Carbon Black Association (Johnson 2003, 2005 through 2007).

Table 4-50: Production of Selected Petrochemicals (Thousand Metric Tons)

Chemical	1990	1995	2000	2001	2002	2003	2004	2005	2006
Carbon Black	1,307	1,619	1,769	1,641	1,682	1,635	1,705	1,651	1,515
Ethylene	16,542	21,215	24,971	22,521	23,623	22,957	25,660	23,954	25,000
Ethylene Dichloride	6,282	7,829	9,866	9,294	9,288	9,952	12,111	11,261	9,737
Methanol	3,785	4,992	4,876	3,402	3,289	3,166	2,937	2,336	1,123

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 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

[11] 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 ($C_2H_2Cl_2$).

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 4-51) 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).

Table 4-51: Carbon Black Feedstock (Primary Feedstock) and Natural Gas Feedstock (Secondary Feedstock) Consumption (Thousand Metric Tons)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Primary Feedstock	1,864	2,308	2,521	2,339	2,398	2,331	2,430	2,353	2,159
Secondary Feedstock	302	374	408	379	388	377	393	381	350

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 4-52. Petrochemical production CO_2 emissions were estimated to be between 1.7 and 3.6 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 35 percent below to 39 percent above the emission estimate of 2.6 Tg CO_2 Eq. Petrochemical production CH_4 emissions were estimated to be between 0.9 and 1.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below to 9 percent above the emission estimate of 1.0 Tg CO_2 Eq.

Table 4-52: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petrochemical Production and CO_2

Emissions from Carbon Black Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	2.6	1.7	3.6	-35%	+39%
Petrochemical Production	CH_4	1.0	0.9	1.1	-9%	+9%

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

Recalculations Discussion

Estimates of CO_2 from carbon black have been revised for 2005 to reflect new production data. The revision resulted in a decrease in emissions of less than one percent.

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 24) 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 from SiC production and consumption in 2006 were 0.2 Tg CO_2 Eq. (207 Gg). Approximately 44 percent of these emissions resulted from SiC production while the remainder result from SiC consumption. CH_4 emissions from SiC production in 2006 were 0.01 Tg CO_2 Eq. CH_4 (0.4 Gg) (see Table 4-53 and Table 4-54).

Table 4-53: 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	2006
CO_2	0.4	0.3	0.2	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**	**0.2**

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

Table 4-54: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (Gg)

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	375	329	248	199	183	202	224	219	207
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 from silicon carbide consumption were calculated by multiplying the annual SiC consumption (production plus net imports) by the percent used in metallurgical and other non-abrasive uses (50 percent) (USGS 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 through 2005a, 2006). Production data for 2006 were obtained from a personal communication with the USGS Minerals Commodity Specialist (Corathers 2007). Silicon carbide consumption by major end use was obtained from the Minerals Yearbook: Silicon (USGS 1991b through 2005b) (see Table 4-55) for years 1990 through 2004 and from the USGS Minerals Commodity Specialist for 2005 and 2006 (Corathers 2006, 2007). Net imports for the entire time series were obtained from the U.S. Census Bureau (2005 through 2007).

Table 4-55: 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
2006	35,000	199,938

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 4-56. Silicon carbide production and consumption CO_2 emissions were estimated 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 10 percent above the emission estimate of 0.01 Tg CO_2 Eq. at the 95 percent confidence level.

Table 4-56: Tier 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Silicon Carbide Production and Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Silicon Carbide Production and Consumption	CO_2	0.2	0.2	0.2	-10%	+10%

Silicon Carbide Production and Consumption	CH_4	+	+	+	-9%	+10%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
+ Does not exceed 0.05 Tg CO_2 Eq. or 0.5 Gg.

Planned Improvements

Future improvements to the carbide production source category include continued research to determine if calcium carbide production and consumption data are available for the United States. If these data are available, calcium carbide emission estimates will be included in this source category.

4.15. 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.

N_2O emissions from this source were estimated to be 15.6 Tg CO_2 Eq. (50 Gg) in 2006 (see Table 4-57). Emissions from nitric acid production have decreased by 7.8 percent since 1990, with the trend in the time series closely tracking the changes in production.

Table 4-57: N_2O Emissions from Nitric Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	17.0	55
1995	18.9	61
2000	18.6	60
2001	15.1	49
2002	16.4	53
2003	15.4	50
2004	15.2	49
2005	15.8	51
2006	15.6	50

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 kg N_2O/metric ton HNO_3 for plants not equipped with NSCR (IPCC 2006). In the process of destroying NO_x, NSCR systems destroy 80 to 90 percent of the N_2O, which is accounted for in the emission factor of 2 kg N_2O/metric ton HNO_3. 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 $(9 \times 0.80) + (2 \times 0.20) = 7.6$ kg N_2O per metric ton HNO_3.

Nitric acid production data for 1990 through 2004 was obtained from the U.S. Census Bureau, *Current Industrial Reports* (2006) and for 2005 through 2006, from the U.S. Census Bureau, *Current Industrial Reports* (2007) (see Table 4-58).

Table 4-58: Nitric Acid Production (Gg)

Year	Gg
1990	7,195
1995	8,019
2000	7,900
2001	6,417
2002	6,941
2003	6,522
2004	6,467
2005	6,711
2006	6,637

Uncertainty

The overall uncertainty associated with the 2006 N_2O emissions estimate from nitric acid production was calculated using the IPCC Guidelines for National Greenhouse Gas Inventories (2006) Tier 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions 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 4-59. N_2O emissions from nitric acid production were estimated to be between 9.4 and 22.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 40 percent below to 41 percent above the 2006 emissions estimate of 15.6 Tg CO_2 Eq.

Table 4-59: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions From Nitric Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	15.6	9.4	22.1	-40%	+41%

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

Recalculations Discussion

The nitric acid production values for 2003 and 2005 have been updated relative to the previous Inventory based on revised production data published by the U.S. Census Bureau (2006, 2007). The updated production data for 2003 resulted in a decrease of 0.6 Tg CO_2 Eq. (3.3 percent) in N_2O emissions relative to the previous Inventory. The updated production data for 2005 resulted in an increase of 1.0 Tg CO_2 Eq. (6.1 percent) in N_2O emissions relative to the previous Inventory. Minor changes in production data due to directly citing U.S. Census Bureau reports in this Inventory resulted in negligible changes in N_2O emissions relative to the previous Inventory (less than one-tenth of one percent) for all other years in the timeseries, respectively. Additionally, the N_2O emission factor for plants not equipped with NSCR systems has been updated based on IPCC Guidelines (2006), which resulted in a slight decrease in emissions in each year of the time series relative to the previous Inventory. Overall, these changes resulted in an average annual decrease in N_2O emissions of 0.9 Tg CO_2 Eq. (4.8 percent) for the period

1990 through 2005 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 and Europe are the major producers. The United States has three companies in four locations accounting for 34 percent of world production, and eight European producers account for a combined 38 percent of world production (CW 2007). Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, plastics, coatings, urethane foams, elastomers, and synthetic lubricants. Commercially, it is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Eighty-four percent of all adipic acid produced in the United States is used in the production of nylon 6,6, 9 percent is used in the production of polyester polyols, 4 percent is used in the production of plasticizers, and the remaining 4 percent is accounted for by other uses, including unsaturated polyester resins and food applications (ICIS 2007). Food grade adipic acid is used to provide some foods with a "tangy" flavor (Thiemens and Trogler 1991).

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 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.[12] 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 5.9 Tg CO_2 Eq. (19 Gg) in 2006 (see Table 4-60). National adipic acid production has increased by approximately 36 percent over the period of 1990 through 2006, 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 in the late 1990s.

Table 4-60: N_2O Emissions from Adipic Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	15.3	49
1995	17.3	56
2000	6.2	20
2001	5.1	16
2002	6.1	20
2003	6.3	20
2004	5.9	19
2005	5.9	19
2006	5.9	19

[12]During 1997, the N_2O emission controls installed by the third plant operated for approximately a quarter of the year.

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 emission estimates for 2003 to 2006 were unavailable and, thus, were calculated by applying 4.4, 4.2, 0.0, and 0.0 percent national production growth rates, respectively. 2003 national production was calculated through linear interpolation between 2002 and 2004 reported national production data. 2005 national production was calculated through linear interpolation between 2004 and 2006 reported national production. Subsequently, the growth rates for 2004, 2005, and 2006 were based on the change between the estimated 2003 production data and the reported 2004 production data, the change between 2004 reported production data and the estimated 2005 production data, and between the estimated 2005 production data and the reported 2006 production data, respectively (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 (IPCC 2006). Emissions are estimated using the following equation:

$$N_2O \text{ emissions} = (\text{production of adipic acid [metric tons \{MT\} of adipic acid]}) \times (0.3 \text{ MT } N_2O \text{ / MT adipic acid}) \times (1 - [N_2O \text{ destruction factor} \times \text{abatement system utility factor}])$$

The "N_2O destruction factor" represents the percentage of N_2O emissions that are destroyed by the installed abatement technology. The "abatement system utility factor" represents the percentage of time that the abatement equipment operates during the annual production period. Overall, in the United States, two of the plants employ catalytic destruction, one plant employs thermal destruction, and the smallest plant uses no N_2O abatement equipment. For the one plant that uses thermal destruction and for which no reported plant-specific emissions are available, the N_2O abatement system destruction factor is assumed to be 98.5 percent, and the abatement system utility factor is assumed to be 97 percent (IPCC 2006).

For 1990 to 2003, 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 and 2006, actual plant production data were obtained for these two plants and used for emission calculations. For 2005, interpolated national production was used for calculating emissions as described above.

National adipic acid production data (see Table 4-61) for 1990 through 2002 were obtained from the American Chemistry Council (ACC 2003). Production for 2003 was estimated based on linear interpolation of 2002 and 2004 reported production. Production for 2004 and 2006 were obtained from *Chemical Week,* Product Focus: Adipic Acid (CW 2005, 2007). Plant capacities for 1990 through 1994 were obtained from *Chemical and Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992 through 1995). Plant capacities for 1995 and 1996 were kept the same as 1994 data. The 1997 plant capacities were taken from *Chemical Market Reporter* "Chemical Profile: Adipic Acid" (CMR 1998). The 1998 plant capacities for all four plants and 1999 plant capacities for three of the plants were obtained from *Chemical Week,* Product Focus: Adipic Acid/Adiponitrile (CW 1999). Plant capacities for 2000 for three of the plants were updated using *Chemical Market Reporter*, "Chemical Profile: Adipic Acid" (CMR 2001). For 2001 through 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. For 2004 to 2006, although plant capacity data are available (CW 1999, CMR 2001, ICIS 2007), they are not used to calculate plant-specific production for these years because plant-specific production data for 2004 and 2006 are also available and are used in our calculations instead (CW 2005, CW 2007).

Table 4-61: Adipic Acid Production (Gg)

Year	Gg
1990	735
1995	830
2000	925
2001	835
2002	921
2003	961
2004	1,002
2005	1,002
2006	1,002

Uncertainty

The overall uncertainty associated with the 2006 N_2O emission estimate from adipic acid production was calculated using the IPCC Guidelines for National Greenhouse Gas Inventories (2006) Tier 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions 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 4-62. N_2O emissions from adipic acid production were estimated to be between 5.0 and 6.9 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 15 percent below to 16 percent above the 2006 emission estimate of 5.9 Tg CO_2 Eq.

Table 4-62: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	5.9	5.0	6.9	-15%	+16%

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

Recalculations Discussion

The adipic acid production value for 2005 was recalculated. In the 1990-2005 Inventory, 2005 production was calculated by applying the annual production growth rate from 2003 to 2004 of 4 percent to 2004 production. In this Inventory, 2005 production was recalculated because 2006 production data is now available (CW 2007). 2005 production was estimated through linear interpolation between 2004 and 2006 reported production data. The updated production value for 2005 resulted in a decrease of 0.3 Tg CO_2 Eq. (4.1 percent) in N_2O emissions relative to the previous inventory. Additionally, changes based on IPCC Guidelines (2006) to the N_2O destruction factor and abatement system utilization factor for one plant resulted in an increase of between 0.1 and 0.2 Tg CO_2 Eq. (0.8 to 3.2 percent) in N_2O emissions in each year of the historical time series, respectively.

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 substances (ODSs) that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990.[13] 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 4-63 and Table 4-64.

Table 4-63: Emissions of HFCs and PFCs from ODS Substitutes (Tg CO_2 Eq.)

Gas	1990	1995	2000	2001	2002	2003	2004	2005	2006
HFC-23	+	+	+	+	+	+	+	+	+
HFC-32	+	+	+	0.1	0.1	0.2	0.3	0.4	0.6
HFC-125	+	0.8	5.2	6.0	6.8	7.8	9.0	10.3	12.3
HFC-134a	+	26.0	56.0	60.3	64.3	67.8	71.3	73.2	73.4
HFC-143a	+	0.5	4.1	5.4	6.8	8.3	10.1	12.2	14.4
HFC-236fa	+	0.2	0.5	0.6	0.6	0.7	0.7	0.8	0.8
CF_4	+	+	+	+	+	+	+	+	+
Others*	0.3	1.6	4.0	3.9	4.3	4.9	5.2	5.4	5.7
Total	**0.3**	**29.1**	**70.0**	**76.3**	**83.0**	**89.8**	**96.6**	**102.3**	**107.3**

+ 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 4-64: Emissions of HFCs and PFCs from ODS Substitution (Mg)

Gas	1990	1995	2000	2001	2002	2003	2004	2005	2006
HFC-23	+	+	1	1	1	1	1	1	1
HFC-32	+	+	44	92	166	268	400	562	913
HFC-125	+	291	1,873	2,150	2,442	2,798	3,220	3,675	4,395
HFC-134a	+	19,992	43,061	46,412	49,455	52,145	54,830	56,345	56,481
HFC-143a	+	132	1,089	1,415	1,781	2,194	2,654	3,200	3,782
HFC-236fa	+	36	85	94	103	111	118	125	131
CF_4	+	+	1	1	1	2	2	2	2
Others*	M	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, C4F10, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—used as an aerosol propellant and also a component of the refrigerant blend R-500 used in chillers—and HFC-134a in refrigeration end-uses. Beginning in 1992, HFC-134a was used in growing amounts as a refrigerant in motor vehicle air-conditioners and in refrigerant blends such as R-404A.[14] In 1993, the use of HFCs

[13] [42 U.S.C § 7671, CAA § 601]
[14] R-404A contains HFC-125, HFC-143a, and HFC-134a.

in foam production 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 107.3 Tg CO_2 Eq. in 2006. 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 of these gases and the introduction of alternative gases and technologies, however, may help to offset this anticipated increase in emissions.

Table 4-65 presents HFCs and PFCs emissions by end-use sector for 1990 through 2006. The end-use sectors that contributed the most toward emissions of HFCs and PFCs as ODS substitutes in 2006 include refrigeration and air-conditioning (91.4 Tg CO_2 Eq., or approximately 85 percent), aerosols (11.6 Tg CO_2 Eq., or approximately 11 percent), and foams (2.4 Tg CO_2 Eq., or approximately 2 percent). Within the refrigeration and air-conditioning end-use sector, motor vehicle air-conditioning was the highest emitting end-use (52.3 Tg CO_2 Eq.), followed by retail food and refrigerated transport. Each of the end-use sectors is described in more detail below.

Table 4-65: Emissions of HFCs and PFCs from ODS Substitutes (Tg CO_2 Eq.) by Sector

Gas	**1990**		**1995**		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Refrigeration/Air Conditioning	+		19.9		57.3	63.6	69.6	75.5	81.8	87.0	91.4
Aerosols	+		8.1		10.1	10.3	10.6	10.8	11.1	11.3	11.6
Foams	+		+		+	+	1.0	1.8	2.0	2.2	2.4
Solvents	+		0.9		2.1	1.8	1.6	1.3	1.3	1.3	1.3
Fire Protection	+		+		+	+	+	+	+	0.5	0.6
Total	**+**		**29.1**		**70.0**	**76.3**	**83.1**	**89.8**	**96.6**	**102.3**	**107.3**

Refrigeration/Air Conditioning

The refrigeration and air-conditioning sector includes a wide variety of equipment types that have historically used CFCs or HCFCs. End uses within this sector include motor vehicle air-conditioning, retail food refrigeration, refrigerated transport (e.g., ship holds, truck trailers, railway freight cars), household refrigeration, residential and small commercial air-conditioning/heat pumps, chillers (large comfort cooling), cold storage facilities, and industrial process refrigeration (e.g., systems used in food processing, chemical, petrochemical, pharmaceutical, oil and gas, and metallurgical industries). As the ODS phaseout is taking effect, most equipment is being or will eventually be retrofitted or replaced to use HFC-based substitutes. Common HFCs in use today in refrigeration/air-conditioning equipment are HFC-134a, R-410A, R-404A, and R-507A. These HFCs are emitted to the atmosphere during equipment manufacture and operation (as a result of component failure, leaks, and purges), as well as at servicing and disposal events.

Aerosols

Aerosol propellants are used in metered dose inhalers (MDIs) and a variety of personal care products and technical/specialty products (e.g., duster sprays and safety horns). Many pharmaceutical companies that produce MDIs—a type of inhaled therapy used to treat asthma and chronic obstructive pulmonary disease—have committed to replace the use of CFCs with HFC-propellant alternatives. The earliest ozone-friendly MDIs were produced with HFC-134a, but eventually, the industry expects to use HFC-227ea as well. Conversely, since the use of CFC propellants was banned in 1978, most consumer aerosol products have not transitioned to HFCs, but to "not-in-kind" technologies, such as solid roll-on deodorants and finger-pump sprays. The transition away from ODS in specialty aerosol products has also led to the introduction of non-fluorocarbon alternatives (e.g., hydrocarbon propellants) in certain applications, in addition to HFC-134a or HFC-152a. These propellants are released into the atmosphere as the aerosol products are used.

Foams

CFCs and HCFCs have traditionally been used as foam blowing agents to produce polyurethane (PU), polystyrene,

polyolefin, and phenolic foams, which are used in a wide variety of products and applications. Since the Montreal Protocol, flexible PU foams as well as other types of foam, such as polystyrene sheet, polyolefin, and phenolic foam, have transitioned almost completely away from fluorocompounds, into alternatives such as CO_2, methylene chloride, and hydrocarbons. The majority of rigid PU foams have transitioned to HFCs—primarily HFC-134a and HFC-245fa. Today, these HFCs are used to produce polyurethane appliance foam, PU commercial refrigeration, PU spray, and PU panel foams—used in refrigerators, vending machines, roofing, wall insulation, garage doors, and cold storage applications. In addition, HFC-152a is used to produce polystyrene sheet/board foam, which is used in food packaging and building insulation. Emissions of blowing agents occur when the foam is manufactured as well as during the foam lifetime and at foam disposal, depending on the particular foam type.

Solvents

CFCs, methyl chloroform (1,1,1-trichloroethane or TCA), and to a lesser extent carbon tetrachloride (CCl_4) were historically used as solvents in a wide range of cleaning applications, including precision, electronics, and metal cleaning. Since their phaseout, metal cleaning end-use applications have primarily transitioned to non-fluorocarbon solvents and not-in-kind processes. The precision and electronics cleaning end-uses have transitioned in part to high-GWP gases, due to their high reliability, excellent compatibility, good stability, low toxicity, and selective solvency. These applications rely on HFC-4310mee, HFC-365mfc, HFC-245fa, and to a lesser extent, PFCs. Electronics cleaning involves removing flux residue that remains after a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or to metal surfaces, and is characterized by products, such as disk drives, gyroscopes, and optical components, that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges. The use of solvents yields fugitive emissions of these HFCs and PFCs.

Fire Protection

Fire protection applications include portable fire extinguishers ("streaming" applications) that originally used halon 1211, and total flooding applications that originally used halon 1301, as well as some halon 2402. Since the production and sale of halons were banned in the United States in 1994, the halon replacement agent of choice in the streaming sector has been dry chemical, although HFC-236ea is also used to a limited extent. In the total flooding sector, HFC-227ea has emerged as the primary replacement for halon 1301 in applications that require clean agents. Other HFCs, such as HFC-23, HFC-236fa, and HFC-125, are used in smaller amounts. The majority of HFC-227ea in total flooding systems is used to protect essential electronics, as well as in civil aviation, military mobile weapons systems, oil/gas/other process industries, and merchant shipping. As fire protection equipment is tested or deployed, emissions of these HFCs are released.

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 (2006). Though the model is more comprehensive than the IPCC default methodology, significant uncertainties still exist with regard to the levels of equipment sales,

equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

The Vintaging Model estimates emissions from 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, comprising over 95 percent of the total emissions, and 5 other end-uses. 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 97.6 and 128.7 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 107.3 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)

Source	Gases	2006 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
Substitution of Ozone Depleting Substances	HFCs and PFCs	107.3	97.6	128.7	-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 decrease of 8.1Tg CO_2 Eq. (13 percent) in HFC and PFC emissions from the substitution of ozone depleting substances for the period 1990 through 2005. The refrigeration and air conditioning sector was the source of the greatest change, with an average annual net decrease of 11.7 Tg CO_2 Eq. (27 percent) in emissions. This decrease can be attributed to changes in the assumptions regarding the quantity of emissions at end of life (disposal) across the entire sector, based on revised assumptions considering input from industry representatives, as well significant modification to assumptions for chiller end uses, based on industry input.

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 but has generally remained above 1990 levels. 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.[15] 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 2006 were estimated to be 13.8 Tg CO_2 Eq. (1.2 Gg) (Table 4-67). This quantity represents a 17 percent decline from 2005 emissions and a 61 percent decline from 1990 emissions. Both declines are primarily due to declines in the HFC-23 emission rate. Three HCFC-22 production plants operated in the United States in 2006, 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
2006	13.8	1

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. Plants that release some of their byproduct HFC-23 periodically measure HFC-23 concentrations in the output stream using gas chromatography. This information is combined with information on quantities of critical feed components (e.g., HF) and/or products (e.g., HCFC-22) to estimate HFC-23 emissions. 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

[15] 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]

(ARAP 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007; 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
2006	154

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 12.4 and 15.2 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 10 percent above and 10 percent below the 2006 emission estimate of 13.8 Tg CO_2 Eq.

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	13.8	12.4	15.2	-10%	+10%

[a] Range of emission reflect a 95 percent confidence interval.

Planned Improvements

A comprehensive review of plant-level estimates of HFC-23 emissions and HCFC-22 production is curretly being conducted. This review includes analysis of measurement methods, quality assurance and quality control efforts, and uncertainties, and verification of both plant- and U.S.-level calculations. This review is anticipated to result in slight time series revisions of HFC-23 emission estimates, but to confirm the overall trend of declining emissions since 1990.

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

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 2006. 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 a 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.

Table 4-70: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (Tg CO_2 Eq.)

Year	Electric Power Systems	Electrical Equipment Manufacturers	Total
1990	26.4	0.3	26.7
1995	20.9	0.5	21.5
2000	14.4	0.7	15.1
2001	14.5	0.6	15.0
2002	13.7	0.8	14.4
2003	13.2	0.7	13.9
2004	13.3	0.7	14.0
2005	13.2	0.8	14.0
2006	12.4	0.8	13.2

Table 4-71: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (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
2006	0.6

Methodology

The estimates of emissions from electric transmission and distribution are comprised of emissions from electric power systems and emissions from the manufacture of electrical equipment. The methodologies for estimating both sets of emissions are described below.

1999 through 2006 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2006 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, 2004 and 2007 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004, 2007). (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV.) Over the period from 1999 to 2006, participating utilities represented between 42 percent and 46 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 2006, if no data was provided, estimates were calculated based on partner-specific trends (i.e., emissions were linearly interpolated between two known emissions data points or extrapolated based on partner-specific transmission mile growth rates). In 2006, non-reporting partners account for approximately 3 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 from reporting utilities were most strongly correlated with their transmission miles. The results of this analysis are not surprising given that, in the United States, SF_6 is contained primarily in transmission equipment rated at or above 34.5 kV. The equations were developed based on the 1999 SF_6 emissions reported by 43 partner utilities (representing approximately 24 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):

$$\text{Emissions (kg)} = 0.884 \times \text{Transmission Miles}$$

Non-partner large utilities (more than 10,000 transmission miles, in kilograms):

$$\text{Emissions (kg)} = 0.578 \times \text{Transmission Miles}$$

Data on transmission miles for each non-partner utility for the years 2000, 2003 and 2006 were obtained from the 2001, 2004 and 2007 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007). The U.S. transmission system grew by over 26,000 miles between 2000 and 2003 and by over 51,000 miles between 2003 and 2006. These periodic increases are assumed to have occurred gradually, therefore transmission mileage were assumed to increase at an annual rate of 1.4 percent between 2000 and 2003 and 2.6 percent between 2003 and 2006.

As a final step, total emissions were determined for each year by summing the partner reported and estimated emissions (reported data was available through the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems), and the non-partner emissions (determined using the 1999 regression equations).

1990 through 1998 Emissions from Electric Power Systems

Because most participating utilities reported emissions only for 1999 through 2006, it was necessary to model SF_6 emissions from electric power systems for the years 1990 through 1998. To do so, EPA 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.)

$$\text{Emissions (kilograms } SF_6) = SF_6 \text{ purchased to refill existing equipment (kilograms)} + \text{nameplate capacity of retiring equipment (kilograms)}$$

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 15.6 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 through 2006 Emissions from Manufacture of Electrical Equipment

The 1990 to 2006 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 2006 were estimated using partner reported data and the total 2006 industry SF_6 bank estimate (128.5 Tg CO_2 Eq. in 2006). Specifically, EPA calculated the ratio of new nameplate capacity to total nameplate capacity of a subset of partners for which new nameplate capacity data was available from 1999 to 2006. EPA then multiplied this ratio by the total industry bank estimate to derive the amount of SF_6 charged into new equipment for the entire industry. The 10 percent emission rate is the average of the "ideal" and "realistic" manufacturing emission rates (4 percent and 17 percent, respectively) identified in a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE) in February 2002 (O'Connell et al. 2002).

Uncertainty

To estimate the uncertainty associated with emissions of SF_6 from electric transmission and distribution, uncertainties associated with three 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 2.1 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 2006 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 58 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 partner provided nameplate capacity data and industry SF_6 bank estimates, 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 11.1 and 15.4 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 13.2 Tg CO_2 Eq.

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	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to 2006 Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Transmission and Distribution	SF_6	13.2	11.1	15.4	-16%	+17%

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

In addition to the uncertainty quantified above, there is uncertainty associated with using global SF_6 sales data to estimate U.S. emission trends from 1990 through 1999. However, the trend in global emissions implied by sales of SF_6 appears to reflect the trend in global emissions implied by changing SF_6 concentrations in the atmosphere. That is, emissions based on global sales declined by 29 percent between 1995 and 1998, and emissions based on atmospheric measurements declined by 27 percent over the same period. 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 2006 were updated based on 1) new data from EPA's SF_6 Emission Reduction Partnership; 2) revisions to the assumptions used in interpolating and extrapolating non-reported partner data; (3) new information on transmission mile growth available in the UDI 2007 database; 4) removal of double counting between parent companies and their subsidiaries in UDI databases; and 5) revision in the methodology for estimating 2001 to 2006 OEM emissions. For the period 1999 through 2006, estimates have been revised to incorporate additional data from new partners. Additionally, partner estimates are now based on partner-specific transmission mile growth rates, obtained via the UDI 2001, 2004, and 2007 databases. Partner data and the industry SF_6 bank estimates are now used to estimate OEM emissions from 2001 onwards, since NEMA data for these years does not exist. Based on the revisions listed above, SF_6 emissions from electric transmission and distribution decreased from 1990 to 2000 and increased from 2001 to 2005, compared to the 1990 to 2005 inventory.

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 2006, total weighted emissions of all fluorinated greenhouse gases by the U.S. semiconductor industry were estimated to be 4.8 Tg CO_2 Eq. Combined emissions of all fluorinated greenhouse gases are presented in Table 4-73 and Table 4-74 below. The rapid growth of this industry and the increasing complexity (growing number of layers) of semiconductor products led to an increase in emissions of 149 percent between 1990 and 1999. The emissions growth rate began to slow after 1997, and emissions declined by 33 percent between 1999 and 2006. The initial implementation of PFC emission reduction methods such as process optimization and abatement technologies is responsible for this decline. Together, industrial growth and use of abatement technologies resulted in a net increase in emissions of 65 percent between 1990 and 2006.

Table 4-73: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq.)

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
CF_4	0.7	1.3	1.8	1.3	1.1	1.0	1.1	1.1	1.2
C_2F_6	1.5	2.5	3.0	2.1	2.2	2.1	2.1	2.0	2.2
C_3F_8	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0
C_4F_8	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
HFC-23	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.3
SF_6	0.5	0.9	1.1	0.7	0.7	0.8	0.8	1.0	1.0
NF_3*	0.0	0.0	0.1	0.1	0.3	0.2	0.2	0.2	0.3
Total	**2.9**	**5.0**	**6.3**	**4.5**	**4.3**	**4.3**	**4.3**	**4.4**	**4.8**

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.

Table 4-74: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Mg)

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
CF_4	115	193	281	202	174	161	172	169	184
C_2F_6	160	272	322	230	241	227	225	217	244
C_3F_8	0	0	18	14	10	14	6	4	5
C_4F_8	0	0	0	0	6	9	9	13	13

HFC-23	15		25		23	15	15	16	17	18	22
SF_6	22		38		45	31	28	35	35	41	40
NF_3	3		6		11	12	32	30	30	26	40

Methodology

Emissions are based on Partner reported emissions data received through the EPA's PFC Reduction/Climate Partnership and the EPA's PFC Emissions Vintage Model (PEVM), a model which estimates industry emissions in the absence of emission control strategies (Burton and Beizaie 2001).[16] The availability and applicability of Partner data differs across the 1990 through 2006 time series. Consequently, 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.

1990 through 1994

For 1990 through 1994, Partnership data was unavailable and emissions were modeled using the PEVM (Burton and Beizaie 2001).[17] 1990 to 1994 emissions are assumed to be primarily uncontrolled, since reduction strategies such as chemical substitution and abatement were not widespread during this period.

PEVM is based on the assumption that PFC emissions from semiconductor manufacturing vary with (1) the number of layers on different kinds of semiconductor devices (including both silicon wafer and metal interconnect layers), and (2) silicon consumption (i.e., the area of semiconductors produced) for each kind of device. The product of these two quantities, Total Manufactured Layer Area (TMLA), constitutes the activity data for semiconductor manufacturing. PEVM also incorporates an emission factor that expresses emissions per average layer per unit of area of silicon consumed during product manufacture. Emissions are estimated by multiplying TMLA by this emission factor.

PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest feature size),[18] and (2) product type (discrete, memory or logic).[19] 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 IC) specific to product type (Burton and Beizaie 2001, ITRS 2007). PEVM derives historical consumption of silicon (i.e., square inches) by linewidth technology from published data on annual wafer starts and average wafer size (VLSI Research, 2007).

The emission factor in PEVM is the average of the four historical emission factors derived by dividing the total

[16] A Partner refers to a participant of the U.S. EPA PFC Reduction/Climate Partnership for the Semiconductor Industry. Through a Memorandum of Understanding (MoU) with the EPA, Partners voluntarily report their PFC emissions to the EPA by way of a third party.

[17] Various versions of the PEVM exist, to reflect changing industrial practices. From 1990 to 1994 emissions estimates are from PEVM v1.0, completed in September 1998. The emission factor used to estimate 1990 to 1994 emissions is an average of the 1995 and 1996 emissions factors, which were derived from Partner reported data for those years

[18] By decreasing features of IC components, more components can be manufactured per device, which increases its functionality. However, as those individual components shrink it requires more layers to interconnect them to achieve the functionality. For example, a microprocessor manufactured with the smallest feature sizes (65 nm) might contain as many as 1 billion transistors and require as many as 11 layers of component interconnects to achieve functionality while a device manufactured with 130 nm feature size might contain a few hundred million transistors and require 8 layers of component interconnects (ITRS, 2007).

[19] Memory devices manufactured with the same feature sizes as microprocessors (a logic device) require approximately one-half the number of interconnect layers, whereas discrete devices require only a silicon base layer and no interconnect layers (ITRS, 2007). Since discrete devices did not start using PFCs appreciably until 2004, they are only accounted for in the PEVM emissions estimates from 2004 onwards.

annual emissions reported by the Partners for each year between 1996 and 1999 by the total TMLA estimated for the Partners in each of those years. Since Partners are not believed to have applied significant emission reduction measures before 2000, the resulting average emission factor does not reflect such measures.

1995 through 1999

For 1995 through 1999, total U.S. emissions were extrapolated from the total annual emissions reported by the Partners (1995 through 1999). Partner-reported emissions are considered more accurate than PEVM estimated emissions, and are used to generate total U.S. emissions when applicable. The emissions reported by the Partners were divided by the ratio of the total layer-weighted capacity of the plants operated by the Partners 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 the Partnership. 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 Partners and non-Partners have similar capacity utilizations and per-layer emission factors. Plant capacity, linewidth technology, and products manufactured information is contained in the World Fab Watch (WFW) database, which is updated quarterly (see for example, Semiconductor Equipment and Materials Industry 2007).

2000 through 2006

The U.S. estimate for the years 2000 through 2006—the period during which Partners began the consequential application of PFC-reduction measures—was estimated using a combination of Partner reported emissions and PEVM modeled emissions. The emissions reported by Partners for each year were accepted as the quantity emitted from the share of the industry represented by those Partners. Remaining emissions (those from non-Partners), however, were estimated using PEVM and the method described above. This is because non-Partners are assumed not to have implemented any PFC-reduction measures, and PEVM models emissions without such measures. The portion of the U.S. total attributed to non-Partners is obtained by multiplying PEVM's total U.S. 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., revisions and additions to the world population of semiconductor manufacturing plants, and changes in IC fabrication practices within the semiconductor industry (see Semiconductor Equipment and Materials Industry 2007)[20,21,22]

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[20] 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 denoted the actual installed capacity instead of the fully-ramped capacity. For 2006, actual installed capacities of new fabs were estimated using an average monthly ramp rate of 1100 wafer starts per month (wspm) derived from various sources such as semiconductor fabtech, industry analysts, and articles in the trade press. The monthly ramp rate was applied from the first-quarter of silicon volume (FQSV), to determine the average design capacity over the 2006 period.

[21] In 2006, 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.

[22] Two versions of PEVM are used to model non-Partner emissions during this period. For the years 2000 to 2003 PEVM v3.2.0506.0507 was used to estimate non-Partner emissions. During this time discrete devices did not use PFCs during manufacturing and, therefore, only memory and logic devices were modeled in the PEVM v3.2.0506.0507. From 2004 onwards discrete device fabrication started to use PFCs, hence PEVM v4.0.0701.0701, the first version of PEVM to account for PFC emissions from discrete devices, was used to estimate non-Partner emissions for this time period.

Gas-Specific Emissions

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 2006 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 2006 were estimated by adding the emissions reported by the Partners to those estimated for the non-Partners.[23]

Data Sources

Partners estimate their emissions using a range of methods. For 2006, 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. Although some of the default emission factors have been updated in the IPCC (2006) guidelines, as of the 2006 reporting year Partners continue to use the IPCC (2000) default emission factors.[24] The Partners with relatively high emissions use leading-edge manufacturing technology, the newest process equipment. When purchased, this equipment is supplied with PFC emission factors, measured using industry standard guidelines (International Sematech, 2006). The larger emitting Partners likely use these process-specific emission factors instead of the less accurate default emission factors provided in IPCC guidelines; however, the documentation regarding Partner emissions is incomplete (Burton and Kshetry, 2007).

Data used to develop emission estimates were prepared in cooperation with the Partnership. Estimates of operating plant capacities and characteristics for Partners and non-Partners were derived from the Semiconductor Equipment and Materials Industry (SEMI) *World Fab Watch* (formerly *International Fabs on Disk*) database (1996 through 2007). Estimates of silicon consumed by line-width from 1990 through 2006 were derived from information from VLSI Research (2007), and the number of layers per line-width was obtained from International Technology Roadmap for Semiconductors: 2006 Update (Burton and Beizaie 2001, ITRS 2007).

Uncertainty

A quantitative uncertainty analysis[25] of this source category was performed using the IPCC-recommended Tier 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The equation used to estimate uncertainty is:

$$\text{U.S. emissions} = \sum \text{Partnership gas-specific submittals} + (\text{non-Partner share of World. TMLA}) \times (\text{PEVM Emission Factor} \times \text{World TMLA})$$

The Monte Carlo analysis results presented below relied on estimates of uncertainty attributed to the four variables on the right side of the equation. Estimates of uncertainty for the four variables were in turn developed using the estimated uncertainties associated with the individual inputs to each variable, error propagation analysis, Monte Carlo simulation and expert judgment. The relative uncertainty associated with World TMLA estimate in 2006 is approximately ±10 percent, based on the uncertainty estimate provided by VLSI, Inc. For the share of World layer-weighted silicon capacity accounted for by non-Partners, a relative uncertainty of ±2 percent was estimated based

[23] 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.

[24] Currently, the majority of Partners use the IPCC (2000) Tier 2c guidelines, which most closely resemble the IPCC (2006) Tier 2a guidelines.

[25] All uncertainties listed in this section are 95 percent confidence intervals.

on a separate Monte Carlo simulation to account for the random occurrence of missing data in the World Fab Watch database, where the simulated distribution of World TMLA capacity share was observed to be approximately log-normally distributed. For the aggregate PFC emissions data supplied to the partnership, a relative uncertainty of ±49 percent was estimated for each gas-specific PFC emissions value reported by an individual Partner, and error propagation techniques were used to estimate uncertainty for total Partnership gas-specific submittals.[26] A relative error of approximately 10.5 percent was estimated for the PEVM emission factor, based on the standard deviation of the 1996 to 1999 emission factors.[27]

Consideration was also given to the nature and magnitude of the potential bias that World activity data (i.e., World TMLA) might have in its estimates of the number of layers associated with devices manufactured at each technology node. The result of a brief analysis indicated that U.S. TMLA overstates the average number of layers across all product categories and all manufacturing technologies for 2004 by 0.12 layers or 2.9 percent. The same upward bias is assumed for World TMLA, and is represented in the uncertainty analysis by deducting the absolute bias value from the World activity estimate when it is incorporated into the Monte Carlo analysis.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-75. The emissions estimate for total U.S. PFC emissions from semiconductor manufacturing were estimated to be between 4.8 and 5.4 Tg CO_2 Eq. at a 95 percent confidence level . This range represents 6 percent below to 6 percent above the 2006 emission estimate of 5.1 Tg CO_2 Eq. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate, but were not explicitly modeled.

Table 4-75: Tier 2 Quantitative Uncertainty Estimates for HFC, PFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	5.1	4.8	5.4	-6%	+6%

[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.

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) and improvements in Partner emission reporting (e.g., adoption of the IPCC (2006) guidelines). 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.)

[26] Error propagation resulted in Partnership gas-specific uncertainties ranging from 15 to 30 percent.

[27] The average of 1996 to 1999 emission factor is used to derive the PEVM emission factor.

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. As of last reporting, 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 3.9 Tg CO_2 Eq. (3,923 Gg) in 2006 (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.

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	4,207
2006	3.9	3,923

In addition to CO_2 emissions, the aluminum production industry is also a source of PFC emissions. During the smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, which are termed "anode effects." These anode effects cause carbon from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF_4 and C_2F_6. In general, the magnitude of emissions for a given 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 87 percent to 2.1 Tg CO_2 Eq. of CF_4 (0.4 Gg) and 0.4 Tg CO_2 Eq. of C_2F_6 (0.04 Gg) in 2006, as shown in Table 4-77 and Table 4-78. This decline is due both to reductions in domestic aluminum production and to actions taken by aluminum smelting companies to reduce the frequency and duration of anode effects. Since 1990, aluminum production has declined by 44 percent, while the average CF_4 and C_2F_6 emission rates (per metric ton of aluminum produced) have each been reduced by 76 percent.

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
2006	2.1	0.4	2.5

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	+
2006	0.3	+

+ Does not exceed 0.05 Gg

In 2006, U.S. primary aluminum production totaled approximately 2.3 million metric tons, a slight decrease from 2005 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 2006 production levels that were approximately 40 percent lower than the levels in 1999, the year with the highest production since 1995.

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, 2005, and 2006. Where available, smelter-specific process data reported under the VAIP were used; however, if the data were incomplete or unavailable, information was supplemented using industry average values recommended by IPCC (2006). Smelter-specific CO_2 process data were provided by 18 of the 23 operating smelters in 1990 and 2000, by 14 out of 16 operating smelters in 2003 and 2004, 14 out of 15 operating smelters in 2005, and 12 out of 13 operating smelters in 2006. 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 13 in 2006, 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 12 out of 13 operating smelters were reported under the VAIP in 2006. Between 1990 and 2005, 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)

This approach corresponds to either the Tier 3 or the Tier 2 approach in the 2006 IPCC Guidelines, depending upon whether the slope-coefficient is smelter-specific (Tier 3) or technology-specific (Tier 2). For 1990 through 2006, smelter-specific slope coefficients were available and were used for smelters representing between 30 and 55 percent of U.S. primary aluminum production. The percentage changed from year to year as some smelters closed or changed hands and as the production at remaining smelters fluctuated. For smelters that did not report smelter-specific slope coefficients, IPCC technology-specific slope coefficients were applied (IPCC 2001, 2006). The slope coefficients were combined with smelter-specific anode effect data collected by aluminum companies and reported under the VAIP, to estimate emission factors over time. For 1990 through 2006, smelter-specific anode effect data were available for smelters representing between 80 and 100 percent of U.S. primary aluminum production. Where smelter-specific anode effect data were not available, industry averages were used.

For all smelters, emission factors were multiplied by annual production to estimate annual emissions at the smelter level. For 1990 through 2006, smelter-specific production data were available for smelters representing between 30 and 100 percent of U.S. primary aluminum production. (For the years after 2000, this percentage was near the high end of the range.) Production at non-reporting smelters was estimated by calculating the difference between the production reported under VAIP and the total U.S. production supplied by USGS and then by allocating this difference to non-reporting smelters in proportion to their production capacity. Emissions were then aggregated across smelters to estimate national emissions.

National primary aluminum production data for 2006 were obtained via communication with USGS (USGS, 2007). For 1990 through 2001 (see Table 4-79) data 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	2,704
2004	2,517
2005	2,478
2006	2,284

Uncertainty

The overall uncertainties associated with the 2006 CO_2, CF_4, and C_2F_6 emission estimates were calculated using a Tier 2 approach, 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 3.7 and 4.1 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 3.9 Tg CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 1.9 and 2.3 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 2.1 Tg CO_2 Eq. Finally, aluminum production-related C_2F_6 emissions were estimated to be between 0.3 and 0.4 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 17 percent below to 17 percent above the emission estimate of 0.4 Tg CO_2 Eq.

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	2006 Emission Estimate	Uncertainty Range Relative to 2006 Emission Estimate[a]			
			(Tg CO_2 Eq.)		(%)	
		(Tg CO_2 Eq.)	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Aluminum Production	CO_2	3.9	3.7	4.1	-5%	+5%
Aluminum Production	CF_4	2.1	1.9	2.3	-9%	+9%
Aluminum Production	C_2F_6	0.4	0.3	0.4	-17%	+17%

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

The 2006 emission estimate was developed using IPCC (2001) slope coefficients for 7 of the 8 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 2006 would probably be on the order of 10 percent lower than current 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. 2006 emission estimates for CF_4 and C_2F_6 are also overestimated.

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

The 2005 emission estimates were updated to reflect revised prebake smelter production data. This change has resulted in a less than one percent increase in PFC and CO_2 emissions for 2005.

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 3.2 Tg CO_2 Eq. (0.1 Gg) of SF_6 in 2006, representing a decrease of approximately 3 percent from 2005 emissions (see Table 4-81). The recent closure of a production facility in Canada has resulted in supply pressures in North America for magnesium ingot that may encourage the expansion of primary magnesium production in the United States (USGS 2007a). The automotive industry is continuing to work towards converting components to magnesium for fuel efficiency gains. As a result of this shift, magnesium die casting processing is forecasted to grow by 3 percent for 2007 with another 4 percent gain in 2008 (NADCA 2007).

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	2.9	0.1
2002	2.9	0.1
2003	3.4	0.1
2004	3.2	0.1
2005	3.3	0.1
2006	3.2	0.1

Methodology

Emission estimates for the magnesium industry incorporate information provided by industry participants in EPA's

SF_6 Emission Reduction Partnership for the Magnesium Industry. The Partnership started in 1999 and, currently, participating companies represent 100 percent of U.S. primary and secondary production and 90 percent of the casting sector production (i.e., die, sand, permanent mold, wrought, and anode casting). Absolute emissions for 1999 through 2006 from primary production, secondary production (i.e., recycling), and die casting were generally reported by Partnership participants. When a Partner did not report emissions, they were estimated based on the metal processed and emission rate reported by that Partner in previous years. (The extrapolation was based on the trend shown by Partners reporting in the current and previous years.) Emissions for one Partner that is a secondary producer were estimated based on the average emission factor for other Partners that are secondary producers.

Emission factors for 2002 to 2006 for sand casting activities were also acquired through the Partnership. The 1999 through 2006 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. 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 average 1995 Partner value of 1.1 kg SF_6 per metric ton.

Die casting emissions for 1999 through 2006, which accounted for 25 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 2006, Partners accounted for all U.S. die casting that was tracked by USGS. 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, emissions 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, wrought, and anode casting) were based on discussions with industry representatives.

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	0.72	2	1	1
2001	0.72	2	1	1
2002	0.71	2	1	1
2003	0.81	2	1	1
2004	0.81	2	1	1
2005	0.76	2	1	1
2006	0.86	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.

Data used to develop SF_6 emission estimates were provided by the Magnesium Partnership participants and the USGS. U.S. magnesium metal production (primary and secondary) and consumption (casting) data from 1990 through 2006 were available from the USGS (USGS 2002, 2003, 2005, 2006, 2007b). Emission factors from 1990 through 1998 were based on a number of sources. Emission factors for primary production were available from U.S. primary producers for 1994 and 1995, and an emission factor for die casting of 4.1 kg per metric ton was available for the mid-1990s from an international survey (Gjestland & Magers 1996).

To estimate emissions for 1990 through 1998, industry emission factors were multiplied by the corresponding metal production and consumption (casting) statistics from USGS. The primary production emission factors were 1.2 kg per metric ton for 1990 through 1993, and 1.1 kg per metric ton for 1994 through 1997. For die casting, an emission factor of 4.1 kg per metric ton was used for the period 1990 through 1996. For 1996 through 1998, the emission factors for primary production and die casting were assumed to decline linearly to the level estimated based on

Partner reports in 1999. This assumption is consistent with the trend in SF_6 sales to the magnesium sector that is reported in the RAND survey of major SF_6 manufacturers, which shows a decline of 70 percent from 1996 to 1999 (RAND 2002). Sand casting emission factors for 2002 through 2006 were provided by the Magnesium Partnership participants and 1990 through 2001 emission factors for this process were assumed to have been the same as the 2002 emission factor. The emission factor for secondary production from 1990 through 1998 was assumed to be constant at the 1999 average partner value. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting), about which less is known, were assumed to remain constant at levels defined in Table 4-82.

Uncertainty

To estimate the uncertainty of the estimated 2006 SF_6 emissions from magnesium production and processing, EPA estimated the uncertainties associated with three variables (1) emissions reported by magnesium producers and processors that participate in the SF_6 Emission Reduction Partnership, (2) emissions estimated for magnesium producers and processors that participate in the Partnership but did not report this year, and (3) emissions estimated for magnesium producers and processors that do not participate in the Partnership. An uncertainty of 5 percent was assigned to the data reported by each participant in the Partnership. If Partners did not report emissions data during the current reporting year, SF_6 emissions data were estimated using available emission factor and production information reported in prior years; the extrapolation was based on the average trend for Partners reporting in the current reporting year and the year prior. The uncertainty associated with the SF_6 usage estimate generated from the extrapolated emission factor and production information was estimated to be 30 percent. For those industry processes that are not represented in Partnership, such as permanent mold and wrought casting, SF_6 emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-82). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. Emissions associated with sand casting activities not entirely captured by the Partnership utilized a Partner-reported emission factor with an uncertainty of 50 percent. Estimated emissions for a secondary production facility participating in the Partnership were assigned an uncertainty of 75 percent due to an absence of reported data. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Additional uncertainties exist in these estimates, such as the basic assumption that SF_6 neither reacts nor decomposes during use. The melt surface reactions and high temperatures associated with molten magnesium could potentially cause some gas degradation. Recent measurement studies have identified SF_6 cover gas degradation in die casting applications on the order of 20 percent (Bartos et al. 2007). 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 2.7 and 3.6 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 14 percent below to 14 percent above the 2006 emissions estimate of 3.2 Tg CO_2 Eq.

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	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Magnesium Production	SF_6	3.2	2.7	3.6	-14%	+14%

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

Recalculations Discussion

Data from the USGS (USGS 2007b) slightly revised the amount of magnesium processed in 2005 for the wrought, sand and permanent mold casting sectors. In addition, wrought production numbers for 1990 and 1992 were revised to match historical USGS publications based on a data review. Revisions were also made to the approach for extrapolating and interpolating data for non-reporting Partners in order to improve accuracy. Emission estimates for secondary production activities by a non-reporting Partner were added for the years 2001 through 2006. The default historical emission factor for secondary production from 1990 to 1998 was also revised to be held constant at the 1999 Partner reported value. These changes resulted in an average annual increase in SF_6 emissions of 0.03 Tg CO_2 Eq. (approximately 0.5 percent) for 1990 to 1998 and 0.6 Tg CO_2 Eq. (approximately 22 percent) for 2001 to 2005 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 2006) that all SF_6 utilized is emitted to the atmosphere. EPA-funded measurements of SF_6 in die casting applications have indicated that the latter assumption may be incorrect, with observed SF_6 degradation on the order of 20 percent (Bartos et al. 2007). 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. Magnesium producers and processers have already begun using these cover gases during this inventory year in a limited fashion; because the amounts are negligible these emissions are only being monitored and recorded at this time. 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.

[BEGIN BOX]

Box 4-1: Potential Emission Estimates of HFCs, PFCs, and SF_6

Emissions of HFCs, PFCs and SF_6 from industrial processes can be estimated in two ways, either as potential emissions or as actual emissions. Emission estimates in this chapter are "actual emissions," which are defined by the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) as estimates that take into account the time lag between consumption and emissions. In contrast, "potential emissions" are defined to be equal to the amount of a chemical consumed in a country, minus the amount of a chemical recovered for destruction or export in the year of consideration. Potential emissions will generally be greater for a given year than actual emissions, since some amount of chemical consumed will be stored in products or equipment and will not be emitted to the atmosphere until a later date, if ever. Although actual emissions are considered to be the more accurate estimation approach for a single year, estimates of potential emissions are provided for informational purposes.

Separate estimates of potential emissions were not made for industrial processes that fall into the following categories:

- *By-product emissions*. Some emissions do not result from the consumption or use of a chemical, but are the unintended by-products of another process. For such emissions, which include emissions of CF_4 and C_2F_6 from aluminum production and of HFC-23 from HCFC-22 production, the distinction between potential and actual emissions is not relevant.
- *Potential emissions that equal actual emissions*. For some sources, such as magnesium production and processing, no delay between consumption and emission is assumed and, consequently, no destruction of the chemical takes place. In this case, actual emissions equal potential emissions.

Table 4-84 presents potential emission estimates for HFCs and PFCs from the substitution of ozone depleting substances, HFCs, PFCs, and SF_6 from semiconductor manufacture, and SF_6 from magnesium production and

processing and electrical transmission and distribution.[28] Potential emissions associated with the substitution for ozone depleting substances were calculated using the EPA's Vintaging Model. Estimates of HFCs, PFCs, and SF_6 consumed by semiconductor manufacture were developed by dividing chemical-by-chemical emissions by the appropriate chemical-specific emission factors from the IPCC *Good Practice Guidance* (Tier 2c). Estimates of CF_4 consumption were adjusted to account for the conversion of other chemicals into CF_4 during the semiconductor manufacturing process, again using the default factors from the IPCC *Good Practice Guidance*. Potential SF_6 emissions estimates for electrical transmission and distribution were developed using U.S. utility purchases of SF_6 for electrical equipment. From 1999 through 2006, estimates were obtained from reports submitted by participants in EPA's SF_6 Emission Reduction Program for Electric Power Systems. U.S. utility purchases of SF_6 for electrical equipment from 1990 through 1998 were backcasted based on world sales of SF_6 to utilities. Purchases of SF_6 by utilities were added to SF_6 purchases by electrical equipment manufacturers to obtain total SF_6 purchases by the electrical equipment sector.

Table 4-84: 2006 Potential and Actual Emissions of HFCs, PFCs, and SF_6 from Selected Sources (Tg CO_2 Eq.)

Source	Potential	Actual
Substitution of Ozone Depleting Substances	179.3	107.3
Aluminum Production	-	2.5
HCFC-22 Production	-	13.8
Semiconductor Manufacture	7.6	4.8
Magnesium Production and Processing	3.2	3.2
Electrical Transmission and Distribution	22.7	13.2

- Not applicable.

[END BOX]

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 2006 are reported in Table 4-85.

Table 4-85: NO_x, CO, and NMVOC Emissions from Industrial Processes (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
NO_x	591	607	626	656	534	528	524	519	515
Other Industrial Processes	343	362	434	457	390	385	381	377	373
Chemical & Allied Product Manufacturing	152	143	95	97	63	61	61	61	61
Metals Processing	88	89	81	86	63	63	63	63	62
Storage and Transport	3	5	14	15	17	17	17	17	17
Miscellaneous*	5	8	2	1	2	1	1	1	1
CO	4,125	3,959	2,217	2,339	1,744	1,724	1,724	1,724	1,724
Metals Processing	2,395	2,159	1,175	1,252	895	895	895	895	895
Other Industrial Processes	487	566	538	558	444	444	444	443	443
Chemical & Allied Product Manufacturing	1,073	1,110	327	338	258	257	257	257	257
Storage and Transport	69	23	154	162	107	107	107	107	107
Miscellaneous*	101	102	23	30	39	22	22	22	22
NMVOCs	2,422	2,642	1,773	1,769	2,036	1,972	1,931	1,890	1,849
Storage and Transport	1,352	1,499	1,067	1,082	1,346	1,304	1,274	1,245	1,215
Other Industrial Processes	364	408	412	381	401	394	386	379	372
Chemical & Allied Product Manufacturing	575	599	230	238	226	223	220	217	214

[28] See Annex 5 for a discussion of sources of SF_6 emissions excluded from the actual emissions estimates in this report.

Metals Processing	111		113		61	65	42	42	42	42	41
Miscellaneous*	20		23		3	4	20	10	9	8	7

* 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 2008), 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.

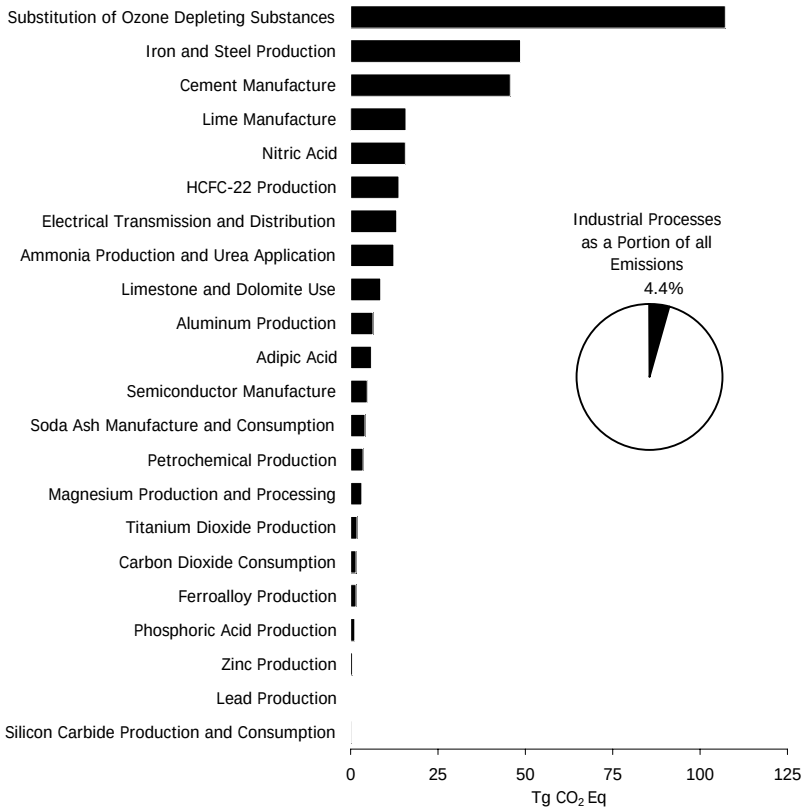

Figure 4-1: 2006 Industrial Processes Chapter Greenhouse Gas Sources

5. Solvent and Other Product Use

Greenhouse gas emissions are produced as a by-product of various solvent and other product uses. In the United States, emissions from Nitrous Oxide (N_2O) Product 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 2006 (see Table 5-1). Indirect greenhouse gas emissions also result from solvent and other product use, and are presented in Table 5-6 in gigagrams (Gg).

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	2006
N_2O from Product Uses									
Tg CO_2 Eq.	4.4	4.6	4.9	4.9	4.4	4.4	4.4	4.4	4.4
Gg	14	15	16	16	14	14	14	14	14

5.1. Nitrous Oxide from Product Uses (IPCC Source Category 3D)

N_2O is a clear, colorless, oxidizing liquefied gas, with a slightly sweet odor. Two companies operate a total of five N_2O production facilities in the United States (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;
- 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 2006 was approximately 15 Gg. N_2O emissions were 4.4 Tg CO_2 Eq. (14 Gg) in 2006 (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).

Table 5-2: N_2O Emissions from N_2O Product Usage (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	4.4	14
1995	4.6	15
2000	4.9	16
2001	4.9	16
2002	4.4	14
2003	4.4	14
2004	4.4	14
2005	4.4	14
2006	4.4	14

Methodology

Emissions from N_2O product usage were calculated by first multiplying the total amount of N_2O produced in the United States by the share of the total quantity of N_2O attributed to each end use. This value was then multiplied by the associated emission rate for each end use. After the emissions were calculated for each end use, they were added together to obtain a total estimate of N_2O product usage emissions. Emissions were determined using the following equation:

$$N_2O \text{ Product Usage Emissions} = \sum_i [\text{Total U.S. Production of } N_2O] \times [\text{Share of Total Quantity of } N_2O \text{ Usage by Sector i}] \times [\text{Emissions Rate for Sector i}]$$

where,

i = Sector.

The share of total quantity of N_2O usage by end use represents the share of national N_2O produced that is used by the specific subcategory (i.e., anesthesia, food processing, etc.). In 2006, 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 (Heydorn 1997). The N_2O was allocated across the following categories: medical applications, food processing propellant, and sodium azide production (pre-1996). A usage emissions rate was then applied for each sector to estimate the amount of N_2O emitted.

Only the medical/dental and food propellant subcategories were estimated to release emissions into the atmosphere, and therefore these subcategories were the only usage subcategories with emission rates. For the medical/dental subcategory, due to the poor solubility of N_2O in blood and other tissues, none of the N_2O is assumed to be metabolized during anesthesia and quickly leaves the body in exhaled breath. Therefore, an emission factor of 100 percent was used for this subcategory (IPCC 2006). For N_2O used as a propellant in pressurized and aerosol food products, none of the N_2O is reacted during the process and all of the N_2O is emitted to the atmosphere, resulting in an emissions factor of 100 percent for this subcategory (IPCC 2006). For the remaining subcategories, all of the N_2O is consumed/reacted during the process, and therefore the emissions rate was considered to be zero percent (Tupman 2002).

The 1990 through 1992 N_2O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997). N_2O production data for 1993 through 1995 were not available. Production data for 1996 was specified as a range in two data sources (Heydorn 1997, Tupman 2002). In particular, for 1996, Heydorn (1997) estimates N_2O production to range between 13.6 and 18.1 thousand metric tons. Tupman (2003) provided a narrower range (i.e., 15.9 to 18.1 thousand metric tons) for 1996 that falls within the production bounds described by Heydorn (1997). Tupman (2003) data are considered more industry specific and current. Therefore, the midpoint of the narrower production range was used to estimate N_2O emissions for years 1993 through 2001 (Tupman 2003). The 2002 and 2003 N_2O production data were obtained from the Compressed Gas Association *Nitrous Oxide Fact Sheet* and *Nitrous Oxide Abuse Hotline* (CGA 2002, 2003). These data were also provided as a range. For example, in 2003, CGA (2003) estimates N_2O production to range between 13.6 and 15.9 thousand metric tons. Due to unavailable data, production for 2004, 2005, and 2006 were held at the 2003 value.

The 1996 share of the total quantity of N_2O used by each subcategory was obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997). The 1990 through 1995 share of total quantity of N_2O used by each subcategory was kept the same as the 1996 number provided by SRI Consulting. The 1997 through 2001share of total quantity of N_2O usage by sector was obtained from communication with a N_2O industry expert (Tupman 2002). The 2002 and 2003 share of total quantity of N_2O usage by sector was obtained from CGA (2002, 2003).

Due to unavailable data, the share of total quantity of N_2O usage data for 2004, 2005, and 2006 was assumed to equal the 2003 value. The emissions rate for the food processing propellant industry was obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997), and confirmed by a N_2O industry expert (Tupman 2002). The emissions rate for all other subcategories was obtained from communication with a N_2O industry expert (Tupman 2002). The emissions rate for the medical/dental subcategory was obtained from the 2006 IPCC Guidelines.

Table 5-3: N_2O Production (Gg)

Year	Gg
1990	16
1995	17
2000	17
2001	17
2002	15
2003	15
2004	15
2005	15
2006	15

Uncertainty

The overall uncertainty associated with the 2006 N_2O emission estimate from N_2O product usage was calculated using the IPCC Guidelines for National Greenhouse Gas Inventories (2006) Tier 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions 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 5-4. N_2O emissions from N_2O product usage were estimated to be between 4.3 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 2 percent below to 2 percent above the 2006 emissions estimate of 4.4 Tg CO_2 Eq.

Table 5-4: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions From N_2O Product Usage (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
N_2O Product Usage	N_2O	4.4	4.3	4.5	2%	+2%

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

Recalculations Discussion

The N_2O emission factor for medical applications has been updated relative to the previous Inventory based on the revised IPCC Guidelines for National Greenhouse Gas Inventories (2006). The updated emission factor resulted in an average increase in N_2O emissions from N_2O product usage relative to the previous inventory for each year in the 1990 through 2005 timeseries of 0.1 Tg CO_2 Eq. (2 percent), respectively.

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, and investigation of

production and use cycles and the potential need to incorporate a time lag between production and ultimate product use and resulting release of N_2O.

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-CH_4 volatile organic compounds (NMVOCs), commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum based solvents. As some of 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 2006 are reported in Table 5-5.

Table 5-5: Emissions of NO_x, CO, and NMVOC from Solvent Use (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
NO_x	**1**	**3**	**3**	**3**	**5**	**5**	**5**	**5**	**5**
Surface Coating	1	2	3	3	5	5	5	5	5
Graphic Arts	+	1	+	+	+	+	+	+	+
Degreasing	+	+	+	+	+	+	+	+	+
Dry Cleaning	+	+	+	+	+	+	+	+	+
Other Industrial Processes[a]	+	+	+	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+	+	+	+
Other	NA	+	+	+	+	+	+	+	+
CO	**5**	**5**	**46**	**45**	**1**	**1**	**1**	**1**	**1**
Surface Coating	+	1	46	45	1	1	1	1	1
Other Industrial Processes[a]	4	3	+	+	+	+	+	+	+
Dry Cleaning	+	1	+	+	+	+	+	+	+
Degreasing	+	+	+	+	+	+	+	+	+
Graphic Arts	+	+	+	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+	+	+	+
Other	NA	NA	+	+	+	+	+	+	+
NMVOCs	**5,216**	**5,609**	**4,384**	**4,547**	**3,881**	**3,862**	**3,854**	**3,846**	**3,839**
Surface Coating	2,289	2,432	1,767	1,863	1,590	1,582	1,579	1,576	1,573
Non-Industrial Processes[b]	1,724	1,858	1,676	1,707	1,457	1,450	1,447	1,444	1,441
Degreasing	675	716	316	331	283	281	281	280	280
Dry Cleaning	195	209	265	272	232	231	230	230	229
Graphic Arts	249	307	222	229	195	194	194	193	193
Other Industrial Processes[a]	85	87	98	103	88	88	88	88	87
Other	+	+	40	42	36	36	36	36	36

[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.

[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.

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 2008), 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.

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.

Figure 6-1: 2006 Agriculture Chapter Greenhouse Gas Emission Sources

In 2006, the agricultural sector was responsible for emissions of 618.9 teragrams of CO_2 equivalent (Tg CO_2 Eq.), or 9 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 23 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 80 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions.

Table 6-1 and Table 6-2 present emission estimates for the Agriculture sector. Between 1990 and 2006, CH_4 emissions from agricultural activities increased by 5 percent, while N_2O emissions fluctuated from year to year, but overall increased by less than 1 percent.

Table 6-1: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH_4	**165.7**	**175.8**	**171.7**	**172.2**	**172.6**	**173.0**	**170.9**	**174.0**	**174.4**
Enteric Fermentation	126.9	132.3	124.6	123.6	123.8	124.6	122.4	124.5	126.2
Manure Management	31.0	35.2	38.8	40.2	41.3	40.7	40.1	41.8	41.4
Rice Cultivation	7.1	7.6	7.5	7.6	6.8	6.9	7.6	6.8	5.9
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.8	0.7	0.8	0.9	0.9	0.8
N_2O	**443.0**	**441.5**	**446.8**	**474.1**	**444.9**	**423.2**	**423.4**	**447.0**	**444.5**
Agricultural Soil Management	430.6	428.3	432.6	459.6	430.5	409.2	409.1	432.5	429.7
Manure Management	12.1	12.8	13.7	14.0	14.0	13.6	13.8	13.9	14.3
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.4	0.4	0.5	0.5	0.5
Total	**608.7**	**617.3**	**618.4**	**646.3**	**617.5**	**596.2**	**594.3**	**620.9**	**618.9**

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	2006
CH_4	**7,890**	**8,373**	**8,174**	**8,201**	**8,219**	**8,236**	**8,138**	**8,284**	**8,304**
Enteric Fermentation	6,044	6,302	5,933	5,886	5,896	5,931	5,828	5,928	6,010
Manure Management	1,474	1,676	1,847	1,915	1,964	1,938	1,908	1,988	1,972
Rice Cultivation	339	363	357	364	325	328	360	326	282

Field Burning of Agricultural Residues	33	32	38	37	34	38	42	41	39
N_2O	**1,429**	**1,424**	**1,441**	**1,529**	**1,435**	**1,365**	**1,366**	**1,442**	**1,434**
Agricultural Soil Management	1,389	1,382	1,395	1,482	1,389	1,320	1,320	1,395	1,386
Manure Management	39	41	44	45	45	44	44	45	46
Field Burning of Agricultural Residues	1	1	1	1	1	1	2	2	2

Note: Totals may not sum due to independent rounding.

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 emitted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest CH_4 emissions among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affects CH_4 emissions. In general, lower feed quality and/or higher feed intake lead to higher CH_4 emissions. Feed intake is positively correlated to animal size, growth rate, and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types (e.g., animals in feedlots or grazing on pasture).

CH_4 emission estimates from enteric fermentation are provided in Table 6-3 and Table 6-4. Total livestock CH_4 emissions in 2006 were 126.2 Tg CO_2 Eq. (6,010 Gg). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71 percent in 2006. Emissions from dairy cattle in 2006 accounted for 24 percent, and the remaining emissions were from horses, sheep, swine, and goats.

From 1990 to 2006, emissions from enteric fermentation have decreased by less than 1 percent. Generally, emissions have been decreasing since 1995 to 2004, mainly due to decreasing populations of both beef and dairy cattle and improved feed quality for feedlot cattle. The last two years have shown an increase in emissions. During this timeframe, populations of sheep have decreased 45 percent since 1990 while horse populations have increased over 80 percent, mostly over the last 5 years. Goat and swine populations have increased 1 percent and 14 percent, respectively, during this timeframe.

Table 6-3: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	1990	1995	2000	2001	2002	2003	2004	2005	2006
Beef Cattle	89.9	96.9	90.4	89.4	89.3	89.5	87.2	88.2	89.2
Dairy Cattle	31.2	29.9	28.9	28.8	29.0	29.2	28.9	29.6	30.3
Horses	1.9	1.9	2.0	2.1	2.3	2.6	3.0	3.5	3.5
Sheep	1.9	1.5	1.2	1.2	1.1	1.1	1.0	1.0	1.0
Swine	1.7	1.9	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	0.3
Total	**126.9**	**132.3**	**124.6**	**123.6**	**123.8**	**124.6**	**122.4**	**124.5**	**126.2**

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	2006
Beef Cattle	4,281	4,616	4,304	4,257	4,251	4,260	4,155	4,198	4,249
Dairy Cattle	1,488	1,422	1,377	1,374	1,381	1,393	1,377	1,411	1,441
Horses	91	92	94	99	108	126	144	166	166
Sheep	91	72	56	55	53	51	49	49	50
Swine	81	88	88	88	90	90	91	92	93
Goats	13	12	12	12	13	13	13	13	13
Total	**6,044**	**6,302**	**5,933**	**5,886**	**5,896**	**5,931**	**5,828**	**5,928**	**6,010**

Note: Totals may not sum due to independent rounding.

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., 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. The Cattle Enteric Fermentation Model (CEFM), developed by EPA to estimate cattle enteric CH_4 emissions, incorporates this information and other analyses of livestock population, feeding practices and production characteristics were 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 create a transition matrix that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Annex 3.9. These

variables include performance factors such as pregnancy and lactation as well as average weights and weight gain. Annual cattle population data were obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service Quick Stats database (USDA 2007).

Diet characteristics were estimated by region for U.S. dairy, beef, and feedlot cattle. These estimates were used to calculate Digestible Energy (DE) values (expressed as the percent of gross energy intake digested by the animal) and CH_4 conversion rates (Y_m) (expressed as the fraction of gross energy converted to CH_4) for each population category. The IPCC recommends Y_m values of 3.0±1.0 percent for feedlot cattle and 6.5±1.0 percent for other well-fed cattle consuming temperate-climate feed types (IPCC 2006). Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed, 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 all cattle types except bulls and calves younger than 7 months,[1] the population was divided into state, 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. The transition matix was used to simulate the age and weight structure of each sub-type on a monthly basis, to more accurately reflect the fluctuations that occur throughout the year. Cattle diet characteristics were then used in conjunction with Tier 2 equations from IPCC (2006) to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, 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 2006. 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 2007). Horse population data were obtained from the FAOSTAT database (FAO 2007), because USDA does not estimate U.S. horse populations annually. Goat population data were obtained for 1992, 1997, and 2002 (USDA 2007); these data were interpolated and extrapolated to derive estimates for the other years. CH_4 emissions from sheep, goats, swine, and horses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC 2006). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. The methodology is the same as that recommended by IPCC (2006).

See Annex 3.9 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation.

[1] Emissions from bulls are estimated using a Tier 1 approach because it is assumed there is minimal variation in population and diets; calves younger than 7 months are assumed to emit little or no CH_4.

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 uncertainty estimates were developed for the 1990 through 2001 inventory report. No significant changes occurred in the method of data collection, data estimation methodology, or other factors that influence the uncertainty ranges around the 2006 activity data and emission factor input variables used in the current submission. Consequently, these uncertainty estimates were directly applied to the 2006 emission estimates.

A total of 185 primary input variables (177 for cattle and 8 for non-cattle) were identified as key input variables for the uncertainty analysis. A normal distribution was assumed for almost all activity- and emission factor-related input variables. Triangular distributions were assigned to three input variables (specifically, cow-birth ratios for the three most recent years included in the 2001 model run) because we wanted to capture the fact that these variables can not be negative. For some key input variables, the uncertainty ranges around their estimates (used for inventory estimation) were collected from published documents and other public sources; others were based on expert opinion and our best estimates. In addition, both endogenous and exogenous correlations between selected primary input variables were modeled. The exogenous correlation coefficients between the probability distributions of selected activity-related variables were developed through expert judgment.

The uncertainty ranges associated with the activity data-related input variables were plus or minus 10 percent or lower. However, for many emission factor-related input variables, the lower- and/or the upper-bound uncertainty estimates were over 20 percent. The results of the quantitative uncertainty analysis (Table 6-5) indicate that, on average, the emission estimate range of this source is approximately 112.3 to 148.9 Tg CO_2 Eq., calculated as 11 percent below and 18 percent above the actual 2006 emission estimate of 126.2 Tg CO_2 Eq. Among the individual cattle sub-source categories, beef cattle account for the largest amount of CH_4 emissions as well as the largest degree of uncertainty in the inventory emission estimates. Among non-cattle, horses account for the largest degree of uncertainty in the inventory emission estimates because there is a higher degree of uncertainty among the FAO population estimates used for horses than for the USDA population estimates used for swine, goats, and sheep.

Table 6-5: Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	126.2	112.3	148.9	-11%	+18%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[b] Note that the relative uncertainty range was estimated with respect to the 2001 emission estimates submitted in 2003 and applied to 2006 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 reviewing and implementing the revised IPCC Guidelines (IPCC 2006). Additionally, as described below, this year the CEFM was modified to allow generation of the estimates by state, which required further QA/QC to ensure consistency of estimates generated by the updated model.

Recalculations Discussion

There were several modifications that had an effect on emission estimates, including:

- The Cfi (a coefficient used for calculating the net energy required for maintenance) used for lactating cattle was adjusted from 0.322 (previously used for all cattle) to 0.386, based on the revised IPCC equations (IPCC 2006). This change had the effect of increasing the energy requirement for maintenance of lactating cows and thus increasing emissions for dairy cows by approximately 7 percent and beef cows by approximately 16 percent.

- During the QA/QC process it was noted that the C factor (a coefficient used in calculating the net energy required for growth) of 0.8 was only being used for some feedlot heifers, and all other cows and heifers were being calculated using a C factor of 1.0. This has been updated so that all cows and heifers use a C factor of 0.8 and all steer use a C factor of 1.0, as stated in the revised IPCC Guidelines (IPCC 2006). This change resulted in an increase in emissions of between three and ten percent in animal subcategories that experience weight gain (e.g., feedlot, replacement, and stocker animals), depending on the subcategory.

- The equation used to calculate the net energy of growth (NEg), which is part of the gross energy equation, was also updated to match the simplified equation provided in the revised IPCC Guidelines (IPCC 2006). The equation now reads:

$$NE_g = 22.02 \times \left(\frac{\text{Weight}}{\text{C} \times \text{MW}} \right)^{0.75} \times \text{WG}^{1.097}$$

Previously the equation used was:

$$NE_g = 4.18 \times 0.0635 \times \left[0.891 \times (\text{Weight} \times 0.96) \times \left(\frac{478}{\text{C} \times \text{MW}} \right) \right]^{0.75} \times (\text{WG} \times 0.92)^{1.097}$$

Where,

NEg = The net energy required for growth, MJ/day

Weight = Average live body weight of the animals in the population, kg

C = A coefficient that is 0.8 for females, 1.0 for steer, and 1.2 for bulls

MW = The mature weight of an adult female in moderate condition, kg

WG = The average weight gain for animals in the population, kg/day

This change resulted in a decrease of less than one half of one percent in animal subcategories that experience growth (i.e., weight gain, including, feedlot, replacement, and stocker animals).

- In the current inventory, the CEFM, which was used to calculate emissions from cattle enteric fermentation, was updated to output results by individual state rather than by regional groupings, during this process two changes occurred. First, the averaging approach used to calculate the step-up DE and Y_m for feedlot animals is based on an average of the feedlot and stocker diet characteristics. Given that we changed the model to run 50 states rather than 7 regions, the final values for the step-up diet characteristics changed slightly. Second, the milk production numbers are now input at the state, rather than regional level, which allows for data input at a more detailed level. Both of these changes had a very small effect on emissions compared to the additional modifications, discussed above.

- Population estimates were revised by FAO for 2001 through 2005 for horses.

- The USDA published revised population estimates that affected historical emissions estimated for swine in

2005. In addition, some historical population estimates for certain beef and dairy populations were also updated as a result of changes in USDA inputs.

As a result of these changes, dairy cattle emissions increased an average of 99 Gg (7.6 percent) per year and beef cattle increased an average of 435 Gg (11.1 percent) per year over the entire time series. Historical emission estimates for swine in 2005 increased by less than one half of one percent as a result of the USDA revisions described above. Historical emission estimates for horses increased by an average of 35 percent from 2001 through 2005.

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. Research is currently underway to update the diet assumptions. There are a variety of models available to predict methane production from cattle. Four of these models (two mechanistic, and two empirical) are being evaluated to determine appropriate Y_m and DE values for each cattle type and state. In addition to the model evaluation, separate research is being conducted to update the assumptions used for cattle diet components for each animal type. At the conclusion of both of these updates, it is anticipated that a peer-reviewed article will be published and will serve as the basis for future emission estimates for enteric fermentation.

In addition to the diet characteristics discussed above several revisions will be investigated, including:

- the possible inclusion of bulls into the CEFM at a Tier 1 or 2 level;
- updating input variables that are from older data sources, such as beef births by month and beef cow lactation rates;
- the possible breakout of other animal types from national estimates to state-level estimates; and
- including bison in the estimates for other domesticated animals.

It is anticipated that these updates may result in significant changes to some of the activity data used in generating emissions. Additionally, since these revised inputs will be state-specific and peer-reviewed, uncertainty ranges around these variables will likely decrease. As a consequence, the current uncertainty analysis will become outdated, and a revision of the quantitative uncertainty surrounding emission estimates from this source category will be initiated.

6.2. Manure Management (IPCC Source Category 4B)

The management of livestock manure can produce anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. $Methane_B$ is produced by the anaerobic decomposition of manure. Direct N_2O emissions are produced as part of the nitrogen cycle through the nitrification and denitrification of the organic nitrogen in livestock manure and urine.[2] Indirect N_2O emissions are produced as result of the volatilization of nitrogen as NH_3 and NO_x and runoff and leaching of nitrogen during treatment, storage and transportation.

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[2] Direct and indirect N_2O 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.) and from livestock manure and urine deposited on pasture, range, or paddock lands are accounted for and discussed in the Agricultural Soil Management source category within the Agriculture sector.

When livestock or poultry manure are stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of materials in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no CH_4. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production. Manure composition, which varies by animal diet, growth rate, and type, including the animal's digestive system, also affects the amount of CH_4 produced. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. However, some higher energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal.

The production of direct N_2O emissions from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For direct N_2O emissions to occur, the manure must first be handled aerobically where ammonia (NH_3) or organic 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 (WMS). Indirect N_2O emissions are produced when nitrogen is lost from the system through volatilization (as NH_3 or NOx) or through runoff and leaching. The vast majority of volatilization losses from these operations are NH_3. Although there are also some small losses of NO_x, there are no quantified estimates available for use, so losses due to volatilization are only based on NH_3 loss factors. Runoff losses would be expected from operations that house animals or store manure in a manner that is exposed to weather. Runoff losses are also specific to the type of animal housed on the operation. Little information is known about leaching from manure management systems as most research focuses on leaching from land application systems. Since leaching losses are expected to be minimal, leaching losses are coupled with runoff losses and the runoff/leaching estimate does not include any leaching losses.

Estimates of CH_4 emissions in 2006 were 41.4 Tg CO_2 Eq. (2,005 Gg), 34 percent higher than in 1990. Emissions increased on average by 0.6 Tg CO_2 Eq. (2.0 percent) annually over this period. The majority of this increase was from swine and dairy cow manure, where emissions increased 34 and 49 percent, respectively. Although the majority of manure in the United States is handled as a solid, producing little CH_4, the general trend in manure management, particularly for dairy and swine (which are both shifting towards larger facilities), is one of increasing use of liquid systems. Also, new regulations limiting the application of manure nutrients have shifted manure management practices at smaller dairies from daily spread to manure managed and stored on site. Although national dairy animal populations have been generally decreasing, some states have seen increases in their dairy populations as the industry becomes more concentrated in certain areas of the country. These areas of concentration, such as California, New Mexico, and Idaho, tend to utilize more liquid-based systems to manage (flush or scrape) and store manure. Thus the shift toward larger facilities is translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This shift was accounted for by incorporating state and WMS-specific CH_4 conversion factor (MCF) values in combination with the 1992, 1997, and 2002 farm-size distribution data reported in the *Census of Agriculture* (USDA 2005). Methane emissions from horses have nearly doubled since 1990 (an 82 percent increase from 1990 to 2006); however, this is due to population increases rather than changes in manure management practices. Overall, horses contribute only 2 percent of CH_4 emissions from animal manure management. From 2005 to 2006, there was a 1 percent decrease in total CH_4 emissions, due to minor shifts in the animal populations and the resultant effects on manure management system allocations and increased use of anaerobic digesters.

In 2006, total N_2O emissions were estimated to be 14.3 Tg CO_2 Eq. (46 Gg); in 1990, emissions were 12.1 Tg CO_2 Eq. (39 Gg). These values include both direct and indirect N_2O emissions from manure management. N_2O emissions have remained fairly steady since 1990. Small changes in N_2O emissions from individual animal groups exhibit the same trends as the animal group populations, with the overall net effect that N_2O emissions showed an 18 percent increase from 1990 to 2006 and a 2.5 percent increase from 2005 through 2006.

Table 6-6 and Table 6-7 provide estimates of CH_4 and N_2O emissions from manure management by animal

category.

Table 6-6: CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq.)

Gas/Animal Type	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH_4[1]	**31.0**	**35.2**	**38.8**	**40.2**	**41.3**	**40.7**	**40.1**	**41.8**	**41.4**
Dairy Cattle	12.0	13.4	15.8	16.6	17.3	17.7	17.2	17.9	17.9
Beef Cattle	2.5	2.6	2.4	2.4	2.4	2.3	2.3	2.3	2.5
Swine	13.1	16.0	17.4	17.8	18.3	17.2	17.1	17.9	17.5
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	0.0	+	+	+	+	+
Poultry	2.8	2.7	2.6	2.7	2.7	2.7	2.6	2.6	2.7
Horses	0.5	0.4	0.5	0.5	0.5	0.6	0.7	0.8	0.8
N_2O[2]	**12.1**	**12.8**	**13.7**	**14.0**	**14.0**	**13.6**	**13.8**	**13.9**	**14.3**
Dairy Cattle	3.5	3.5	3.6	3.6	3.7	3.7	3.7	3.7	3.8
Beef Cattle	5.5	5.9	6.7	6.9	6.7	6.3	6.5	6.5	6.7
Swine	1.2	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	0.0	+	+	+	+	+
Poultry	1.5	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.8
Horses	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4
Total	**43.0**	**48.0**	**52.5**	**54.2**	**55.2**	**54.3**	**53.9**	**55.7**	**55.7**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.
[1]Includes CH_4 emission reductions due to anaerobic digestion.
[2]Includes both direct and indirect N_2O emissions.

Table 6-7: CH_4 and N_2O Emissions from Manure Management (Gg)

Gas/Animal Type	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH_4[1]	**1,474**	**1,676**	**1,847**	**1,915**	**1,964**	**1,938**	**1,908**	**1,988**	**1,972**
Dairy Cattle	572	638	751	792	822	844	818	854	852
Beef Cattle	120	121	114	117	113	112	111	112	117
Swine	623	762	830	849	873	821	815	853	832
Sheep	7	5	4	4	4	4	4	4	4
Goats	1	1	1	1	1	1	1	1	1
Poultry	131	128	125	129	127	127	126	126	126
Horses	22	21	22	23	25	29	34	39	39
N_2O[2]	**39**	**41**	**44**	**45**	**45**	**44**	**44**	**45**	**46**
Dairy Cattle	11	11	12	12	12	12	12	12	12
Beef Cattle	18	19	22	22	22	20	21	21	22
Swine	4	5	5	5	5	5	5	5	5
Sheep	+	+	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+	+	+
Poultry	5	5	5	5	6	6	6	6	6
Horses	1	1	1	1	1	1	1	1	1

Note: Totals may not sum due to independent rounding.
[1]Includes CH_4 emission reductions due to anaerobic digestion.
[2]Includes both direct and indirect N_2O emissions.
+ Less than 0.5 Gg.

Methodology

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal type. The calculation of emissions requires the following information:

- Animal population data (by animal type and state);
- Amount of N 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, 1998b, 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 (VS) 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 VS from lagoon systems. Direct N_2O emission factors for all systems were set equal to default IPCC factors (IPCC 2006). For indirect N_2O, the default indirect N_2O emission factors suggested by IPCC were used: 0.010 kg N_2O-N/kg N for volatilization and 0.0075 kg -N/kg N for runoff/leaching. The amount of nitrogen that is lost due to volatilization of NH_3 and NO_X ($Frac_{Gas}$) is based on WMS-specific volatilization values as estimated from U.S. EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). The amount of nitrogen that is lost due to runoff and leaching ($Frac_{runoff/leaching}$) is based on regional cattle runoff data from EPA's Office of Water (EPA 2002b).

CH_4 emissions were estimated using the VS production for livestock. For all cattle groups except bulls and calves, regional animal-specific VS production rates that are related to the diet of the animal for each year of the inventory were used (Pederson et al., 2007). For 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- and WMS-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 for 1990-2005 were estimated based on data from the EPA AgSTAR program, including information presented in the *AgSTAR Digest* (EPA 2000, 2003b, 2006). Anaerobic digestion reductions for 2006 were calculated based on data from an AgSTAR digester inventory (ERG 2008).

Nitrogen excretion rates 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.

Direct N_2O emissions were estimated by determining total Kjeldahl nitrogen (TKN)[3] production for all livestock wastes using a national average N 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- and WMS-specific direct N_2O emission factors were then applied to total nitrogen production to estimate direct N_2O emissions.

Indirect N_2O emissions were calculated by first estimating the amount of nitrogen loss from volatilization and runoff/leaching by multiplying the N excreted by $Frac_{Gas}$ and $Frac_{Runoff/Leaching}$. The N losses were then multiplied by the indirect N_2O emission factors to estimate indirect 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. The quantitative uncertainty analysis for this source category was performed in 2002 through the IPCC-recommended Tier 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The uncertainty analysis was developed based on the methods used to estimate CH_4 and N_2O emissions from manure management systems. A normal probability distribution was assumed for each source data category. The series of equations used were condensed into a single equation for each animal type and state. The equations for each animal group contained four to five variables around which the uncertainty analysis was performed for each state.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-8 Manure management CH_4 emissions in 2006 were estimated to be between 34.0 and 49.7 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2006 emission estimate of 41.4 Tg CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 12.0 and 17.7 Tg CO_2 Eq. (or approximately 16 percent below and 24 percent above the actual 2006 emission estimate of 14.3 Tg CO_2 Eq.).

Table 6-8: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O (Direct and Indirect) Emissions from Manure Management (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	41.4	34	49.7	-18%	+20%
Manure Management	N_2O	14.3	12.0	17.7	-16%	+24%

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

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Tier 2 activities focused on comparing estimates for the previous and current inventories for N_2O emissions[4] from managed systems and CH_4 emissions from livestock manure. All errors identified were corrected. Order of magnitude checks were also conducted, and corrections made where needed. Manure N data were checked by comparing state-level data with bottom up estimates derived at the county level and summed to the state level. Similarly, a comparison was made by animal and WMS type for the full time series, between national level estimates for nitrogen excreted and the sum of county estimates for the full time series.

[3]Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

[4]N_2O emissions in the previous inventory reflect only direct emissions whereas the current N_2O emissions include both direct and indirect emissions from livestock manure management.

Recalculations Discussion

There was a major change in the N_2O and CH_4 emissions calculations for the 2006 inventory. These emissions are now calculated from the "bottom-up" such that CH_4 and N_2O are calculated for each animal group, manure management system, and state. These values are then summed to calculate the total greenhouse gas emissions from manure management in the United States. This methodology differs from previous inventories which calculated state weighted average N_2O emission factors and methane conversion factors (MCFs). Although this new methodology does not alter the overall estimates of greenhouse gases associated with this section, it now allows emissions to be viewed by animal type and manure management system at the state and national level.

In the previous N_2O inventory, dairy heifers and beef on feed each had a separate WMS distribution for managed systems and unmanaged systems. The managed WMS distribution was used to calculate a state average EF for managed systems. In the new inventory methodology, dairy heifers and beef on feed have one WMS distribution that represents managed and unmanaged systems. For all animals, emissions are calculated for each WMS using the EF for that system, and not using a state average EF. This change in calculation methodology results in a slightly different (less than one percent change) emission estimate for these animal groups.

The inventory now includes indirect N_2O emissions in the manure management sector associated with N losses from volatilization of nitrogen as ammonia (NH_3), nitrogen oxides (NO_x), and leaching and runoff, as recommended by IPCC (2006). These indirect N_2O emissions are added to the direct N_2O emissions to present a more complete picture of N_2O emissions from manure management.

The days per year used in N_2O calculations was changed from 365 to 365.25 to include leap years and to be consistent with the CH_4 inventory calculations.

Methane emission reductions from anaerobic digestion for 2006 were calculated from an AgSTAR digester inventory by summing the estimated emission reductions by animal type (ERG 2008). Anaerobic digestion reductions in previous years were based on data obtained from AgSTAR Digests (EPA 2000, 2003b, 2006).

Errors were identified in the calculation of the sheep WMS distribution; population values for other states were incorrectly distributed in the calculations. Correcting this error resulted in very small changes in N_2O emissions estimates from sheep.

Changes were made to the current calculations involving animal population data. Animal population data were updated to reflect the final estimates reports from USDA NASS (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a, 2004a-e, 2006a-c, 2007a-d). The population data may differ from previous inventories because some values changed due to USDA NASS review. For horses, state-level populations were estimated using the national FAO population data (FAO 2007) and the state distributions from the 1992, 1997, and 2002 Census of Agriculture (USDA 2005). The FAO horse population estimates for recent years increased dramatically between the 2005 and 2006 inventories, resulting in a much larger estimated horse population, and therefore greater greenhouse gas emissions from this sector.

With these recalculations, CH_4 emission estimates from manure management systems are slightly higher than reported in the previous inventory for dairy cattle and swine, as well as horses for years 2001 through 2005. On average, annual CH_4 emission estimates are more than those of the previous inventory by about one percent.

N_2O emission estimates from manure management systems have increased by approximately 30 percent for all years of the current inventory compared to the previous inventory due to the change in calculation methodology, which incorporates direct and indirect N_2O emissions. The most significant changes in N_2O emissions compared to the previous inventory occurred in the poultry and swine sectors, whose emissions were approximately 70 percent higher due to the inclusion of indirect N_2O emissions.

Changes were made to the Cattle Enteric Fermentation Model that produces the VS estimates for all cattle groups except bulls and calves. Refer to the Recalculations section in the Enteric Fermentation to see specific changes made to the model.

Planned Improvements

The manure management inventory will be updated to reflect changes in the Cattle Enteric Fermentation Model (CEFM). In addition, efforts will be made to ensure that the manure management inventory and CEFM are using the same data sources and variables where appropriate.

The American Society of Agricultural Engineers proposed new standards for manure production characteristics in 2004 and finalized them in 2005. These data were investigated and evaluated for incorporation into future estimates.

A method to better estimate anaerobic digester CH_4 emission reductions will be investigated. This method would include separating systems with anaerobic digesters from the total animal population before estimating CH_4 emissions, and then estimating emissions from the digesters using the amount of biogas/CH_4 collected and a 99 percent destruction efficiency.

The uncertainty analysis will be updated for in the future to more accurately assess uncertainty of emission calculations. This update is necessary due to the extensive changes in emission calculation methodology in the 1990 through 2006 inventory, including estimation of emissions at the WMS level and the use of new calculations and variables for indirect N_2O emissions.

The current methodology for calculating runoff for indirect N_2O emissions will be reevaluated. Currently runoff is estimated at all manure management systems based on outdoor cattle operations. A new methodology may be incorporated which takes into account more recent model runs from EPA's Office of Water.

In order to improve the efficiency of MCF calculations, MCFs will be calculated in a database instead of spreadsheets in the next inventory. Calculating MCFs in a database will also increase the overall efficiency of CH_4 emission estimates by linking directly to the database that calculates CH_4 estimates.

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,[5] 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.[6] 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 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 2006, CH_4 emissions from rice cultivation were 5.9 Tg CO_2 Eq. (282 Gg). Although annual emissions fluctuated unevenly between the years 1990 and 2006, ranging from an annual decrease of 14 percent to an annual increase of 17 percent, there was an overall decrease of 17 percent over the sixteen-year period, due to an overall decrease in primary crop area.[7] The factors that affect the rice acreage in any year vary from state to state, although the price of rice relative to competing crops is the primary controlling variable in most states.

Table 6-9: CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq.)

State	1990		1995		2000	2001	2002	2003	2004	2005	2006
Primary	**5.1**		**5.6**		**5.5**	**5.9**	**5.7**	**5.4**	**6.0**	**6.0**	**5.1**
Arkansas	2.1		2.4		2.5	2.9	2.7	2.6	2.8	2.9	2.5
California	0.7		0.8		1.0	0.8	0.9	0.9	1.1	0.9	0.9
Florida	+		+		+	+	+	+	+	+	+
Louisiana	1.0		1.0		0.9	1.0	1.0	0.8	1.0	0.9	0.6
Mississippi	0.4		0.5		0.4	0.5	0.5	0.4	0.4	0.5	0.3
Missouri	0.1		0.2		0.3	0.4	0.3	0.3	0.3	0.4	0.4
Oklahoma	+		+		+	+	+	+	+	+	+
Texas	0.6		0.6		0.4	0.4	0.4	0.3	0.4	0.4	0.3
Ratoon	**2.1**		**2.1**		**2.0**	**1.7**	**1.1**	**1.5**	**1.6**	**0.8**	**0.9**
Arkansas	+		+		+	+	+	+	+	+	+
Florida	+		0.1		0.1	+	+	+	+	+	+
Louisiana	1.1		1.1		1.3	1.1	0.5	1.0	1.1	0.5	0.5
Texas	0.9		0.8		0.7	0.6	0.5	0.5	0.5	0.4	0.4
Total	**7.1**		**7.6**		**7.5**	**7.6**	**6.8**	**6.9**	**7.6**	**6.8**	**5.9**

[5] 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.
[6] 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.
[7] The 14 percent decrease occurred between 2005 and 2006; the 17 percent increase happened between 1993 and 1994.

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

Table 6-10: CH_4 Emissions from Rice Cultivation (Gg)

State	1990	1995	2000	2001	2002	2003	2004	2005	2006
Primary	**241**	**265**	**260**	**283**	**274**	**255**	**283**	**287**	**241**
Arkansas	102	114	120	138	128	124	132	139	119
California	34	40	47	40	45	43	50	45	44
Florida	1	2	2	1	1	+	1	1	1
Louisiana	46	48	41	46	45	38	45	45	29
Mississippi	21	24	19	22	22	20	20	22	16
Missouri	7	10	14	18	15	15	17	18	18
Oklahoma	+	+	+	+	+	+	+	+	+
Texas	30	27	18	18	18	15	19	17	13
Ratoon	**98**	**98**	**97**	**81**	**52**	**73**	**77**	**39**	**41**
Arkansas	+	+	+	+	+	+	+	1	+
Florida	2	4	2	2	2	2	2	+	1
Louisiana	52	54	61	52	25	50	50	22	22
Texas	45	40	34	27	24	22	24	17	18
Total	**339**	**363**	**357**	**364**	**325**	**328**	**360**	**326**	**282**

+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

Methodology

IPCC (2006) recommends using harvested rice areas, area-based daily emission factors (i.e., amount of CH_4 emitted per day per unit harvested area), and length of growing season to estimate annual CH_4 emissions from rice cultivation. This inventory uses the recommended methodology and employs Tier 2 U.S.-specific emission factors derived from rice field measurements. State-specific and daily emission factors were not available, however, so average U.S. seasonal emission factors were used. Seasonal emissions have been found to be much higher for ratooned crops than for primary crops, so emissions from ratooned and primary areas are estimated separately using emission factors that are representative of the particular growing season. This approach is consistent with IPCC (2006).

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 6-11. Primary crop areas for 1990 through 2006 for all states except Florida and Oklahoma were taken from U.S. Department of Agriculture's *Field Crops Final Estimates 1987–1992* (USDA 1994), *Field Crops Final Estimates 1992–1997* (USDA 1998), *Field Crops Final Estimates 1997–2002* (USDA 2003), and *Crop Production Summary* (USDA 2005 through 2007). 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; Gaston Cantens (2004, 2005), Vice President of Corporate Relations of the Florida Crystals Company; and Rene Gonzalez (2007a), Plant Manager of Sem-Chi Rice Company. Harvested rice areas for Oklahoma, which also are not reported by USDA, were obtained from Danny Lee of the Oklahoma Farm Services Agency (2003 through 2007). 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, 2005, and 2006, when the ratooned area was less than 1 percent of the primary area (Slaton 1999 through 2001a; Wilson 2002 through 2007). 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), about 77 percent of the primary area in 2004 (Cantens 2005), 0 percent of the primary area in 2005 (there was no ratooning this year due to Hurricane Wilma), and about 28 percent of the primary area in 2006 (Gonzalez 2007a). 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, dropped

to 13 percent in 2005 and increased to 20 percent in 2006 (Linscombe 1999, 2001a, 2002 through 2007; 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, 27 percent in 2005 and increased to 39 percent in 2006 (Klosterboer 1999, 2000, 2001a, 2002, 2003; Stansel 2004, 2005; Texas Agricultural Experiment Station 2006, 2007). California, Mississippi, Missouri, and Oklahoma have not ratooned rice over the period 1990 through 2006 (Guethle 1999, 2000, 2001a, 2002 through 2007; Lee 2003 through 2007; Mutters 2002 through 2005; Street 1999 through 2003; Walker 2005, 2007).

Table 6-11: Rice Areas Harvested (Hectares)

State/Crop	1990	1995	2000	2001	2002	2003	2004	2005	2006
Arkansas									
Primary	485,633	542,291	570,619	656,010	608,256	588,830	629,300	661,675	566,572
Ratoon*	0	0	0	0	0	0	0	662	6
California	159,854	188,183	221,773	190,611	213,679	205,180	238,770	212,869	211,655
Florida									
Primary	4,978	9,713	7,801	4,562	5,077	2,369	3,755	4,565	4,575
Ratoon	2,489	4,856	3,193	2,752	2,734	2,369	2,899	0	1,295
Louisiana									
Primary	220,558	230,676	194,253	220,963	216,512	182,113	215,702	212,465	139,620
Ratoon	66,168	69,203	77,701	66,289	32,477	63,739	64,711	27,620	27,924
Mississippi	101,174	116,552	88,223	102,388	102,388	94,699	94,699	106,435	76,487
Missouri	32,376	45,326	68,393	83,772	73,654	69,203	78,915	86,605	86,605
Oklahoma	617	364	283	265	274	53	158	271	17
Texas									
Primary	142,857	128,693	86,605	87,414	83,367	72,845	88,223	81,344	60,704
Ratoon	57,143	51,477	43,302	34,966	30,846	27,681	30,878	21,963	23,675
Total Primary	**1,148,047**	**1,261,796**	**1,237,951**	**1,345,984**	**1,303,206**	**1,215,291**	**1,349,523**	**1,366,228**	**1,146,235**
Total Ratoon	**125,799**	**125,536**	**124,197**	**104,006**	**66,056**	**93,790**	**98,488**	**50,245**	**52,899**
Total	**1,273,847**	**1,387,333**	**1,362,148**	**1,449,991**	**1,369,262**	**1,309,081**	**1,448,011**	**1,416,473**	**1,199,135**

* Arkansas ratooning occurred only in 1998, 1999, 2005, and 2006.
Note: Totals may not sum due to independent rounding.

To determine what CH_4 emission factors should be used for the primary and ratoon crops, CH_4 flux information from rice field measurements in the United States was collected. Experiments 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[8] were then sorted by season (i.e., primary and ratoon) and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added). The experimental results from primary crops with added synthetic and organic fertilizer (Bossio et al. 1999; Cicerone et al. 1992; Sass et al. 1991a, 1991b) were averaged to derive an emission factor for the primary crop, and the experimental results from ratoon crops with added synthetic fertilizer (Lindau and Bollich 1993, Lindau et al. 1995) were averaged to derive an emission factor for the ratoon crop. The resultant emission factor for the primary crop is 210 kg CH_4/hectare-

[8] 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 IPCC (2006) default emission factors.

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 2006 were estimated to be between 2.1 and 12.8 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 65 percent below to 117 percent above the actual 2006 emission estimate of 5.9 Tg CO_2 Eq.

Table 6-12: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	5.9	2.1	12.8	-65%	117%

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

QA/QC and Verification

A source-specific QA/QC plan for 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

When compiling the previous inventory, no data on area harvested and percent of area ratooned in Florida were available for 2005, and consequently 2004 data was held constant. This year, Gonzalez (2007a) was able to provide data for 2005 as well as 2006, resulting in an decrease of about 0.6 percent in the estimate for 2005.

6.4. Agricultural Soil Management (IPCC Source Category 4D)

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and denitrification.[9] 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 to the soil, including: fertilization; application of managed livestock manure and other organic materials such as sewage sludge; deposition of manure on soils by domesticated animals in pastures, rangelands, and paddocks (PRP) (i.e., by grazing animals and other animals whose manure is not managed); production of N-fixing crops and forages; retention of crop residues; and drainage and cultivation of organic cropland soils (i.e., soils with a high organic matter content, otherwise known as histosols).[10] 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.[11] Indirect emissions of N_2O occur through two pathways: (1) volatilization and subsequent atmospheric deposition of applied N,[12] 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 (cropland, grassland, forest lands, settlements, and managed manure) are reported in this chapter.

Figure 6-2: Agricultural Sources and Pathways of N that Result in N_2O Emissions

Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions from this source in 2006 were 429.7 Tg CO_2 Eq. (1,386 Gg N_2O) (see Table 6-13 and Table 6-14). Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2006, although overall emissions were 0.2 percent lower in 2006 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 80 percent of total direct emissions, while grassland accounted for approximately 20 percent. Estimated direct and indirect N_2O emissions by sub-source category are provided in Table 6-15 and Table 6-16.

Table 6-13: N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)*

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Direct	**379.4**	**373.7**	**386.4**	**404.8**	**386.0**	**364.0**	**370.7**	**385.1**	**379.3**
Cropland	292.1	296.5	312.4	330.0	305.5	292.0	298.3	307.2	303.6
Grassland	87.4	77.2	74.0	74.8	80.6	72.0	72.5	77.9	75.8

[9] 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).

[10] Drainage and cultivation of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby enhancing N_2O emissions from these soils.

[11] Asymbiotic N fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[12] 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.

Indirect (All Land-Use Types)	**51.1**	**54.6**	**46.1**	**54.8**	**44.4**	**45.1**	**38.4**	**47.4**	**50.4**
Cropland	30.1	30.5	28.4	28.9	24.8	27.8	21.6	28.4	30.2
Grassland	20.6	23.6	17.1	25.2	18.9	16.7	16.1	18.3	19.5
Forest Land	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements	0.4	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6
Total	**430.6**	**428.3**	**432.6**	**459.6**	**430.5**	**409.2**	**409.1**	**432.5**	**429.7**

* Quality control has uncovered an error in the estimates for direct emissions from cropland. The error is currently being corrected and revised estimates will be provided after public review (See QA/QC for more discussion on the error).
+ Less than 0.05 Tg CO_2 Eq.

Table 6-14: N_2O Emissions from Agricultural Soils (Gg N_2O)*

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Direct	**1,224**	**373.7**	**1,247**	**1,306**	**1,245**	**1,174**	**1,196**	**1,242**	**1,224**
Cropland	942	296.5	1,008	1,064	985	942	962	991	979
Grassland	282	77.2	239	241	260	232	234	251	244
Indirect (All Land-Use Types)	**165**	**54.6**	**149**	**177**	**143**	**146**	**124**	**153**	**163**
Cropland	97	30.5	92	93	80	90	70	92	97
Grassland	67	23.6	55	81	61	54	52	59	63
Forest Land	+	0.1	+	+	+	+	+	+	+
Settlements	1	0.5	2	2	2	2	2	2	2
Total	**1,389**	**428.3**	**1,395**	**1,482**	**1,389**	**1,320**	**1,320**	**1,395**	**1,386**

* Quality control has uncovered an error in the estimates for direct emissions from cropland. The error is currently being corrected and revised estimates will be provided after public review (See QA/QC for more discussion on the error).
+ Less than 0.5 Gg N_2O

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	2006
Cropland	**292.1**	**296.5**	**312.4**	**330.0**	**305.5**	**292.0**	**298.3**	**307.2**	**303.6**
Mineral Soils	**289.3**	**293.7**	**309.5**	**327.1**	**302.6**	**289.1**	**295.4**	**304.4**	**300.7**
Synthetic Fertilizer	111.9	118.6	116.6	123.8	117.5	107.6	116.6	112.2	111.9
Organic Amendments[a]	17.5	18.5	18.9	20.8	20.1	17.9	19.2	17.6	18.8
Residue N[b]	18.8	21.0	22.2	20.9	19.0	23.2	19.5	20.6	22.0
Other[c]	141.1	135.6	151.9	161.7	146.0	140.4	140.2	153.9	147.9
Organic Soils	**2.8**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**
Grassland	**87.4**	**77.2**	**74.0**	**74.8**	**80.6**	**72.0**	**72.5**	**77.9**	**75.8**
Synthetic Fertilizer	3.0	2.6	2.5	2.6	2.7	2.5	2.5	2.5	2.6
PRP Manure	19.8	18.4	19.6	18.5	23.3	19.2	20.9	18.9	19.6
Managed Manure[d]	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Sewage Sludge	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5
Residue N[b]	12.5	11.4	10.4	10.9	10.8	10.3	10.5	11.2	10.4
Other[c]	51.3	44.0	40.7	41.8	42.8	39.2	37.6	44.2	42.2
Total	**379.4**	**373.7**	**386.4**	**404.8**	**386.0**	**364.0**	**370.7**	**385.1**	**379.3**

* Quality control has uncovered an error in the estimates for direct emissions from cropland. The error is currently being corrected and revised estimates will be provided after public review (See QA/QC for more discussion on the error).
[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 (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Cropland	**30.1**	**30.5**	**28.4**	**28.9**	**24.8**	**27.8**	**21.6**	**28.4**	**30.2**
Volatilization and Atm. Deposition	5.8	6.1	6.7	6.1	6.0	6.4	6.1	6.6	6.5
Surface Leaching & Run-Off	24.3	24.4	21.7	22.8	18.8	21.4	15.5	21.8	23.7
Grassland	**20.6**	**23.6**	**17.1**	**25.2**	**18.9**	**16.7**	**16.1**	**18.3**	**19.5**
Volatilization and Atm. Deposition	10.7	10.2	9.3	9.4	9.3	9.4	9.2	10.1	9.4
Surface Leaching & Run-Off	9.9	13.4	7.8	15.8	9.6	7.2	6.9	8.2	10.1
Forest Land	**+**	**0.1**	**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	0.1
Settlements	0.4	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6
Volatilization and Atm. Deposition	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Surface Leaching & Run-Off	0.2	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Total	**51.1**	**54.6**	**46.1**	**54.8**	**44.4**	**45.1**	**38.4**	**47.4**	**50.4**

+ Less than 0.05 Tg CO_2 Eq.

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 states 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 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 is cultivated, and also low in many western states where rainfall and access to irrigation water are limited.

Direct emissions (Tg CO_2 Eq./county/year) from grasslands are highest in the western United States (Figure 6-4) where a high proportion of the land is used for cattle grazing. Some areas in the Great Lake states, the Northeast, and Florida have moderate emissions even though emissions from these areas tend to be high on a per unit area basis, because the total amount of grazed land is much lower than states in the West.

Indirect emissions for croplands 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 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 the Carolinas are also relatively high compared to direct emissions because these soils tend to be coarse-textured.

Figure 6-3: Major Crops, Average Annual Direct N_2O Emissions, 1990–2006 (Tg CO_2 Eq./state/year)

[Figure will be available after public review]

Figure 6-4: Grasslands, Average Annual Direct N_2O Emissions, 1990–2006 (Tg CO_2 Eq./state/year)

[Figure will be available after public review]

Figure 6-5: Major Crops, Average Annual N Losses Leading to Indirect N_2O Emissions, 1990–2006 (Tg CO_2 Eq./state/year)

[Figure will be available after public review]

Figure 6-6: Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions, 1990–2006 (Tg CO_2 Eq./state/year)

[Figure will be available after public review]

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 asymbiotic fixation of N from the atmosphere[13] and decomposition of soil organic matter and litter.

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 further elaboration). The Tier 1 IPCC methodology was used to estimate (1) direct emissions from non-major crops on mineral soils, (2) the portion of the grassland direct emissions that were not estimated with the Tier 3 DAYCENT model, and (3) direct emissions from drainage and cultivation of organic cropland soils. The Tier 1 approach was based on the *2006 IPCC Guidelines* (IPCC 2006). A combination of DAYCENT and the IPCC Tier 1 method was used to estimate indirect emissions from soils.

Several recommendations from IPCC (2006) have been adopted 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 a 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 soils 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). IPCC (2006) recommends reporting all emissions from managed lands, largely because management affects all processes leading to soil N_2O emissions. This is particularly the case for croplands. In past Inventory reports, attempts were made to subtract "background" emissions (i.e., estimates of what the emissions might have been if the lands were unmanaged). However, this approach leads to likely inaccuracies because unmanaged, native lands display more soil organic C and mineralization than occur in the cropland soils of today. Moreover, if background emissions could be measured or modeled based on processes unaffected by anthropogenic activity, they would be a very small portion of the total emissions due to the high inputs of N to agricultural soils from fertilization. Given the recommendation from IPCC (2006) and the influence of management on all processes leading to N_2O emissions from soils in agricultural

[13] 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.

systems, the decision was made to report total emissions from managed lands for this source category. Annex 3.11 provides more detailed information on the methodologies and data used to calculate N_2O emissions from each component.

[BEGIN BOX]

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, and thus it is critical to evaluate the output of Tier 3 methods with measured data in order to demonstrate the adequacy of the method for estimating emissions (IPCC 2006). Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding N cycling. Tier 1 assumes that N added to a system is subject to N_2O emissions only during that year; e.g., N added as fertilizer or through fixation contributes to N_2O emission for that year, but cannot be stored in soils and contribute to N_2O emission in subsequent years. This is a simplifying assumption used in the Tier 1 approach, which is likely to create bias in estimated N_2O emissions for a specific year. In contrast, the process-based model used in the Tier 3 approach includes such legacy effects when N is mineralized from soil organic matter and emitted as N_2O during subsequent years.

[END BOX]

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, soybeans, 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 (i.e., state) and national levels due to the scale of management data.

Nitrous oxide emission estimates from DAYCENT are influenced by 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). To approximate emissions by activity, the amount of mineral N added to the soil for each of these sources was determined and then divided by the total amount of mineral N that was made available in the soil according to the DAYCENT model. The percentages were then multiplied by the total 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. However, this approach allows for further disaggregation by source of N, which is valuable for reporting purposes.

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 instead of burning or collecting residues), 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 the first three 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). Amendment data for 1997 were scaled to estimate values for other years based on the availability of managed manure N for application to soils in 1997 relative to other years. The amount of available nitrogen from managed manure for each livestock type was calculated by first 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. Population data used for cattle, swine, and sheep were downloaded from the USDA NASS Population Estimates Database (USDA 2007a). Poultry population data were obtained from USDA NASS reports (USDA 1995a, 1995b, 1998a, 1999, 2004a, 2004b, 2006a, 2006b, 2007b, 2007c). Horse population data were obtained from the FAOSTAT database (FAO 2007). Goat population data for 1992, 1997, and 2002 were obtained from the *Census of Agriculture* (USDA 2005); 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, 1997, and 2002 *Census of Agriculture* (USDA

2005). Once the animal populations for each livestock type and management system were estimated, these populations were multiplied by a typical animal mass constant (USDA 1996, ASAE 1999; NRC 2000, ERG 2003, EPA 1992, Safley 2000) to derive total animal mass for each animal type in each management system. Total Kjeldahl N[14] excreted per year for each livestock type and management system was then calculated using daily rates of N excretion per unit of animal mass (USDA 1996, ASAE 1999). The annual amounts of Kjeldahl N were then summed over all livestock types and management systems to derive estimates of the annual managed manure N produced. Nitrogen available for application was estimated for managed systems based on the total amount of N produced in manure minus N losses and including the addition of N from bedding materials. Nitrogen losses include direct nitrous oxide emissions, volatilization of ammonia and NO_x, and runoff and leaching; more information on these losses is available in Annex 3.10, Manure Management. Animal-specific bedding factors were set equal to IPCC default factors (IPCC 2006). The estimated amount of manure available for application was adjusted for the small percent of poultry manure used for cattle feed between 1990 and 2002 (Carpenter 1992, Carpenter and Starkey 2007). The remaining manure N that was not applied to major crops and grassland was assumed to be applied to non-major crop types. 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.

- 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 treated as separate activity data in 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 simulations produced per-area estimates of N_2O emissions (g N_2O-N m^{-2}) for major crops, which were multiplied by the cropland area data to obtain county-scale emission estimates. Cropland area data were from NASS (USDA 2006g). 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, 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 than the Tier 1 method.

Non-Major Crop Types on Mineral Cropland Soils

The Tier 1 methodology (IPCC 2006) was used to estimate direct N_2O emissions for mineral cropland soils that are managed for production of non-major crop types, including barley, oats, tobacco, sugarcane, sugar beets,

[14] Total Kjeldahl N is a measure of organically bound N and ammonia N in both solid and liquid wastes.

sunflowers, millet, rice, peanuts, and other crops which were not included in the DAYCENT simulations. Estimates of direct N_2O emissions from N applications to non-major crop types were based on mineral soil N that was made available from the following practices: (1) the application of synthetic commercial fertilizers, (2) application of other commercial organic fertilizers;[15] and (3) the retention of above- and below-ground crop residues. Non-manure organic amendments were not included in the DAYCENT simulations because county-level data were not available and this source of fertilizer is a very small portion of total organic amendments. Consequently, non-manure organic amendments, as well as manure amendments not included in the DAYCENT simulations, were included in the Tier 1 analysis. The following sources were used to derive activity data.

- A process-of-elimination approach was used to estimate N fertilizer additions for non-major crops, because little information exists on their fertilizer application rates. The total amount of fertilizer used on farms has been estimated by the USGS from sales records (Ruddy et al. 2006), and these data were aggregated to obtain state-level N additions to farms. After subtracting the portion of fertilizer applied to major crops and grasslands (see sections on Major Crops and Grasslands for information on data sources), the remainder of the total fertilizer used on farms was assumed to be applied on non-major crops.

- A process-of-elimination approach was used to estimate manure N additions for non-major crops, because little information exists on application rates for these crops. The amount of manure N applied to major crops and grasslands was subtracted from total manure N available for land application (see sections on Major Crops and Grasslands for information on data sources), and this difference was assumed to be applied to non-major crops.

- Non-manure organic fertilizer additions were based on organic fertilizer consumption statistics, which were converted to units of N using average organic fertilizer N content (TVA 1991, 1992a, 1993, 1994; AAPFCO 1995 through 2000a, 2000b, 2002 through 2007).

- Crop residue N was derived by combining amounts of above- and below-ground biomass, which were determined based on crop production yield statistics (USDA 1994a, 1998b, 2003, 2005i, 2006b, 2007), 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 (IPCC 2006) to derive an estimate of 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 due to drainage and cultivation of organic soils at a state scale. State-scale estimates of the total area of drained and cultivated organic soils were obtained from the Natural Resources Inventory (NRI) (USDA 2000b, as extracted by Eve 2001 and amended by Ogle 2002), using temperature and precipitation data from Daly et al. (1994, 1998) to subdivide areas into temperate and tropical climates. Data were available for 1982, 1992 and 1997, which were linearly interpolated and extrapolated to estimate areas for the other years in the inventory time series. 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 method described in the IPCC

[15] Other commercial organic fertilizers include manure, dried blood, dried manure, tankage, compost, other, but excludes manure and sewage sludge, which are used as commercial fertilizers.

(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, which may or may not be improved with practices such as irrigation and interseeding legumes.

DAYCENT was used to simulate county-scale N_2O emissions from grasslands 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, soil, and synthetic N fertilizer data as discussed under the section for Major Crop Types on Mineral Cropland Soils. Managed manure N amendments to grasslands were estimated from Edmonds et al. (2003) and adjusted for annual variation using data on the availability of managed manure N for application to soils, according to methods described in 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 simulations produced per-area estimates of N_2O emissions (g N_2O-N m^{-2}) for pasture and rangelands, which were multiplied by the reported pasture and rangeland areas in the county. Grassland area data were obtained from the 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 2006, 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 63 agricultural 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. The remainder of the PRP manure N excretions were assumed to be excreted on federal grasslands (i.e., DAYCENT simulations were only conducted for privately-owned grasslands), and the N_2O emissions were estimated using the Tier 1 method with IPCC default emission factors (IPCC 2006).

Sewage sludge was assumed to be applied on grasslands because of the heavy metal content and other pollutants in human waste that limit its use as an amendment to croplands. Sewage sludge application was estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007). Sewage sludge data on soil amendments 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 (IPCC 2006).

Total Direct N_2O Emissions from Cropland and Grassland Soils

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

This section describes the methods used for estimating indirect soil N_2O emissions from all land-use types (i.e., croplands, grasslands, forest lands, and settlements), based on losses of N through volatilization, leaching, and runoff. The amount of N from volatilization, leaching, and runoff is 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). After quantifying the amount of N added to soils that is subject to volatilization, leaching, and runoff, the indirect N_2O emissions 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) and deposition of PRP 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 Volatilized N from Managed Soils

Similarly to the direct emissions calculation, several approaches were combined to estimate the amount of applied N that was transported from croplands, grasslands, forest lands, and settlements, 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 Tier 1 method was used for areas that were not simulated with DAYCENT (i.e., non-major croplands, sewage sludge application on grasslands, PRP manure N excretion on federal grasslands) (IPCC 2006). The IPCC (2006) default emission factor was used to estimate indirect N_2O emissions associated with the amount of volatilized N (Table 6-16).

Indirect N_2O from Leaching/Runoff

As in the calculations of indirect emissions from volatilized N, several approaches were combined to estimate the amount of applied N that was transported from croplands, grasslands, forest lands, and settlements through leaching and surface runoff into water bodies. DAYCENT was used to simulate the amount of N transported from major cropland types and most grasslands. N transport from all other areas (i.e., non-major croplands, sewage sludge amendments on grasslands, PRP manure N excreted on federal grasslands, in addition to N inputs on settlements and forest lands) was estimated using the IPCC (2006) default factors for the amount of N subject to leaching and runoff from mineral fertilizer, manure, above- and below-ground crop residues, soil organic matter decomposition and asymbiotic fixation. The IPCC (2006) default emission factor was used to estimate indirect N_2O emissions associated with N losses through leaching and runoff (Table 6-16).

Uncertainty

Uncertainty was estimated differently for each of the following four components of N_2O emissions from agricultural soil management: (1) direct emissions calculated by DAYCENT, (2) the components of indirect emissions (N volatilized and leached or runoff) calculated by DAYCENT (3) direct emissions not calculated by DAYCENT, and (4) indirect emissions not calculated by DAYCENT.

For direct emissions calculated using DAYCENT, uncertainty in the results was attributed to model inputs (i.e., activity data, weather and soil conditions) 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). The 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). This same Monte Carlo analysis was used to derive uncertainty for the volatilization, runoff, and leaching of N that had been estimated with DAYCENT. 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 application 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 available for application in each year of the inventory relative to 1997 was used to adjust the amount of area amended with manure, under the assumption that changing the amount of manure N available for application 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 availability). 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 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 from USDA cropping survey data (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 2006. Note that the current application only addresses structural uncertainty in cropland estimates; further development will be needed to address this uncertainty 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). Model structural uncertainty was not assessed for N volatilization and leaching/runoff, because sufficient data from field experiments were not available.

A simple error propagation method (IPCC 2006) was used to estimate uncertainties for direct emissions estimated with Tier 1 methods, including management of non-major crops (mineral fertilization, crop residues, organic fertilizers) and N inputs that were not addressed in the DAYCENT simulations (i.e., sewage sludge N, PRP manure N excreted on federal grasslands). Similarly, indirect emissions from N inputs that were not simulated with DAYCENT were calculated according to the IPCC methodology using the simple error propagation method (IPCC 2006). PDFs for the proportion of N subject to volatilization, leaching and runoff, as well as indirect N_2O emission factors were based on IPCC (2006), and PDFs for the activity data were based on the uncertainties associated underlying survey information and calculations.[16] For lands simulated by DAYCENT, uncertainty in indirect emissions was derived using the simple error propagation approach, combining uncertainty from the DAYCENT outputs for N volatilization and leaching/runoff with uncertainty in the indirect N_2O emission factors (IPCC 2006).

After estimating uncertainties in the Tier 1 and Tier 3 inventory estimates, uncertainties were combined using simple error propagation (IPCC 2006), and the results are summarized in Table 6-17. Agricultural direct soil N_2O emissions in 2006 were estimated to be between 275.7 and 505.1 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 27 percent below and 33 percent above the 2006 emission estimate of 379.3 Tg CO_2 Eq. The indirect soil N_2O emissions in 2006 were estimated to range from 28.0 to 113.2 Tg CO_2 Eq. at a 95 percent confidence level, indicating an uncertainty of 44 percent below and 125 percent above the 2006 emission estimate of 50.4 Tg CO_2 Eq.

[16] With the exception of organic fertilizers and crop yields, which were assumed to have a default ±50 percent uncertainty.

Table 6-17: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2006 (Tg CO_2 Eq. and Percent)*

Source	Gas	2006 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	379.3	275.7	505.1	-27%	33%
Indirect Soil N_2O Emissions	N_2O	50.4	28.0	113.2	-44%	125%

* Quality control has uncovered an error in the estimates for direct emissions from cropland. The error is currently being corrected and revised estimates will be provided after public review (See QA/QC for more discussion on the error).
Note: Due to lack of data, uncertainties in managed manure N production and PRP manure N production are currently treated as certain.

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. DAYCENT estimates of N_2O emissions were closer to measured values at all sites except for Colorado irrigated corn (Figure 6-7). In general, IPCC Tier 1 methodology tends to over-estimate when observed values are low and under-estimate when observed values are high, while DAYCENT estimates are less biased. This is not surprising because DAYCENT accounts for site-level factors (weather, soil type) that are not accounted for by the IPCC Tier 1 method. 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 0.73 and 0.96 for annual N_2O emissions and NO_3 leaching, respectively. This comparison demonstrates that DAYCENT provides relatively high predictive capability for N_2O emissions and NO_3 leaching, and is also an improvement over the IPCC Tier 1 method (see additional information in Annex 3.11).

Figure 6-7: Comparison of measured emissions at field sites with modeled emissions using the DAYCENT simulation model

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. An error was identified in direct N_2O estimates from major crops. The units were not converted correctly with the transfer of data between the DAYCENT model and the structural uncertainty estimator, leading to an over-estimation of direct N_2O emissions from major crops. The error has not been resolved in this version of the Inventory, but will be corrected after public review. 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.

Recalculations Discussion

Revisions in the calculations for the Agricultural Soil N_2O Inventory included (1) using state-level N data for on-farm use to estimate synthetic N fertilizer application on non-major crops, (2) including uncertainty in DAYCENT outputs of N volatilization and N leaching/runoff in the calculation of uncertainty for indirect emissions, (3) using a default uncertainty of ±50 percent for Tier 1 uncertainties that were addressed in previous inventory, including crop yields and organic fertilizers, (4) assuming that manure N available for land application not accounted for by the DAYCENT simulations was applied to non-major crop types, and (5) revising DAYCENT parameterization for sorghum.

In the past Inventory, N fertilizer application to minor crops was based on total N available for application after subtracting the amount applied to major crops, settlements, and forest lands. In the latest Inventory, a USGS study (Ruddy et al. 2006) provides data from sales records about the on-farm use of fertilizers, which were used to

estimate the amount of N applied to non-major crops after subtracting the amount estimated for major crops from the DAYCENT simulations. Previously it was assumed that 90 percent of the synthetic N fertilizer used in the United States was applied to agricultural soils whereas the on-farm use data raise the amount to 97 percent. In addition, after accounting for the amount applied to major crops and grasslands in the DAYCENT simulations, the latest Inventory assumes that all manure N available for agricultural land application is applied to non-major crops. Due to these changes, direct N_2O emissions from non-major crops are approximately 83 percent higher, on average, compared to the previous Inventory. The revised parameterization for sorghum had a minor influence on the emission estimates.

Planned Improvements

Three major improvements are planned for the Agricultural Soil Management sector. The first improvement is to incorporate more land survey data from the 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, which 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 four out of every five years from 1979 to 1997, and then every year after 1998. 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 N_2O 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 currently only evaluated for emission estimates in croplands, but structural uncertainty is likely to be significant for grasslands as well, and it is anticipated that the analysis of structural uncertainty 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.

The third planned improvement is to further evaluate the application of manure to major and minor crops, as well as N recovery and losses from manure management systems and field application. Manure amendments are a key source of N leading to N_2O emissions so any further improvements in this estimation will reduce uncertainties in the emission estimates. We will also evaluate potential for change in application rates over time due to regulation of confined animal feeding operations; this will improve the emission estimates and reduce uncertainty. Additional improvements are minor but will lead to more accurate estimates, including updating DAYMET weather for more recent years.

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.[17] Annual emissions from this source over the period 1990 to 2006 have remained relatively constant, averaging approximately 0.8 Tg CO_2 Eq. (36 Gg) of CH_4 and 0.4 Tg CO_2 Eq. (1 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	2006
CH_4	**0.7**	**0.7**	**0.8**	**0.8**	**0.7**	**0.8**	**0.9**	**0.9**	**0.8**
Wheat	0.1	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	0.1
Sugarcane	+	+	+	+	+	+	+	+	+
Corn	0.3	0.3	0.4	0.3	0.3	0.4	0.4	0.4	0.4
Barley	+	+	+	+	+	+	+	+	+
Soybeans	0.1	0.2	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**	**0.5**
Wheat	+	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+	+
Corn	0.1	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	0.3
Peanuts	+	+	+	+	+	+	+	+	+
Total	**1.1**	**1.0**	**1.3**	**1.2**	**1.1**	**1.2**	**1.4**	**1.4**	**1.3**

+ 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	2006
CH_4	**33**	**32**	**38**	**37**	**34**	**38**	**42**	**41**	**39**
Wheat	7	5	5	5	4	6	5	5	4
Rice	4	4	4	4	3	5	4	5	4
Sugarcane	1	1	1	1	1	1	1	1	1
Corn	13	13	17	16	15	17	20	19	18
Barley	1	1	1	+	+	+	+	+	+
Soybeans	7	8	10	11	10	9	11	11	12
Peanuts	+	+	+	+	+	+	+	+	+
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**2**	**2**
Wheat	+	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+	+	+
Soybeans	1	1	1	1	1	1	1	1	1

[17] The fraction of rice straw burned each year is significantly higher than that for other crops (see "Methodology" discussion below).

Peanuts	+	+	+	+	+	+	+	+	+
CO	**691**	**663**	**792**	**774**	**709**	**800**	**879**	**860**	**825**
NOx	**28**	**29**	**35**	**35**	**33**	**34**	**39**	**39**	**38**

+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

Methodology

The Tier 2 methodology used for estimating greenhouse gas emissions from field burning of agricultural residues in the United States is consistent with IPCC (2006) (for more details, see Box 6-2). In order to estimate the amounts of carbon (C) and nitrogen (N) released during burning, the following equation was used:[18]

$$CH_4 \text{ and } N_2O \text{ Emissions from Field Burning of Agricultural Residues} = (\text{Fraction of Residues Burned In Situ}) \times (\text{Mass of Fuel Available for Combustion}) \times (\text{Burning Efficiency}) \times (\text{Emission Factor}) \times 10^{-3}$$

Where:

Burning Efficiency = The proportion of prefire fuel biomass consumed

To calculate the mass of fuel available for combustion, the following equation was used:

$$\text{Mass of Fuel Available for Combustion} = (\text{Annual Crop Production}) \times (\text{Residue/Crop Product Ratio}) \times (\text{Dry Matter Content of the Residue})$$

To calculate the emission factor, the following equation was used:

$$\text{Emission Factor} = (\text{Combustion Efficiency}) \times (\text{C or N Content of the Residue}) \times (\text{Emissions Ratio}) \times (\text{Conversion Factor}) \times 1{,}000$$

Where:

Combustion Efficiency = The proportion of CH_4 or N_2O released with respect to the total amount of C or N available in the burned material, respectively
Emissions Ratio = g CH_4-C/g C released or g N_2O-N/g N released
Conversion Factor = Molecular weight ratio of CH_4:C or N_2O: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).

[BEGIN BOX]

Box 6-2: Comparsion of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

This Inventory calculates emissions from Burning of Agricultural Residues using a Tier 2 methodology that is based on IPCC/UNEP/OECD/IEA (1997) and incorporates crop- and country-specific emission factors and variables. The equation used in this Inventory varies slightly in form from the one presented in the IPCC (2006) guidelines, but both equations rely on the same underlying variables. The IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues. IPCC (2006) default

[18] 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.

factors are provided only for four crops (wheat, corn, rice, and sugarcane), while this Inventory analyzes emissions from seven crops. A comparison of the methods and factors used in (1) this year's Inventory and (2) the default IPCC (2006) approach was undertaken to determine the magnitude of the difference in overall estimates resulting from the two approaches. Since the default IPCC (2006) approach calls for area burned data that are currently unavailable for the United States, estimates of area burned were developed using USDA data on area harvested for each crop multiplied by the estimated fraction of residue burned for that crop (see Table 6-22).

The IPCC (2006) default run resulted in 20 percent higher emissions of CH_4 and 36 percent higher emissions of N_2O than the current estimates in this inventory. It was determined that it is reasonable to maintain the current methodology, since the IPCC (2006) defaults are only available for four crops and are worldwide average estimates, while current Inventory estimates are based on U.S.-specific, crop-specific, published data.

[END BOX]

Crop production data for all crops except rice in Florida and Oklahoma were taken from the USDA's *Field Crops, Final Estimates 1987–1992, 1992–1997, 1997–2002* (USDA 1994, 1998, 2003), and *Crop Production Summary* (USDA 2005, 2006, 2007). 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; Gonzalez 2007a), and crop yields for Arkansas (USDA 1994, 1998, 2003, 2005, 2006) were applied to Oklahoma acreages[19] (Lee 2003 through 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 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; Guethle 2007; Klosterboer 1999a, 1999b, 2000 through 2003; Lancero 2006, 2007; Lee 2005 through 2007; Lindberg 2002 through 2005; Linscombe 1999a, 1999b, 2001 through 2007; Najita 2000, 2001; Sacramento Valley Basinwide Air Pollution Control Council 2005, 2007; Schueneman 1999a, 1999b, 2001; Stansel 2004, 2005; Street 2001 through 2003; Texas Agricultural Experiment Station 2006, 2007; Walker 2004 through 2007; Wilson 2003 through 2007) (see Table 6-21). The estimates provided for Florida remained constant over the entire 1990 through 2006 period, while the estimates for all other states varied over the time series, except for Missouri, which remained constant through 2005 and dropped in 2006. 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 2006 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).

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). 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

[19] Rice production yield data are not available for Oklahoma, so the Arkansas values are used as a proxy.

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 N content of peanuts is from Ketzis (1999). These data are listed in Table 6-22. 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 6-23) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 6-20: Agricultural Crop Production (Gg of Product)

Crop	1990	1995	2000	2001	2002	2003	2004	2005	2006
Wheat	74,292	59,404	60,641	53,001	43,705	63,814	58,738	57,280	49,316
Rice	7,114	7,947	8,705	9,794	9,601	9,084	10,565	10,150	8,813
Sugarcane	25,525	27,922	32,762	31,377	32,253	30,715	26,320	24,137	26,752
Corn*	201,534	187,970	251,854	241,377	227,767	256,278	299,914	282,311	267,598
Barley	9,192	7,824	6,919	5,407	4,940	6,059	6,091	4,613	3,920
Soybeans	52,416	59,174	75,055	78,671	75,010	66,778	85,013	83,368	86,770
Peanuts	1,635	1,570	1,481	1,940	1,506	1,880	1,945	2,209	1,576

*Corn for grain (i.e., excludes corn for silage).

Table 6-21: Percent of Rice Area Burned by State

State	1990	1995	2000	2001	2002	2003	2004	2005	2006
Arkansas	13%	13%	13%	13%	16%	22%	17%	22%	27%
California	75%	59%	27%	23%	13%	14%	11%	16%	10%
Florida[a]	0%	0%	0%	0%	0%	0%	0%	0%	0%
Louisiana	6%	6%	5%	4%	3%	3%	3%	3%	5%
Mississippi	10%	10%	40%	40%	8%	65%	23%	23%	25%
Missouri	18%	18%	18%	18%	18%	18%	18%	18%	3%
Oklahoma	90%	90%	90%	90%	90%	100%	88%	94%	0%
Texas	1%	1%	0%	0%	0%	0%	0%	0%	0%

[a]Although rice is cultivated in Florida, crop residue burning is illegal.

Table 6-22: 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 6-23: 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).

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 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 and 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 6-24. CH_4 emissions from field burning of agricultural residues in 2006 were estimated to be between 0.3 and 1.5 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 65 percent below and 79 percent above the 2006 emission estimate of 0.8 Tg CO_2 Eq. Also at the 95 percent confidence level, N_2O emissions were estimated to be between 0.2 and 0.9 Tg CO_2 Eq. (or approximately 64 percent below and 73 percent above the 2006 emission estimate of 0.5 Tg CO_2 Eq.).

Table 6-24: 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	2006 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	0.8	0.3	1.5	-65%	79%
Field Burning of Agricultural Residues	N_2O	0.5	0.2	0.9	-64%	73%

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

QA/QC and Verification

A source-specific QA/QC plan for 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 2005 and 2006 were updated using data from USDA (2007). This change resulted in an increase in the CH_4 emission estimate for 2005 of 0.2 percent, and a decrease in the N_2O emission estimate for 2005 of 0.1 percent. In addition, a more robust uncertainty analysis was run this year, taking into account shared variables between the Field Burning of Agricultural Residues and Rice Cultivation sources and correcting errors that were identified in the uncertainty analysis undertaken for the previous inventory. These changes resulted in a greater uncertainty range surrounding the 2006 estimates than those presented in the previous inventory for the 2005 emission estimates.

Planned Improvements

The estimated 3 percent of crop residue burned for all crops, except rice, is based on data gathered from several state greenhouse gas inventories. This fraction is the most statistically significant input to the emissions equation, and an important area for future improvement. More crop- and state-specific information on the fraction burned will be investigated by literature review and/or by contacting state departments of agriculture.

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.

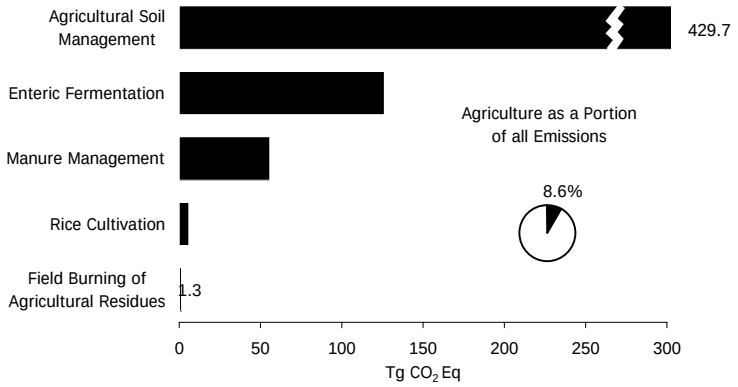
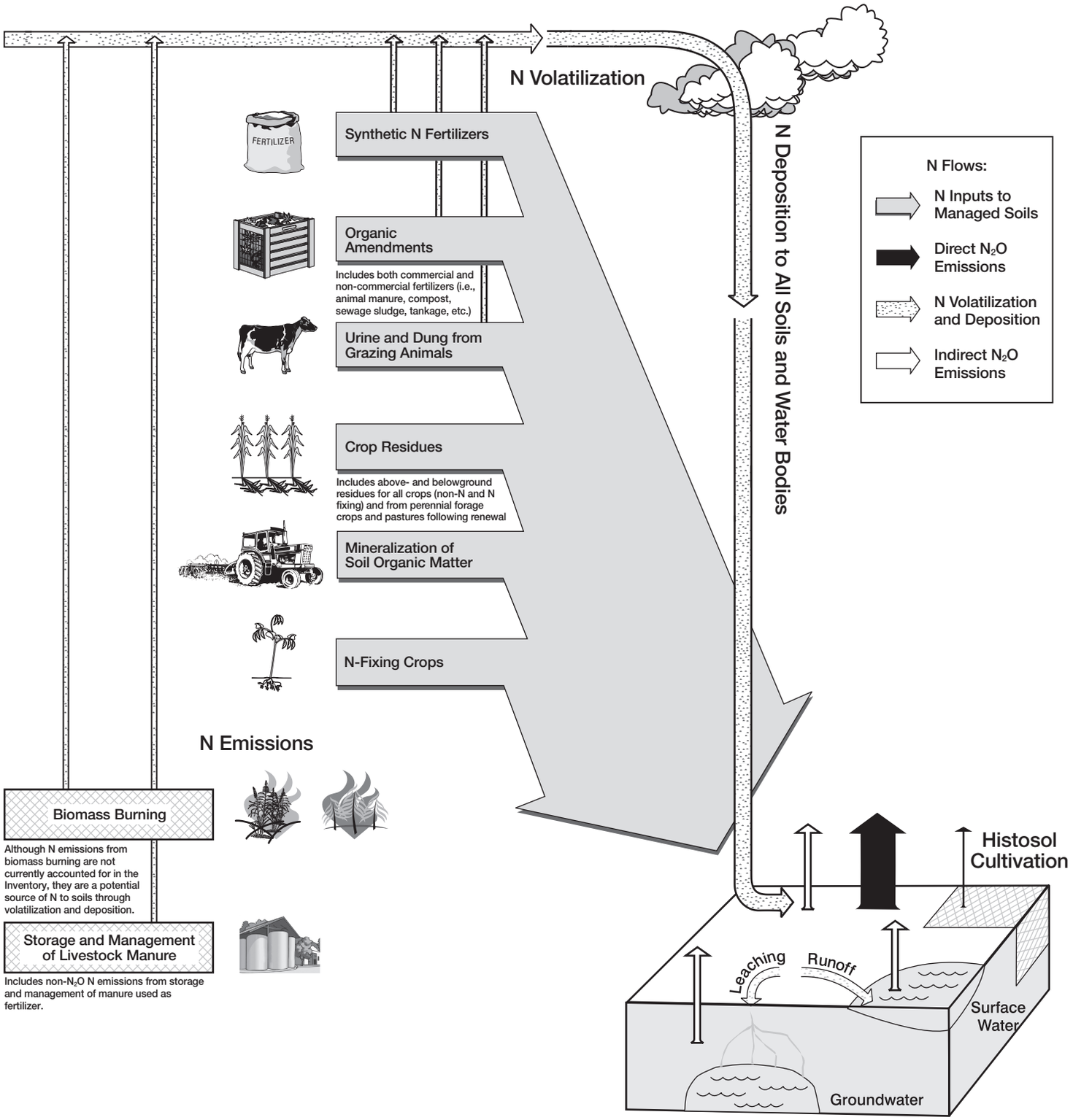


Figure 6-1: 2006 Agriculture Chapter Greenhouse Gas Sources



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.

To Be Inserted

Figure 6-3: Major Crops, Average Annual Direct N_2O Emissions, 1990–2006 (Tg CO_2 Eq./state/year)

To Be Inserted

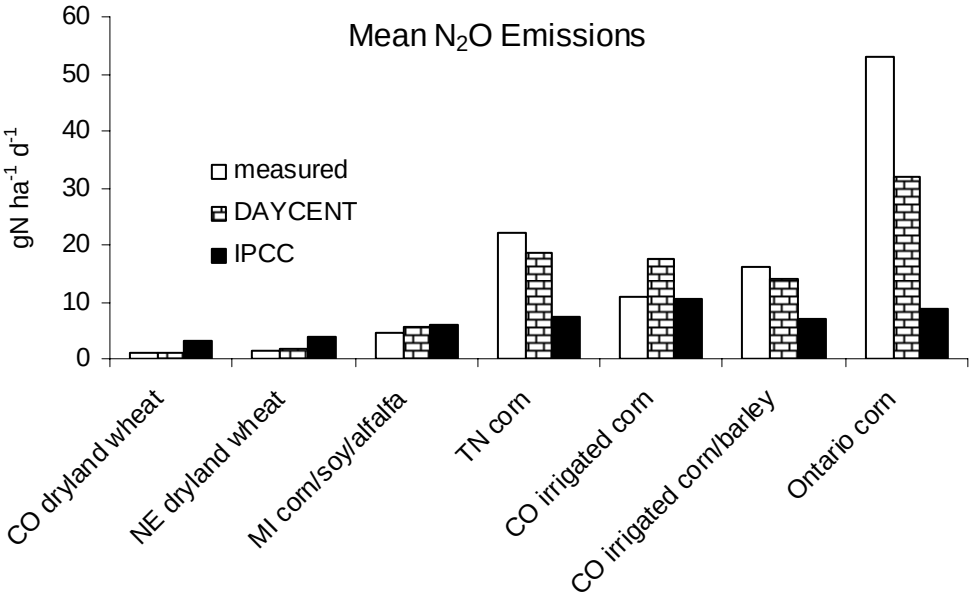
Figure 6-4: Grasslands, Average Annual Direct N_2O Emissions, 1990–2006 (Tg CO_2 Eq./state/year)

To Be Inserted

Figure 6-5: Major Crops, Average Annual N Losses Leading to Indirect N_2O Emissions, 1990–2006 (Tg CO_2 Eq./state/year)

To Be Inserted

Figure 6-6: Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions, 1990–2006 (Tg CO_2 Eq./state/year)


Mean N_2O Emissions
gN ha^{-1} d^{-1}
60
50
40
30
20
10
0
measured
DAYCENT
IPCC
CO dryland wheat
NE dryland wheat
MI corn/soy/alfalfa
TN corn
CO irrigated corn
CO irrigated corn/barley
Ontario corn

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) and urea fertilization. Fluxes are reported for four agricultural land use/land-use change categories: *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*. Fluxes resulting from *Settlements Remaining Settlements* include those from urban trees and soil fertilization. Landfilled yard trimmings and food scraps are accounted for separately under *Other*.

The estimates in this chapter, with the exception of CO_2 fluxes from wood products and urban trees, and CO_2 emissions from liming and urea fertilization, are based on activity data collected at multiple-year intervals, which are in the form of forest, land-use, and municipal solid waste surveys. CO_2 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. CO_2 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 2006 resulted in a net C sequestration of 882.9 Tg CO_2 Eq. (240.8 Tg C) (Table 7-1 and Table 7-2). This represents an offset of approximately 14.8 percent of total U.S. CO_2 emissions. Total land use, land-use change, and forestry net C sequestration[2] increased by approximately 20 percent between 1990 and 2006. 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 a net C sink from 1990 through 1994 and then remained a fairly constant emission source. Emissions from *Land Converted to Cropland* declined between 1990 and 2006.

Table 7-1: Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

[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."

[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 act as a sink. This is also referred to as net C sequestration.

Sink Category	1990	1995	2000	2001	2002	2003	2004	2005	2006
Forest Land Remaining Forest Land[1]	**(621.7)**	**(659.9)**	**(550.7)**	**(623.4)**	**(697.3)**	**(730.9)**	**(741.4)**	**(743.6)**	**(745.1)**
Changes in Forest Carbon Stocks	(621.7)	(659.9)	(550.7)	(623.4)	(697.3)	(730.9)	(741.4)	(743.6)	(745.1)
Cropland Remaining Cropland	**(30.1)**	**(39.4)**	**(38.4)**	**(40.0)**	**(40.3)**	**(40.5)**	**(40.9)**	**(41.0)**	**(41.8)**
Mineral and Organic Soil Carbon Stock Changes	(30.1)	(39.4)	(38.4)	(40.0)	(40.3)	(40.5)	(40.9)	(41.0)	(41.8)
Land Converted to Cropland	**14.7**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**
Mineral and Organic Soil Carbon Stock Changes	14.7	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4
Grassland Remaining Grassland	**(1.9)**	**16.6**	**16.4**	**16.4**	**16.4**	**16.4**	**16.3**	**16.3**	**16.2**
Mineral and Organic Soil Carbon Stock Changes	(1.9)	16.6	16.4	16.4	16.4	16.4	16.3	16.3	16.2
Land Converted to Grassland	**(14.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**
Mineral and Organic Soil Carbon Stock Changes	(14.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)	(16.3)
Settlements Remaining Settlements[2]	**(60.6)**	**(71.5)**	**(82.4)**	**(84.6)**	**(86.8)**	**(88.9)**	**(91.1)**	**(93.3)**	**(95.5)**
Urban Trees	(60.6)	(71.5)	(82.4)	(84.6)	(86.8)	(88.9)	(91.1)	(93.3)	(95.5)
Other	**(22.8)**	**(13.3)**	**(10.8)**	**(10.9)**	**(11.0)**	**(9.4)**	**(8.9)**	**(9.3)**	**(9.8)**
Landfilled Yard Trimmings and Food Scraps	(22.8)	(13.3)	(10.8)	(10.9)	(11.0)	(9.4)	(8.9)	(9.3)	(9.8)
Total	**(736.6)**	**(774.5)**	**(672.9)**	**(749.6)**	**(826.0)**	**(860.3)**	**(873.0)**	**(877.9)**	**(882.9)**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.
[1] Estimates include C stock changes on both Forest Land Remaining Forest Land and Land Converted to Forest Land.
[2] Estimates include C stock changes on both Settlements Remaining Settlements and Land Converted to Settlements.

Table 7-2: Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Tg C)

Sink Category	1990	1995	2000	2001	2002	2003	2004	2005	2006
Forest Land Remaining Forest Land[1]	**(169.6)**	**(180.0)**	**(150.2)**	**(170.0)**	**(190.2)**	**(199.3)**	**(202.2)**	**(202.8)**	**(203.2)**
Changes in Forest Carbon Stocks	(169.6)	(180.0)	(150.2)	(170.0)	(190.2)	(199.3)	(202.2)	(202.8)	(203.2)
Cropland Remaining Cropland	**(8.2)**	**(10.7)**	**(10.5)**	**(10.9)**	**(11.0)**	**(11.0)**	**(11.1)**	**(11.2)**	**(11.4)**
Mineral and Organic Soil Carbon Stock Changes	(8.2)	(10.7)	(10.5)	(10.9)	(11.0)	(11.0)	(11.1)	(11.2)	(11.4)
Land Converted to Cropland	**4.0**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**
Mineral and Organic Soil Carbon Stock Changes	4.0	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Grassland Remaining Grassland	**(0.5)**	**4.5**	**4.5**	**4.5**	**4.5**	**4.5**	**4.5**	**4.4**	**4.4**
Mineral and Organic Soil Carbon Stock Changes	(0.5)	4.5	4.5	4.5	4.5	4.5	4.5	4.4	4.4
Land Converted to Grassland	**(3.9)**	**(4.5)**	**(4.5)**	**(4.5)**	**(4.5)**	**(4.5)**	**(4.5)**	**(4.5)**	**(4.5)**
Mineral and Organic Soil Carbon Stock Changes	(3.9)	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)

Settlements Remaining Settlements[2]	**(16.5)**	**(19.5)**	**(22.5)**	**(23.1)**	**(23.7)**	**(24.3)**	**(24.9)**	**(25.4)**	**(26.0)**
Urban Trees	(16.5)	(19.5)	(22.5)	(23.1)	(23.7)	(24.3)	(24.9)	(25.4)	(26.0)
Other	**(6.2)**	**(3.6)**	**(2.9)**	**(3.0)**	**(3.0)**	**(2.6)**	**(2.4)**	**(2.5)**	**(2.7)**
Landfilled Yard Trimmings and Food Scraps	(6.2)	(3.6)	(2.9)	(3.0)	(3.0)	(2.6)	(2.4)	(2.5)	(2.7)
Total	**(200.9)**	**(211.2)**	**(183.5)**	**(204.4)**	**(225.3)**	**(234.6)**	**(238.1)**	**(239.4)**	**(240.8)**

Note: 1 Tg C = 1 teragram C = 1 million metric tons C. Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

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

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

Emissions from Land Use, Land-Use Change, and Forestry are shown in Table 7-3 and Table 7-4. The application of synthetic fertilizers to forest and settlement soils in 2006 resulted in direct N_2O emissions of 2.2 Tg CO_2 Eq. (7 Gg N_2O). Direct N_2O emissions from fertilizer application increased by approximately 97 percent between 1990 and 2006. Forest fires in 2006 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).

Table 7-3: Emissions from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Source Category	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	**7.1**	**7.0**	**7.5**	**7.8**	**8.5**	**8.3**	**7.6**	**7.9**	**8.0**
Cropland Remaining Cropland: Liming of Agricultural Soils & Urea Fertilization	7.1	7.0	7.5	7.8	8.5	8.3	7.6	7.9	8.0
CH_4	**7.1**	**4.0**	**14.0**	**6.0**	**10.4**	**8.1**	**6.9**	**11.6**	**11.6**
Forest Land Remaining Forest Land: Forest Fires	7.1	4.0	14.0	6.0	10.4	8.1	6.9	11.6	11.6
N_2O	**1.8**	**1.9**	**3.3**	**2.7**	**3.2**	**3.0**	**3.0**	**3.3**	**3.3**
Forest Land Remaining Forest Land: Forest Fires	0.7	0.4	1.4	0.6	1.1	0.8	0.7	1.2	1.2
Forest Land Remaining Forest Land: Forest Soils[1]	0.1	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Settlements Remaining Settlements: Settlement Soils[2]	1.0	1.4	1.5	1.8	1.8	1.9	1.9	1.8	1.8
Total	**16.0**	**13.0**	**24.8**	**16.5**	**22.1**	**19.3**	**17.4**	**22.8**	**22.9**

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.

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

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

Table 7-4: Non-CO_2 Emissions from Land Use, Land-Use Change, and Forestry (Gg)

Source Category	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	**7,084**	**7,049**	**7,541**	**7,825**	**8,549**	**8,260**	**7,555**	**7,854**	**8,012**
Cropland Remaining Cropland: Liming of Agricultural Soils & Urea Fertilization	7,084	7,049	7,541	7,825	8,549	8,260	7,555	7,854	8,012
CH_4	**337**	**189**	**667**	**285**	**494**	**384**	**330**	**551**	**551**
Forest Land Remaining Forest Land: Forest Fires	337	189	667	285	494	384	330	551	551
N_2O	**6**	**6**	**11**	**9**	**10**	**10**	**10**	**11**	**11**
Forest Land Remaining Forest Land: Forest Fires	2	1	5	2	3	3	2	4	4

Forest Land Remaining Forest Land:									
Forest Soils[1]	0	1	1	1	1	1	1	1	1
Settlements Remaining Settlements:									
Settlement Soils[2]	3	4	5	6	6	6	6	6	6

Note: These estimates include direct emissions only. Indirect N_2O emissions are reported in the Agriculture chapter. Totals may not sum due to independent rounding.

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

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

7.1. Representation of the U.S. Land Base

A national land-use categorization system that is consistent and complete both temporally and spatially is needed in order to assess land use and land-use change status and the associated greenhouse gas fluxes over the inventory time series. This system should be consistent with IPCC (2006), such that all countries reporting on national greenhouse gas fluxes to the UNFCCC should (1) describe the methods and definitions used to determine areas of managed and unmanaged lands in the country (2) describe and apply a consistent set of definitions for land-use categories over the entire national land base and time series associated with the greenhouse gas inventory, such that increases in the land areas within particular land use categories are balanced by decreases in the land areas of other categories, and (3) account for greenhouse gas fluxes on all managed lands. The implementation of such a system helps to ensure that estimates of greenhouse gas fluxes are as accurate as possible. This section of the national greenhouse gas inventory has been developed in order to comply with this guidance.

Multiple databases are utilized to track land management in the United States, which are also used as the basis to categorize the land area into the following six IPCC land-use categories:[3] Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land (IPCC 2006). The primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI)[4] and the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA) Database.[5] The U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD)[6] is also used to identify land uses in regions that were not included in the NRI or FIA. In 1990, the United States had a total of 243 million hectares of Forest Land, 169 million hectares of Cropland, 301 million hectares of Grassland, 32 million hectares of Wetlands, 32 million hectares of Settlements, and 28 million hectares in the Other Land[7] category (Table 7-5). By 2006, the total area in Forest Land had increased by 3.9 percent to 252 million hectares, Cropland had declined by 4.0 percent to 162 million hectares, Grassland declined by 2.8 percent to 293 million hectares, Wetlands decreased by 4.8 percent to 31 million hectares, Settlements increased by 32.2 percent to 42 million hectares, and Other Land decreased by 11.1 percent to 25 million hectares.

Table 7-5. Land use areas during the inventory reporting period (millions of hectares)

Land Use	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Forest Land	243	246	249	250	250	251	251	252	252
Cropland	169	166	163	163	162	162	162	162	162
Grassland	301	296	296	295	295	294	294	293	293
Wetlands	32	32	31	31	31	31	31	31	31
Settlements	32	36	40	41	41	42	42	42	42

[3] Land-use category definitions are provided in the Methodology section.

[4] NRI data is available at <http://www.ncgc.nrcs.usda.gov/ products/nri/index.html>.

[5] FIA data is available at <http://fia.fs.fed .us/tools-data/data/>.

[6] NLCD data is available at <http://www.mrlc.gov/>.

[7] *Other Land* is a miscellaneous category that includes lands that are not classified into the other five land-use categories. It also allows the total of identified land areas to match the national area.

Other Land	28	28	25	25	25	25	25	25	25

Note: Unmanaged land is not currently estimated because the only land designated as unmanaged occurs in Alaska, which has not been included in the current US land representation assessment. See planned improvements for discussion on plans to include Alaska in future inventory reports.

Dominant land uses vary by region, largely due to climate patterns, soil types, geology, proximity to coastal regions, and historical settlement patterns, although all land-uses occur within each of the fifty states (Figure 7-1). Forest Land tends to be more common in the eastern states, mountainous regions of the western United States, and Alaska. Cropland is concentrated in the mid-continent region of the United States, and Grassland is more common in the western United States. Wetlands are fairly ubiquitous throughout the United States, though they are more common in the upper Midwest and eastern portions of the country. Settlements are more concentrated along the coastal margins and in the eastern states.

Figure 7-1. Regional variation in area of Forest Land, Cropland, Grassland, Wetlands and Settlements within the United States during 2006 (million hectares)

[maps will be provided after public review.]

Methodology

IPCC Approaches for Representing Land Areas

IPCC (2006) describes three approaches for representing land areas. Approach 1 provides data on the total area for each individual land-use category, but does not provide detailed information on changes of area between categories and is not spatially explicit other than at the national or regional level. With Approach 1, total net conversions between categories can be detected, but not the individual changes between the land-use categories that led to those net changes. Approach 2 introduces tracking of individual land-use changes between the categories (e.g. forest land to cropland, cropland to forest land, grassland to cropland, etc.). Approach 3 extends Approach 2 by allowing each land-use conversion to be tracked on a spatially explicit basis. The three approaches are not presented as hierarchical tiers and are not mutually exclusive.

According to IPCC (2003), the approach or mix of approaches selected by an inventory agency should reflect the calculation needs and national circumstances. For this analysis, the NRI, FIA, and the NLCD have been combined to provide a complete representation of land use for managed lands. These data sources are described in more detail later in this section. The NRI and the FIA data surveys meet the standards for Approach 3, but the data from NLCD that are currently utilized only meet the standards for Approach 1.[8] Consequently, Approach 1 is being used to provide a full representation of land use in the current inventory. The United States is pursuing an effort to analyze available data with the intent of moving beyond Approach 1 in future inventories.

Definitions of Land Use in the United States

Managed and Unmanaged Land

The U.S. definitions of managed and unmanaged lands are similar to the basic IPCC (2006) definition of managed land, but with some additional elaboration to reflect national circumstances. Based on the following definitions, most lands in the United States are classified as managed:

- *Managed Land*: Land is considered managed if direct human intervention has influenced its condition. Direct intervention includes altering or maintaining the condition of the land to produce commercial or non-commercial products or services; to serve as transportation corridors or locations for buildings, landfills, or

[8] A new NLCD product is being developed that will meet the standards of Approach 3 data, with explicit information on land cover change, opposed to information based solely on land cover for individual years.

other developed areas for commercial or non-commercial purposes; to extract resources or facilitate acquisition of resources; or to provide social functions for personal, community or societal objectives. Managed land also includes legal protection of lands (e.g., wilderness, preserves, parks, etc.) for conservation purposes (i.e., meets societal objectives).[9]

- *Unmanaged Land:* All other land is considered unmanaged. Unmanaged land is largely comprised of areas inaccessible to human intervention due to the remoteness of the locations, or lands with essentially no development interest or protection due to limited personal, commercial or social value. Though these lands may be influenced indirectly by human actions such as atmospheric deposition of chemical species produced in industry, they are not influenced by a direct human intervention.[10]

Land-Use Categories

As with the definition of managed lands, IPCC (2003, 2006) provide general non-prescriptive definitions for the six main land-use categories: Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land. In order to reflect U.S. circumstances, country-specific definitions have been developed, based predominantly on criteria used in the land-use surveys for the United States. Specifically, the definition of Forest Land is based on the FIA definition of forest,[11] while definitions of Cropland, Grassland, and Settlements are based on the NRI.[12] The definitions for Other Land and Wetlands are based on the IPCC (2006) definitions for these categories.

- *Forest Land:* A land-use category that includes land that is at least 10 percent stocked[13] by forest trees of any size, or land formerly having such tree cover, and not currently developed for a non-forest use. The minimum area for classification as Forest Land is one acre (0.40 ha). Roadside, stream-side, and shelterbelt strips of timber must be at least 120 feet (36.58 m) wide to qualify as Forest Land. Unimproved roads and trails, streams and other bodies of water, or natural clearings in forested areas are classified as Forest Land, if less than 120 feet (36.58 m) in width or one acre (0.40 ha) in size. Improved roads within Forest Land, however, are extracted from forest area estimates and included in Other Land. Grazed woodlands, fields reverting to forest, and pastures that are not actively maintained are included if the above qualifications are satisfied. Forest Land consists of three main subcategories: timberland, reserved forest land, and other forest land.[14] Forest Land also includes woodlands, which describes forest types consisting primarily of species that have their diameter measured at root collar, and for which there are no site index equations, nor stocking guides. These may include areas with degrees of stocking between 5 and 9.9 percent. The FIA regions with woodland areas are, however, considering new definitions that should result in all Forest Land meeting the minimum 10 percent stocking threshold.

- *Cropland:* A land-use category that includes areas used for the production of adapted crops for harvest, this category includes both cultivated and non-cultivated lands. Cultivated crops include row crops or close-grown crops and also hay or pasture in rotation with cultivated crops. Non-cultivated cropland includes continuous

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[9] Wetlands are an exception to this general definition, because these lands, as specified by IPCC (2006), are only considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands is difficult, however, due to limited data availability. Wetlands are not characterized by use within the NRI. Therefore, unless wetlands are managed for cropland or grassland, it is not possible to know if they are artificially created or if the water table is managed based on the use of NRI data.

[10] There will be some areas that qualify as Forest Land or Grassland according to the land use criteria, but are classified as unmanaged land due to the remoteness of their location.

[11] See <http://socrates.lv-hrc.nevada.edu/fia/ab/issues/pending/glossary/Glossary_5_30_06.pdf>.

[12] See <http://www.nrcs.usda.gov/technical/land/nri01/glossary.html>.

[13] The percentage stocked refers to the degree of occupancy of land by trees, measured either by basal area or number of trees by size and spacing or both, compared to a stocking standard.

[14] These subcategory definitions are fully described in the Forest Land Remaining Forest Land section.

hay, perennial crops (e.g., orchards) and horticultural cropland. Cropland also includes land with alley cropping and windbreaks,[15] as well as lands in temporary fallow or enrolled in conservation reserve programs (i.e., set-asides[16]). Roads through Cropland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Cropland area estimates and are, instead, classified as Other Land.

- *Grassland:* A land-use category on which the plant cover is composed principally of grasses, grass-like plants, forbs or shrubs suitable for grazing and browsing, and includes both pastures and native rangelands. This includes areas where practices such as clearing, burning, chaining, and/or chemicals are applied to maintain the grass vegetation. Savannas, some wetlands and deserts, in addition to tundra are considered Grassland.[17] Woody plant communities of low forbs and shrubs, such as mesquite, chaparral, mountain shrub, and pinyon-juniper, are also classified as Grassland if they do not meet the criteria for Forest Land. Grassland includes land managed with agroforestry practices such as silvipasture and windbreaks, assuming the stand or woodlot does not meet the criteria for Forest Land. Roads through Grassland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Grassland area estimates and are, instead, classified as Other Land.

- *Wetlands:* A land-use category that includes land covered or saturated by water for all or part of the year. Managed Wetlands are those where the water level is artificially changed, or were created by human activity. IPCC (2006) provides guidance under "Wetlands" for managed peatlands and flooded lands, such as reservoirs developed for hydroelectricity, irrigation, and navigation. Certain areas that fall under the managed Wetlands definition are covered in other areas of the IPCC guidance and/or the inventory, including Cropland (e.g., rice cultivation), Grassland, and Forest Land (including drained or undrained forested wetlands).

- *Settlements:* A land-use category consisting of units of 0.25 acres (0.1 ha) or more that includes residential, industrial, commercial, and institutional land; construction sites; public administrative sites; railroad yards; cemeteries; airports; golf courses; sanitary landfills; sewage treatment plants; water control structures and spillways; parks within urban and built-up areas; and highways, railroads, and other transportation facilities if they are surrounded by urban or built-up areas. Also included are tracts of less than 10 acres (4.05 ha) that may meet the definitions for Forest Land, Cropland, Grassland, or Other Land but are completely surrounded by urban or built-up land, and so are included in the settlement category.

- *Other Land:* A land-use category that includes bare soil, rock, ice, non-settlement transportation corridors, and all land areas that do not fall into any of the other five land-use categories. It allows the total of identified land areas to match the managed national area. It also specifically includes roads through forests (excluding unimproved roads/trails) and all types of roads through Grassland and Cropland areas that are discernible using aerial photography or remote sensing imagery (i.e., interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads).

Land Use Data Sources: Description and Application to U.S. Land Area Classification

U.S. Land Use Data Sources

The three main data sources for land area and use data in the United States are the NRI, FIA, and the NLCD. The NRI is conducted by the USDA Natural Resources Conservation Service and is designed to assess soil, water, and

[15] Currently, there is no data source to account for biomass C stock change associated with woody plant growth and losses in alley cropping systems and windbreaks in cropping systems, although these areas are included in the cropland land base.

[16] A set-aside is cropland that has been taken out of active cropping and converted to some type of vegetative cover, including, for example, native grasses or trees.

[17] IPCC guidelines (2006) do not include provisions to separate desert and tundra as land categories.

related environmental resources on nonfederal lands. The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the U.S. Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit (typically a 160-acre (64.75 ha) square quarter-section), three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land-use information (Nusser and Goebel 1997). The NRI survey utilizes data derived from remote sensing imagery and site visits in order to provide detailed information on land use and management, particularly for croplands, and is used as the basis to account for C stock changes in agricultural lands. The NRI survey was conducted every 5 years between 1982 and 1997, but shifted to annualized data collection in 1998.

The FIA program, conducted by the USFS, is used to obtain forest area and management data FIA engages in a hierarchical system of sampling, with sampling categorized as Phases 1 through 3, in which sample points for phases are subsets of the previous phase. Phase 1 refers to collection of remotely-sensed data (either aerial photographs or satellite imagery) primarily to classify land into forest or non-forest and to identify landscape patterns like fragmentation and urbanization. Phase 2 is the collection of field data on a network of ground plots that enable classification and summarization of area, tree, and other attributes associated with forest land uses. Phase 3 plots are a subset of Phase 2 plots where data on indicators of forest health are measured. Data from all three phases are also used to estimate C stock changes for forest land. Historically, FIA inventory surveys had been conducted periodically, with all plots in a state being measured at a frequency of every 5 to 14 years. A new national plot design and annual sampling design was introduced by FIA about ten years ago. Most states, though, have only recently been brought into this system. Annualized sampling means that a portion of plots throughout each state is sampled each year, with the goal of measuring all plots once every 5 years. See Annex 3.12 to see the specific survey data available by state.

Because NRI only includes land use information for non-federal land, and the FIA only records for forest land,[18] major gaps exist when the datasets are combined, such as federal grassland operated by the Bureau of Land Management (BLM), USDA, and National Park Service, as well as most of Alaska[19]. Consequently, the NLCD is used as a supplementary database to account for federal land areas that are not included in the NRI and FIA databases. The NLCD is a land cover classification scheme, available for 1992 and 2001, that has been applied over the conterminous United States. It is based primarily on Landsat Thematic Mapper imagery. The NLCD contains 21 categories of land cover information, which have been aggregated into the six IPCC land-use categories, and the data are available at a spatial resolution of 30 meters. The NLCD is strictly a source of land cover information, however, and does not provide the necessary site conditions, crop types and management information from which to estimate C stock changes on those lands.

Along with the incorporation of NLCD data, another major step has been taken to address gaps, as well as overlaps in the representation of the U.S. land base between the Agricultural Carbon Stock Inventory (*Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*) and Forest Land Carbon Stock Inventory (*Forest Land Remaining Forest Land* and *Land Converted to Forest Land*), which are based on the NRI and FIA databases, respectively. NRI, which covers only non-federal land, and FIA have different criteria for classifying forest land, leading to discrepancies in the resulting estimates of forest land area on non-federal land. Similarly, there are discrepancies between the NLCD and FIA data for forest land on federal lands. Moreover, dependence exists between the Forest Land area and the amount of land designated as other land uses in the NRI and NLCD, such as grassland, cropland and wetland, and thus there are inconsistencies in the Forest Land definitions among the three databases. FIA is the main database for forest statistics, and consequently, the NRI and NLCD were adjusted to achieve consistency with FIA estimates of Forest Land. The adjustments were made at a state-scale, and it was assumed that the majority of the discrepancy in forest area was

[18] FIA does collect some data on nonforest land use, but these are held in regional databases versus the national database. The status of these data is being investigated.

[19] The survey programs also do not include U.S. Territories with the exception of non-federal lands in Puerto Rico, which are included in the NRI survey. Furthermore, NLCD does not include coverage for U.S. Territories.

associated with an under- or over-prediction of grassland and wetland area in the NRI and NLCD due to differences in Forest Land definitions. Specifically, the Forest Land area for a given state according to the NRI and NLCD was adjusted to match the FIA estimates for non-federal and federal land, respectively. Adjustments were allotted to grassland and wetlands, based on the proportion of land within each of these land-use categories at the state-level. A higher proportion of grassland led to a larger adjustment in grassland area and vice versa. In a second step, corresponding increases or decreases were made in the area estimates of grassland and wetland from the NRI and NLCD, in order to balance the change in forest area, and therefore not change the overall amount of managed land within an individual state.

There are minor differences between the U.S. Census Survey[20] land area estimates and the land use surveys derived for the inventory because of discrepancies in the reporting approach for the census and the methods used in the NRI, FIA and NLCD. The area estimates of land-use categories, based on NRI, FIA and NLCD, are derived from remote sensing data instead of the land survey approach used by the U.S. Census Survey. More importantly, the U.S. Census Survey does not provide a time series of land-use change data or land management information, which is critical for conducting emission inventories and is provided from the NRI and FIA surveys. Regardless, the total difference between the U.S. Census Survey and the data sources used in the inventory is relatively minor, estimated at about 6 million hectares for the total land base of over 800 million hectares currently included in the Inventory, or a 0.7 percent difference.

Approach for Combining Data Sources

The managed land base in the United States has been classified into the six IPCC land-use categories using definitions[21] developed to meet national circumstances, while adhering to IPCC (2006). In practice, the land was initially classified into a variety of land-use categories using the NRI, FIA and NLCD, and then aggregated into the six broad land uses identified in IPCC (2006). Details on the approach used to combine data sources for each land use are described below along with gaps that will be reconciled as part of ongoing planned improvements:

- *Forest Land*: Both non-federal and federal forest lands on both the continental United States and coastal Alaska are covered by FIA. FIA is used as the basis for both Forest Land area data as well as to estimate C stocks and fluxes on Forest Land. Interior Alaska is not currently surveyed by FIA and at this time the NLCD cannot be used to classify land use in this region. FIA surveys are currently being conducted on U.S. territories and will become available in the future. FIA data will also be collected in Hawaii in the future.

- *Cropland*: Cropland is classified using the NRI, which covers all non-federal lands, within 49 states, including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Cropland area data as well as to estimate C stocks and fluxes on Cropland. Cropland in Alaska and U.S. territories are excluded from both NRI data collection and the NLCD[22]. Though crops are grown on some federal lands, these Cropland areas are considered minimal and are excluded from the inventory.

- *Grassland*: Grassland on non-federal lands is classified using the NRI within 49 states, including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Grassland area data as well as to estimate C stocks and fluxes on Grassland. Alaska and U.S. territories are excluded from both NRI data collection and the current release of the NLCD product[23]. Grassland on federal BLM lands, National Parks and within USFS lands are covered by the NLCD. Department of Defense grasslands are also included in area estimates using the NLCD.

- *Wetlands*: NRI captures wetlands on non-federal lands within 49 states, while federal wetlands are covered by

[20] See <http://www.census.gov/geo/www/tiger>.

[21] Definitions are provided in the previous section.

[22] With the exception of non-federal cropland in Puerto Rico, which are included in the NRI survey.

[23] With the exception of non-federal grasslands in Puerto Rico, which are included in the NRI survey.

the NLCD. Alaska and U.S. territories are excluded. This currently includes both managed and unmanaged wetlands as no database has yet been applied to make this distinction. See *Planned Improvements* for details.

- *Settlements*: The NRI captures non-federal settlement area in 49 states. If areas of Forest Land or Grassland under 10 acres (4.05 ha) are contained within settlements or urban areas, they are classified as Settlements (urban) in the NRI database. If these parcels exceed the 10 acre (4.05 ha) threshold and are grassland, they will be classified as such by NRI. If within an urban area, a forested area is classified as nonforest by FIA, regardless of size. Settlements on federal lands are covered by NLCD. Settlements in Alaska and U.S. territories are currently excluded from NRI and NLCD.

- *Other Land*: Any land not falling into the other five land categories and, therefore, categorized as Other Land is classified using the NRI and NLCD. Other land in Alaska and U.S. territories are excluded from the NLCD.

Some lands can be classified into one or more categories due to multiple uses that meet the criteria of more than one definition. However, a ranking has been developed for assignment priority in these cases. The ranking process is initiated by distinguishing between managed and unmanaged lands. The managed lands are then assigned, from highest to lowest priority, in the following manner:

Settlements > *Cropland* > *Forest Land* > *Grassland* > *Wetlands* > *Other Land*

Settlements are given the highest assignment priority because they are extremely heterogeneous with a mosaic of patches that include buildings, infrastructure and travel corridors, but also open grass areas, forest patches, riparian areas, and gardens. The latter examples could be classified as Grassland, Forest Land, Wetlands, and Cropland, respectively, but when located in close proximity to settlement areas they tend to be managed in a unique manner compared to non-settlement areas. Consequently, these areas are assigned to the Settlements land-use category. Cropland is given the second assignment priority, because cropping practices tend to dominate management activities on areas used to produce food, forage or fiber. The consequence of this ranking is that crops in rotation with grass will be classified as Cropland, and land with woody plant cover that is used to produce crops (e.g., orchards) is classified as Cropland, even though these areas may meet the definitions of Grassland or Forest Land, respectively. Similarly, Wetlands that are used for rice production are considered Croplands. Forest Land occurs next in the priority assignment because traditional forestry practices tend to be the focus of the management activity in areas with woody plant cover that are not croplands (e.g., orchards) or settlements (e.g., housing subdivisions with significant tree cover). Grassland occurs next in the ranking, while Wetlands and Other Land complete the list.

Priority does not reflect the level of importance for reporting GHG emissions and removals on managed land, but is intended to classify all areas into a single land use. Currently, the IPCC does not make provisions in the guidelines for assigning land to multiple uses. For example, a Wetland is classified as Forest Land if the area has sufficient tree cover to meet the stocking and stand size requirements. Similarly, Wetlands are classified as Cropland if they are used to produce a crop, such as rice. In either case, emissions from Wetlands are included in the inventory if human interventions are influencing emissions from Wetlands in accordance with the guidance provided in IPCC (2006).

Planned Improvements

Area data by land-use category are not estimated for major portions of Alaska and any of the U.S. territories. A key planned improvement is to incorporate land use data from these areas in the national greenhouse gas emissions inventory. For Alaska, a new NLCD 2001 data product will be used to cover those land areas presently omitted. Fortunately, most of the managed land in the United States is included in the current land use statistics, but a complete accounting is a key goal for the near future. Data sources will be evaluated for representing land use in U.S. Territories.

Another planned improvement is to utilize Approach 3-type area data for the U.S. land base. A new NLCD product, with spatially-explicit information on land-use change is currently being developed and will qualify as Approach 3. By using this new data product in combination with the existing NRI and FIA databases, land-use statistics will be

further subdivided by land-use change categories as recommended in IPCC (2006). This will include land remaining in a land-use category and land converted to another land-use category (e.g., *Forest Land Remaining Forest Land*, *Cropland Converted to Forest Land*, *Grassland Converted to Forest Land*). The additional subdivisions will provide more explicit land-use change statistics than currently reported, and also provide better accounting of emissions and stock changes associated with land use activities.

Additional work will be done to reconcile differences in Forest Land estimates between the NRI and FIA, evaluating the assumption that the majority of discrepancies in Forest Land areas are associated with an over- or under-estimation of Grassland and Wetland area. In some regions of the United States, a discrepancy in Forest Land areas between NRI and FIA may be associated with an over- or under-prediction of other land uses.

There are also other databases that may need to be reconciled with the NRI and NLCD datasets, particularly for Settlements and Wetlands. Urban area estimates, used to produce C stock and flux estimates from urban trees, are currently based on population data (1990 and 2000 U.S. Census data). Using the population statistics, "urban clusters" are defined as areas with more than 500 people per square mile. The USFS is currently moving ahead with an urban forest inventory program so that urban forest area estimates will be consistent with FIA forest area estimates outside of urban areas, which would be expected to reduce omissions and overlap of forest area estimates along urban boundary areas. For Wetlands, current estimates using the NRI and NLCD databases will be compared and reconciled to the extent possible with the Army Corps of Engineers National Inventory of Dams (ACE 2005) which provides data on the total surface area of reservoirs created by dams.

7.2. Forest Land Remaining Forest Land

Changes in Forest Carbon Stocks (IPCC Source Category 5A1)

For estimating C stocks or stock change (flux), C in forest ecosystems can be divided into the following five storage pools (IPCC 2003):

- Aboveground biomass, which includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This category includes live understory.
- Belowground biomass, which includes all living biomass of coarse living roots greater than 2 mm diameter.
- Dead wood, which includes all non-living woody biomass either standing, lying on the ground (but not including litter), or in the soil.
- Litter, which includes the litter, fumic, and humic layers, and all non-living biomass with a diameter less than 7.5 cm at transect intersection, lying on the ground.
- Soil organic C (SOC), including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the aboveground pools.

In addition, there are two harvested wood pools necessary for estimating C flux:

- Harvested wood products 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 in SWDS, the C contained in the wood may be released many years or decades later, or may be stored almost permanently in the SWDS.

This section quantifies the net changes in C stocks in the five forest C pools and two harvested wood pools. The net change in stocks for each pool is estimated, and then the changes in stocks are summed over all pools to estimate total net flux. The focus on C implies that all C-based greenhouse gases are included, and the focus on stock change suggests that specific ecosystem fluxes do not need to be separately itemized in this report. 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.

Figure 7-2: Forest Sector Carbon Pools and Flows

Approximately 33 percent (303 million hectares) of the U.S. land area is forested, of which approximately 251 million hectares are located in the conterminous 48 states (Smith et al. in press). These 251 million hectares are considered managed and are included in this inventory. The additional 52 million hectares are located in Alaska and Hawaii. This inventory includes approximately 3.7 million hectares of Alaska forest, which are in the southeast and south central regions of Alaska and represent the majority of the state's managed forest land. Survey data are not yet available from Hawaii. While Hawaii and U.S. territories have relatively small areas of forest land and will probably not affect the overall C budget to a great degree, these areas will be included as sufficient data becomes available. Agroforestry systems are also not currently accounted for in the 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).

Sixty-eight percent of U.S. forests (207 million hectares) are classified as timberland, meaning they meet minimum levels of productivity and are available for timber harvest. Nine percent of Alaska forests and 81 percent of forests in the conterminous United States are classified as timberlands. Of the remaining nontimberland forests, 30 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 66 million hectares are lower productivity forest lands (Smith et al. in press). Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than other forest lands.

Forest land declined by approximately 10 million hectares over the period from the early 1960s to the late 1980s. Since then, forest area has increased by about 7 million hectares. These trends in forest area represent average annual change 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 that leads to an increased rate of growth increases the eventual biomass density of the forest, thereby increasing the uptake of C.[24] Net volume of growing stock on U.S. timberlands increased by 36 percent from 1953 to 1997. Though harvesting forests removes much of the aboveground C, there is a positive growth to harvest ratio on U.S. timberlands (AF&PA 2001) . The reversion of cropland to forest land increases C storage in biomass, forest floor, and soils. The net effects of forest management and the effects of land-use change involving forest land are captured in the estimates of C stocks and fluxes presented in this chapter.

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, as well as timber harvesting and use have resulted in net uptake (i.e., net sequestration) of C each year from 1990 through 2006. The rate of forest clearing begun in the 17th century following European settlement had slowed by the late 19th century. Through the later part of the 20th century many areas of previously forested land in the United States were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still affect C fluxes from these forest lands. More recently, the 1970s and 1980s saw a resurgence of federally-sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests have also affected net C fluxes. Because most of the timber harvested from U.S. forests is used in wood products, and many discarded wood products are disposed of in SWDS rather than by incineration, significant quantities of C in harvested wood are transferred to long-term storage pools rather than being released rapidly to the atmosphere (Skog and Nicholson 1998, Skog in preparation). The size of these long-term C storage pools has increased during the last century.

Changes in C stocks in U.S. forests and harvested wood were estimated to account for net sequestration of 745.1 Tg **CO_2** Eq. (203.2 Tg C) in 2006 (Table 7-6, Table 7-7, 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. Overall, average C in forest ecosystem biomass (aboveground and belowground) increased from 71 to 75 Mg C/ha between 1990 and 2007 (see Table A-4 for average C densities by specific regions and forest types). Forest land in the conterminous United States was approximately 244, 249, and 251 million hectares for 1987, 1997, and 2007, respectively, which amounts to a 3 percent increase over the period (Smith et al. in press). Continuous, regular annual surveys are not available over the period for each state; therefore, estimates for non-survey years were derived by interpolation between known data points. Survey years vary from state to state, and national estimates are a composite of individual state surveys. Therefore, changes in sequestration over the interval 1990 to 2006 are the result of the sequences of new inventories for each state. Net annual sequestration increased by 20 percent for 2006 relative to 1990. C in forest ecosystem biomass had the greatest effect on total change. As discussed above, this was due to increased C density and total forest land. Management practices that increase C stocks on forest land, as well as afforestation and reforestation efforts influence the trends of increased C densities in forests and increased forest land in the United States.

Table 7-6. 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	2006
Forest	**(489.1)**	**(540.5)**	**(436.8)**	**(529.0)**	**(598.0)**	**(635.1)**	**(635.1)**	**(635.1)**	**(635.1)**
Aboveground Biomass	(287.6)	(318.4)	(335.4)	(367.7)	(384.4)	(406.5)	(406.5)	(406.5)	(406.5)
Belowground Biomass	(54.2)	(62.4)	(67.2)	(73.7)	(76.9)	(80.9)	(80.9)	(80.9)	(80.9)
Dead Wood	(40.1)	(57.5)	(44.9)	(50.0)	(53.0)	(56.9)	(56.9)	(56.9)	(56.9)
Litter	(63.3)	(34.9)	(17.3)	(36.3)	(47.7)	(56.2)	(56.2)	(56.2)	(56.2)
Soil Organic Carbon	(43.9)	(67.5)	28.0	(1.3)	(36.0)	(34.5)	(34.5)	(34.5)	(34.5)
Harvested Wood	**(132.6)**	**(119.4)**	**(113.9)**	**(94.5)**	**(99.2)**	**(95.9)**	**(106.3)**	**(108.5)**	**(110.0)**

[24] The term "biomass density" refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. Dry biomass is 50 percent C by weight.

Products in use	(64.8)	(55.2)	(47.0)	(31.9)	(35.1)	(35.4)	(45.5)	(47.3)	(45.3)
SWDS	(67.9)	(64.1)	(66.9)	(62.6)	(64.2)	(60.4)	(60.8)	(61.2)	(64.7)
Total Net Flux	**(621.7)**	**(659.9)**	**(550.7)**	**(623.4)**	**(697.3)**	**(730.9)**	**(741.4)**	**(743.6)**	**(745.1)**

Note: Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a large portion of Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Forest area estimates are based on interpolation and extrapolation of inventory data as described in the text and in Annex 3.12. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Table 7-7. Net Annual Changes in C Stocks (Tg C/yr) in Forest and Harvested Wood Pools

Carbon Pool	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Forest	**(133.4)**	**(147.4)**	**(119.1)**	**(144.3)**	**(163.1)**	**(173.2)**	**(173.2)**	**(173.2)**	**(173.2)**
Aboveground Biomass	(78.4)	(86.8)	(91.5)	(100.3)	(104.8)	(110.9)	(110.9)	(110.9)	(110.9)
Belowground Biomass	(14.8)	(17.0)	(18.3)	(20.1)	(21.0)	(22.1)	(22.1)	(22.1)	(22.1)
Dead Wood	(10.9)	(15.7)	(12.2)	(13.6)	(14.5)	(15.5)	(15.5)	(15.5)	(15.5)
Litter	(17.3)	(9.5)	(4.7)	(9.9)	(13.0)	(15.3)	(15.3)	(15.3)	(15.3)
Soil Organic C	(12.0)	(18.4)	7.6	(0.4)	(9.8)	(9.4)	(9.4)	(9.4)	(9.4)
Harvested Wood	**(36.2)**	**(32.6)**	**(31.1)**	**(25.8)**	**(27.1)**	**(26.1)**	**(29.0)**	**(29.6)**	**(30.0)**
Products in Use	(17.7)	(15.1)	(12.8)	(8.7)	(9.6)	(9.7)	(12.4)	(12.9)	(12.3)
SWDS	(18.5)	(17.5)	(18.2)	(17.1)	(17.5)	(16.5)	(16.6)	(16.7)	(17.7)
Total Net Flux	**(169.6)**	**(180.0)**	**(150.2)**	**(170.0)**	**(190.2)**	**(199.3)**	**(202.2)**	**(202.8)**	**(203.2)**

Note: Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a large portion of Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Stock estimates for forest and harvested wood C storage pools are presented in Table 7-8. 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 7-4 shows county-average C densities for live trees on forest land, including both above- and belowground biomass.

Table 7-8. Forest area (1000 ha) and C Stocks (Tg C) in Forest and Harvested Wood Pools

	1990	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
Forest Area (1000 ha)	**245,799**	**249,036**	**252,251**	**252,798**	**253,443**	**254,155**	**254,889**	**255,624**	**256,358**	**257,093**
Carbon Pools (Tg C)										
Forest	**40,106**	**40,810**	**41,535**	**41,654**	**41,798**	**41,962**	**42,135**	**42,308**	**42,481**	**42,654**
Aboveground Biomass	14,547	14,955	15,405	15,496	15,596	15,701	15,812	15,923	16,034	16,145
Belowground Biomass	2,896	2,974	3,063	3,081	3,102	3,123	3,145	3,167	3,189	3,211
Dead Wood	2,453	2,515	2,592	2,605	2,618	2,633	2,648	2,664	2,679	2,695
Litter	4,557	4,641	4,680	4,684	4,694	4,707	4,723	4,738	4,753	4,769
Soil Organic C	15,652	15,725	15,795	15,788	15,788	15,798	15,807	15,817	15,826	15,835
Harvested Wood	**1,862**	**2,033**	**2,193**	**2,224**	**2,250**	**2,277**	**2,303**	**2,332**	**2,362**	**2,392**
Products in Use	1,231	1,311	1,382	1,395	1,404	1,413	1,423	1,436	1,448	1,461
SWDS	631	722	810	829	846	863	880	896	913	931
Total C Stock	**41,968**	**42,843**	**43,728**	**43,878**	**44,048**	**44,238**	**44,438**	**44,640**	**44,843**	**43,376**

Forest Area estimates include portions of Alaska, which represents an addition relative to previous versions of this table. Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a large portion of Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Forest area estimates are based on interpolation and extrapolation of inventory data as described in 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 2006 requires estimates of C stocks for 2006 and 2007.

Figure 7-3: Estimates of Net Annual Changes in C Stocks for Major C Pools

Figure 7-4: Average C Density in the Forest Tree Pool in the Conterminous United States During 2006

[BEGIN BOX]

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. Non- CO_2 greenhouse gas emissions from forest fires are also quantified in a separate section below.

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).

Table 7-9: Estimates of CO_2 (Tg/yr) emissions for the lower 48 states and Alaska[1]

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

[1] Note that these emissions have already been accounted for in the net C sequestration estimates (i.e., net Tflux already accounts for the amount sequestered minus any emissions)T.

[END BOX]

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 FIA program (Frayer and Furnival 1999, USDA Forest Service 2006a). Inventories include forest lands[25] 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, state-level data are sometimes subdivided or additional inventory sources are used to produce the consistent state or sub-state inventories.

The principal FIA 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. First, older FIA plot- and tree-level data—not in the FIADB format—are used if available. Second, Resources Planning Act Assessment (RPA) databases, which are periodic, plot-level only, summaries of state inventories, are used mostly to provide the data at or before 1990. A detailed list of the specific inventory data used in this inventory 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. 2007). 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

[25] 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.

inventory data do not provide measurements of individual trees; tree 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 C (SOC) includes all organic material in soil to a depth of 1 meter but excludes the coarse roots of the biomass or dead wood pools. Estimates of SOC are based on the national STATSGO spatial database (USDA 1991), 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 (2006). 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 2007 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 2003 through 2006 on Table 7-6 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 methods are based on IPCC (2006) guidance for estimating HWP C. IPCC (2006) provides methods that allow Parties to report HWP Contribution using one of several different accounting approaches: production, stock change and atmospheric flow, as well as a default method that assumes there is no change in HWP C stocks (see Annex 3-12 for more details about each approach). The United States uses the production accounting approach to report HWP Contribution. Under the production approach, C in exported wood is estimated as if it remains in the United States, and C in imported wood is not included in inventory estimates. Though reported U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches, the stock change and atmospheric flow approaches, are also presented for comparison (see Annex 3.12). Annual estimates of change are calculated by tracking the additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in solid waste disposal sites (SWDS).

Solidwood products added to pools include lumber and panels. End-use categories for solidwood include single and

multifamily housing, alteration and repair of housing, and other end-uses. There is one product category and one end-use category for paper. Additions to and removals from pools are tracked beginning in 1900, with the exception that additions of softwood lumber to housing begins in 1800. Solidwood and paper product production and trade data are from USDA Forest Service and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census; 1976; Ulrich, 1985, 1989; Steer 1948; AF&PA 2006a 2006b; Howard 2003 & 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.

There are 5 annual HWP variables that are used in varying combinations to estimate HWP Contribution using any one of the three main approaches listed above. These are:

1A) annual change of C in wood and paper products in use in the United States,

1B) annual change of C in wood and paper products in SWDS in the United States,

2A) annual change of C in wood and paper product in use in the United States and other countries where the wood came from trees harvested in the United States,

2B) annual change of C in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,

3) C in imports of wood, pulp, and paper to the United States,

4) C in exports of wood, pulp and paper from the United States, and

5) C in annual harvest of wood from forests in the United States.

The sum of variables 2A and 2B yields the estimate for HWP Contribution under the production accounting approach. A key assumption for estimating these variables is that products exported from the United States and held in pools in other countries have the same half lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS as they would in the United States.

Uncertainty

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 7-10) 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, 2007); 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 approach. The uncertainty analysis is based on Skog et al. (2004), with later revisions made in conjunction with overall revisions in the HWP model (Skog in preparation). The uncertainty analysis for HWP 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 2006 flux estimate for forest C stocks is estimated to be between -579.0 and -913.2 Tg CO_2 Eq. at a 95 percent confidence level. This includes a range of -471.2 to -802.2 Tg CO_2 Eq. in forest ecosystems and -85.5 to -136.8 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 in because the total is based on summing the two independent uncertain parts, as discussed above.

Table 7-10: Tier 2 Quantitative Uncertainty Estimates for Net CO_2 Flux from Forest Land Remaining Forest Land: Changes in Forest C Stocks (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2006 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	(635.1)	(802.2)	(471.2)	-26%	+26%
Harvested Wood Products	CO_2	(110.0)	(136.8)	(85.5)	-24%	+22%
Total Forest	**CO_2**	**(745.1)**	**(913.2)**	**(579.0)**	**-23%**	**+22%**

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.

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 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 process for developing annualized estimates of forest ecosystem C stocks based on the individual state surveys and the C conversion factors are identical to that presented in the previous inventory (Smith et al. 2007). However, revised estimates of forest ecosystem C stock increased by 3 percent for 1990 and 2005. Similarly, estimated net stock change increased by 4 percent for 1990 and by 6 percent for 2005. The addition of newly available forest inventory data as well as some refinements in previously existing data were the principal factors contributing to these changes. Inventory data changed for 31 of the 48 states included in the previous inventory. However, not all of the changes are apparent in the list of inventory data used for C estimates (Table A-186) because some changes involved reclassification and recalculation of existing data. In addition, a portion of Alaska forest is included in this inventory for the first time. Carbon stock and change estimates for the early 1990s are still sensitive to updates made over the last year, which are primarily associated with the most recent data per state, because 13 of the 49 states are still entirely or partly based on two C stock estimates (Table A-186). Thus, even an update for a 2006 C stock, for example, is propagated throughout the interval when stock change is linearly interpolated between the two stocks.

The basic model and data used to estimate HWP contribution under the production approach are unchanged since the previous inventory (Skog in preparation). However, minor modifications to some model coefficients resulted in slight increases in estimated C sequestration so that net annual additions to C in HWP increased by 0.5 and 5 percent for 1990 and 2005, respectively, with an average increase of 3 percent across the sixteen years. Modifications to parameters included: (1) shorter half-life for decay in dumps and (2) separation of decay in dumps from decay in landfills.

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. To date, five states are not yet reporting any data from the annualized sampling design of FIA: Hawaii, Mississippi, Oklahoma, New Mexico and Wyoming. Estimates for these states are currently based on older, periodic data. Hawaii and U.S. territories will also be included when appropriate forest C data are available. In addition, the more intensive sampling of down dead wood, litter, and soil organic C on some of the permanent FIA plots continues and will substantially improve resolution of C pools at the plot level for all U.S. forest land when this information becomes available. Improved resolution, incorporating more of Alaska's forests, and using annualized sampling data as it becomes available for those states currently not reporting are planned for future reporting.

As more information becomes available about historical land use, the ongoing effects of changes in land use and forest management will be better accounted for in estimates of soil C (Birdsey and Lewis 2003, Woodbury et al. 2006, Woodbury et al. 2007). Currently, soil C estimates are based on the assumption that soil C density depends only on broad forest type group, not on land-use history. However, long-term residual effects on soil and forest floor C stocks are likely after land-use change. Estimates of such effects are being developed based on methods described by Woodbury et al. (2007), and preliminary results demonstrate effects on soil organic C and forest floor.

Additional development is required to link model results with: 1) the C change methods used for this inventory (Smith et al. 2007), and 2) a consistent representation of the land base and land-use change for the United States (See *7.1 Representation of the U.S. Land Base in the National Greenhouse Gas Inventory* for more details).

Similarly, agroforestry practices, such as windbreaks or riparian forest buffers along waterways, are not currently accounted for in the inventory. In order to properly account for the C stocks and fluxes associated with agroforestry, research will be needed that provides the basis and tools for including these plantings in a nation-wide inventory, as well as the means for entity-level reporting.

Non-CO_2 Emissions From Forest Fires

[This section will be updated with new estimates and text prior to public review]

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 7-11: Estimated Non-CO_2 Emissions from Forest Fires (Tg CO_2 Eq.) for U.S. forests[1]

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**

[1] Calculated based on C emission estimates in *Changes in Forest Carbon Stocks* and default factors in IPCC (2003).

Table 7-12: Estimated Non- CO_2 Emissions from Forest Fires (Gg Gas) for U.S. forests[1]

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

[1] 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 7-13: 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 7-14.

Table 7-14: Tier 2 Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires in *Forest Land Remaining Forest Land* (Tg CO_2 Eq. and Percent)

Source	Gas	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
Non-CO_2 Emissions from Forest Fires	CH_4	11.6	3.2	21.5	-71%	92%
	N_2O	1.2	0.3	2.2	-70%	93%

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. N_2O emissions from forest soils are estimated to have increased by a multiple of 5.5 from 1990 to 2006. 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 7-15.

Table 7-15. 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	0.2
1995	0.2	0.5
2000	0.3	1.0
2001	0.3	1.1
2002	0.3	1.1
2003	0.3	1.1
2004	0.3	1.1
2005	0.3	1.1
2006	0.3	1.1

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. 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 Sate 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 not be substantial 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, 2005, and 2006, 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. IPCC (2006) does not incorporate any of these variables into the default methodology 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 estimated. However, the total quantity of organic N inputs to soils is included in the Agricultural Soil Management and *Settlements Remaining Settlements* sections.

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates were assigned a default level[26] of uncertainty at ±50 percent, and area receiving fertilizer was assigned a ±20 percent according to expert knowledge (Binkley 2004). IPCC (2006) provided estimates for the uncertainty associated with direct N_2O emission factor for synthetic N fertilizer application to soils. A simple error propagation (IPCC 2006) was used combine these uncertainties and the results are summarized in Table 7-16. N_2O fluxes from soils were estimated to be between 0.1 and 1.1 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the 2006 emission estimate of 0.3 Tg CO_2 Eq.

Table 7-16: 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	2006 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	N_2O	0.3	0.1	1.1	-59%	+211%

[26] Uncertainty is unknown for the fertilization rates so a conservative value of ±50% was used in the analysis.

Fluxes from Soils

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*.

Recalculations Discussion

No recalculations were performed for the time series.

Planned Improvements

State-level area data will be acquired for southeastern pine plantations receiving fertilizer to estimate soil N_2O emission by state and provide information about regional variation in emission patterns.

7.3. Land Converted to Forest Land (IPCC Source Category 5A2)

Land-use change is constantly occurring, and areas under a number of differing land-use types are converted to forest each year, just as forest land is converted to other uses. However, the magnitude of these changes is not currently known. Given the paucity of available land-use information relevant to this particular IPCC source category, it is not possible to separate CO_2 or N_2O fluxes on *Land Converted to Forest Land* from fluxes on *Forest Land Remaining Forest Land* at this time.

7.4. Cropland Remaining Cropland (IPCC Source Category 5B1)

Mineral and Organic Soil Carbon Stock Changes

Soils contain both organic and inorganic forms of C, but soil organic C (SOC) stocks are the main source 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) and IPCC (2006) recommends reporting changes in soil organic C stocks due to agricultural land-use and management activities on mineral soils and organic soils.[27]

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,

[27] CO_2 emissions associated with liming are also estimated but included in a separate section of the report.

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.

Cropland Remaining Cropland includes all cropland in a year of the inventory that had been cropland for the last 20 years[28] 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[29] 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.

Of the two sub-source categories, land-use and land management of mineral soils was the most important component of total net C stock change between 1990 and 2006 (see Table 7-17 and Table 7-18). In 2006, mineral soils were estimated to remove about 69.5 Tg CO_2 Eq. (19.0 Tg C). This rate of C storage in mineral soils represented about a 20 percent increase in the rate since the initial reporting year of 1990. Emissions from organic soils were about 27.7 Tg CO_2 Eq. (7.5 Tg C) in 2006. In total, U.S. agricultural soils in *Cropland Remaining Cropland* removed approximately 41.8 Tg CO_2 Eq. (11.4 Tg C) in 2006.

Table 7-17: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (Tg CO_2 Eq.)

Soil Type	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Mineral Soils	(57.5)	(67.0)	(66.1)	(67.7)	(68.0)	(68.1)	(68.5)	(68.7)	(69.5)
Organic Soils	27.4	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7
Total Net Flux	**(30.1)**	**(39.4)**	**(38.4)**	**(40.0)**	**(40.3)**	**(40.5)**	**(40.9)**	**(41.0)**	**(41.8)**

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.

Table 7-18: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (Tg C)

Soil Type	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Mineral Soils	(15.7)	(18.3)	(18.0)	(18.5)	(18.5)	(18.6)	(18.7)	(18.7)	(19.0)
Organic Soils	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Total Net Flux	**(8.2)**	**(10.7)**	**(10.5)**	**(10.9)**	**(11.0)**	**(11.0)**	**(11.1)**	**(11.2)**	**(11.4)**

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.

The net increase in soil C stocks (39 percent for 2006, relative to 1990) was largely due to an increase in annual

[28] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification was based on less than 20 years of recorded land-use history for the time series from 1982 to 2001.

[29] Note that removals occur through crop and forage uptake of CO_2 into biomass C that is later incorporated into soils pools.

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 (2006), cropland enrolled in the Conservation Reserve Program accounts for 32 percent of the increase of C stocks for *Cropland Remaining Cropland* on mineral soils (Table 7-18).

The spatial variability in annual CO_2 flux associated with C stock changes in mineral and organic soils is displayed in Figure 7-5 and Figure 7-6. The highest rates of sequestration in mineral soils occurred in the Midwest, where there were the largest amounts of cropland managed with conservation tillage. 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.

Figure 7-5: Net C Stock Change for Mineral Soils in *Cropland Remaining Cropland*, 2006

[Figures will be included after public review.]

Figure 7-6: Net C Stock Change for Organic Soils in *Cropland Remaining Cropland*, 2006

[Figures will be included after public review.]

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; and (2) agricultural land-use and management activities on organic soils for *Cropland Remaining Cropland*.

Soil C stock changes were estimated for *Cropland Remaining Cropland* (as well as agricultural land falling into the IPCC categories *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*) according to land-use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 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.[30] 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 were subdivided into four inventory time periods, 1980 through 1984, 1985 through 1989, 1990 through 1994, and 1995 through 2000.

NRI points were classified as *Cropland Remaining Cropland* for an inventory time period (e.g., 1990 through 1994 and 1995 through 2000) if the land use had been cropland for 20 years.[31] Cropland includes all land used to

[30] NRI points were classified as agricultural if under grassland or cropland management in 1992 and/or 1997.

[31] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the

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

An IPCC 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 The remaining crops on mineral soils were estimated using an IPCC Tier 2 method (Ogle et al. 2003), including vegetables, tobacco, perennial/horticultural crops, rice, and crops rotated with these crops. The Tier 2 method was also used for very gravelly, cobbly or shaley soils (greater than 35 percent by volume). Mineral SOC stocks were estimated using a Tier 2 method for these areas, because the 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, accounting 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 soils 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, 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 through 1984, 1985 through 1989, 1990 through 1994, and 1995 through 2000, using NRI data from 1982, 1987, 1992, and 1997, respectively.

[BEGIN BOX]

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 under the IPCC categorization scheme). Input variables to the

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classification was based on less than 20 years of recorded land-use history for the time series from 1982 to 2001.

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.

[END BOX]

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 then adjusted using county-level estimates of manure available for application in other years of the inventory. Specifically, county-scale ratios of manure available in other years relative to 1997 were used to adjust the area amended with manure (see Annex 3.13 for further details). Greater availability of managed manure N relative to 1997 was, thus, assumed to increase the amount of area amended with manure, while reduced availability of manure N relative to 1997 was assumed to reduce the amended area.

The amount of manure produced by each livestock type was calculated for managed and unmanaged waste management systems. Managed systems include feedlots or other housing (which requires manure to be collected and managed); unmanaged systems include daily spread, pasture, range, and paddock systems. 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. Population data used for cattle, swine, and sheep were downloaded from the USDA NASS Population Estimates Database (USDA 2007a). Poultry population data were obtained from USDA NASS reports (USDA 1995a, 1995b, 1998a, 1999, 2004a, 2004b, 2006a, 2006b, 2007b, 2007c). Horse population data were obtained from the FAOSTAT database (FAO 2007). Goat population data for 1992, 1997, and 2002 were obtained from the *Census of Agriculture* (USDA 2005); 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, 1997, and 2002

Census of Agriculture (USDA 2005).

Manure amendments were an input to the Century Model based on manure N available for application from all managed or unmanaged systems except Pasture/Range/Paddock.[32] Data on the county-level N available for application were estimated for managed systems based on the total amount of N excreted in manure minus N losses and including the addition of N from bedding materials. N losses include direct nitrous oxide emissions, volatilization of ammonia and NOx, and runoff and leaching. More information on these losses is available in the description of the Manure Management source category. Animal-specific bedding factors were set equal to IPCC default factors (IPCC 2006). For unmanaged systems, it is assumed that no N losses or additions occur.

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, which were obtained from an NRI database, 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 had 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 2006 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 IPCC Tier 2 method, data on climate, soil types, land-use, and land management activity were used to classify land area to apply appropriate stock change factors. MLRAs formed the base spatial unit for mapping climate regions in the United States; each MLRA represents a geographic unit with relatively similar soils, climate, water resources, and land uses (NRCS 1981).[33] MLRAs were classified into climate regions according to the IPCC categories using the PRISM climate database of Daly et al. (1994).

Reference C stocks were estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2003, 2006). Changing the reference condition was necessary because soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than those that are not considered cultivated cropland.

U.S.-specific stock change factors were derived from published literature to determine the impact of management practices on SOC storage, including changes in tillage, cropping rotations and intensification, and land-use change between cultivated and uncultivated conditions (Ogle et al. 2003, Ogle et al. 2006).[34] 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

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[32] Pasture/Range/Paddock manure additions to soils are addressed in the *Grassland Remaining Grassland* and *Land Converted to Grassland* categories.

[33] The polygons displayed in Figure 7-5 through Figure 7-6 are the Major Land Resource Areas.

[34] 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.

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 2006 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 2006 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 USDA-FSA (2007) for 1998 through 2006, and the differences in mineral soil areas were multiplied by 0.5 metric tons C per hectare per year to estimate the net effect on soil C stocks. The stock change rate is based on estimations using the IPCC method (see Annex 3.13 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Cropland Remaining Cropland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), with U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. 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 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 2006.

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). Uncertainty estimates are presented in Table 7-19 for 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 soil C stocks occurring within *Cropland Remaining 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 *Cropland Remaining Cropland* ranged from 38 percent below and 35 percent above the 2006 stock change estimate of -41.8 Tg CO_2 Eq.

Table 7-19: Quantitative Uncertainty Estimates for C Stock Changes occurring within *Cropland Remaining Cropland* (Tg CO_2 Eq. and Percent)

Source	2006 Flux Estimate[1] (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[1] (Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: *Cropland Remaining Cropland*, Tier 3 Inventory Methodology	(64.0)	(74.1)	(53.5)	-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)	(2.5)	(3.7)	(1.2)	-50%	+50%
Organic Soil C Stocks: *Cropland Remaining Cropland*, Tier 2 Inventory Methodology	27.7	15.8	36.9	-43%	+33%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in *Cropland Remaining Cropland*	**(41.8)**	**(57.9)**	**(27.3)**	**-38%**	**+35%**

[1] Flux estimates based on soil C stock changes.

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. The manure amendment records were not recorded correctly in a subset of the Century model output; corrective actions were taken to resolve this error. 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

Two changes were implemented in the current inventory that led to a change in the time series. First, there was a modification in the land use classification. The classification is based on the land use in a specific year of the inventory and the previous 20 years. However, in the 1990 through 2005 inventory, each point was only classified once based on the entire NRI time series of the land-use history. This approach led to incorrect classifications for the early 1990s. For example, a NRI point may have been cropland in 1982, 1987 and 1992, but converted to grassland in 1997. In the previous inventory, the NRI point would be classified as *Land Converted to Grassland* for the entire inventory from 1990 through 2005. This is incorrect for the early 1990s because the point was *Cropland Remaining Cropland* during those years. Second, the time series for manure N between 1990 and 2006, which was used to adjust manure applications relative to 1997, was based on manure N available for application rather than manure N production. Overall, the recalculations resulted in an average annual decrease of 1.9 Tg CO_2 Eq. for the period 1990 through 2005, compared to the previous inventory.

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, and is anticipated to be completed by the public review period.

The second improvement is to incorporate additional crops into the Tier 3 approach. Currently, crops such as

vegetables, rice, 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. This improvement is expected to reduce uncertainties in the inventory results.

The third 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 fourth 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 simulation. Results are aggregated and evaluated at larger scales such as MLRAs 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 final 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, providing a more rigorous accounting of uncertainties associated with the Tier 3 method.

CO_2 Emissions from Agricultural Liming

IPCC (2006) recommends reporting CO_2 emissions from lime additions (in the form of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) to agricultural soils. Limestone and dolomite are added by land managers to ameliorate acidification. When these compounds come in contact with acid soils, they degrade, thereby generating CO_2. The rate and ultimate magnitude of degradation of applied limestone and dolomite depends on the soil conditions, climate regime, and the type of mineral applied. Emissions from liming have fluctuated over the past sixteen years, ranging from 3.9 Tg CO_2 Eq. to 5.0 Tg CO_2 Eq. In 2006, liming of agricultural soils in the United States resulted in emissions of 4.4 Tg CO_2 Eq. (1.2 Tg C), representing about a 6 percent decrease in emissions since 1990. (Table 7-17 and Table 7-18).

Table 7-20: Emissions from Liming of Agricultural Soils (Tg CO_2 Eq.)

Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
Liming of Soils[1]	4.7	4.4	4.3	4.4	5.0	4.6	3.9	4.3	4.4

Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

[1] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland,* and *Land Converted to Grassland.*

Table 7-21: Emissions from Liming of Agricultural Soils (Tg C)

Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
Liming of Soils[1]	1.3	1.2	1.2	1.2	1.4	1.2	1.1	1.2	1.2

Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.
[1] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland,* and *Land Converted to Grassland.*

Methodology

CO_2 emissions from degradation of limestone and dolomite applied to agricultural soils were estimated using a Tier 2 methodology consistent with IPCC (2006). The annual amounts of limestone and dolomite applied (see Table 7-22) were multiplied by CO_2 emission factors from West and McBride (2005). These emission factors (0.059 metric ton C/metric ton limestone, 0.064 metric ton C/metric ton dolomite) are lower than the IPCC default emission factors, because they account for the portion of agricultural lime that may leach through the soil and travel by rivers to the ocean (West and McBride 2005). 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; Willett 2007; USGS 2007). 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 2006 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 2006 data, the previous year's fractions were applied to a 2006 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2007* (USGS 2007).

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. Since limestone and dolomite activity data are also available at the state level, the national-level estimates reported here were broken out by state for the first time this year, but are not reported here.

Table 7-22: Applied Minerals (Million Metric Tons)

Mineral	1990	1995	2000	2001	2002	2003	2004	2005	2006
Limestone	19.01	17.30	15.86	16.10	20.45	18.71	15.50	18.09	18.20
Dolomite	2.36	2.77	3.81	3.95	2.35	2.25	2.33	1.85	1.87

Note: These numbers represent amounts applied to all agricultural land, including *Land Converted to Cropland, Grassland Remaining Grassland,* and *Land Converted to Grassland.*

Uncertainty

Uncertainties in the estimates of emissions from liming result from both the emission factors and the activity data. The emission factors used for limestone and dolomite take into account the fate of C following application to soils,

including: dissolution of liming constituents; leaching of bicarbonates into the soil and transport to the ocean; and emissions to the atmosphere (West and McBride 2005). The C accounting behind these emission factors entails assumptions about several uncertain factors. First, it is uncertain what fraction of agricultural lime is dissolved by nitric acid (HNO_3)—a process that releases CO_2—and what portion reacts with carbonic acid (H_2CO_3), resulting in the uptake of CO_2. The fractions can vary depending on soil pH and N fertilizer use. The second major source of uncertainty is the fraction of bicarbonate (HCO_3^-) that leaches through the soil profile and is transported into groundwater, which can eventually be transferred into rivers and into the ocean. This fraction can vary depending on the soil pH and whether calcium (Ca^{2+}) and magnesium (Mg^{2+}) liming constituents that might otherwise accompany HCO_3^-, are taken up by crops, remain in the upper soil profile, or are transported through or out of the soil profile. Finally, the emission factors do not account for the time that is needed for leaching and transport processes to occur.

There are several sources of uncertainty in the limestone and dolomite activity data. When reporting data to the USGS (or U.S. Bureau of Mines), some producers do not distinguish between limestone and dolomite. In these cases, data are reported as limestone, so this reporting could lead to an overestimation of limestone and an underestimation of dolomite. In addition, the total quantity of crushed stone listed each year in the *Minerals Yearbook* excludes American Samoa, Guam, Puerto Rico, and the U.S. Virgin Islands.

Uncertainty regarding limestone and dolomite activity data inputs was estimated at ±15 percent and assumed to be uniformly distributed around the inventory estimate (Tepordei 2003b). Analysis of the uncertainty associated with the emission factors included the following: the fraction of agricultural lime dissolved by nitric acid versus the fraction that reacts with carbonic acid, and the portion of bicarbonate that leaches through the soil and is transported to the ocean. Uncertainty regarding the time associated with leaching and transport was not accounted for, but should not change the uncertainty associated with CO_2 emissions (West 2005). The uncertainty associated with the fraction of agricultural lime dissolved by nitric acid and the portion of bicarbonate that leaches through the soil were each modeled as a smoothed triangular distribution between ranges of 0 percent to 100 percent. The uncertainty surrounding these two components largely drives the overall uncertainty estimates reported below.

A Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the uncertainty of CO_2 emissions from liming. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-23. CO_2 emissions from Liming of Agricultural Soils in 2006 were estimated to be between 0.2 and 7.9 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 95 percent below to 80 percent above the 2006 emission estimate of 4.4 Tg CO_2 Eq.

Table 7-23: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Liming of Agricultural Soils (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emissions Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emissions Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Liming of Agricultural Soils[1]	CO_2	4.4	0.2	7.9	-95%	80%

[a]Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[1] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland,* and *Land Converted to Grassland.*

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. The QA/QC analysis did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

Several adjustments were made in the current inventory to improve the results. The quantity of applied minerals reported in the previous inventory for 2005 has been revised. Consequently, the reported emissions resulting from

liming in 2005 have also changed. In the previous inventory, 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). 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 2005. These values have replaced those used in the previous inventory to calculate the quantity of minerals applied to soil and the emissions from liming.

CO_2 Emissions from Urea Fertilization

The use of urea ($CO(NH_2)_2$) as fertilizer leads to emissions of CO_2 that was fixed during the industrial production process. Urea in the presence of water and urease enzymes is converted into ammonium (NH_4^+), hydroxyl ion (OH^-), and bicarbonate (HCO_3^-). The bicarbonate then evolves into CO_2 and water. Emissions from urea fertilization in the US totaled 3.6 Tg CO_2 Eq. (1.0 Tg C) in 2006 (Table 7-24 and Table 7-25). Emissions from urea fertilization have fluctuated over the past sixteen years, ranging from 2.3 Tg CO_2 Eq. to 3.7 Tg CO_2 Eq.

Table 7-24: CO_2 Emissions from Urea Fertilization in *Cropland Remaining Cropland* (Tg CO_2 Eq.)

Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
Urea Fertilization[1]	2.4	2.7	3.2	3.4	3.6	3.7	3.7	3.5	3.6

Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

[1] Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland,* and *Land Converted to Grassland.*

Table 7-25: CO_2 Emissions from Urea Fertilization in *Cropland Remaining Cropland* (Tg C)

Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
Urea Fertilization[1]	0.7	0.7	0.9	0.9	1.0	1.0	1.0	1.0	1.0

Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

[1] Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland,* and *Land Converted to Grassland.*

Methodology

Carbon dioxide emissions from the application of urea to agricultural soils were estimated using the IPCC (2006) Tier 1 methodology. The annual amounts of urea fertilizer applied (see Table 7-26) were derived from state-level fertilizer sales data provided in *Commercial Fertilizers* (TVA 1991, 1992, 1993, 1994; AAPFCO 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006) and were multiplied by the default IPCC (2006) emission factor of 0.20, which is equal to the C content of urea on an atomic weight basis. Because fertilizer sales data are reported in fertilizer years (July through June), a calculation was performed to convert the data to calendar years (January through December). According to historic monthly fertilizer use data (TVA 1992b), 65 percent of total fertilizer used in any fertilizer year is applied between January through June of that calendar year, and 35 percent of total fertilizer used in any fertilizer year is applied between July through December of the previous calendar year. Fertilizer use data for the 2007 fertilizer year were not available in time for publication, so July through December 2006 fertilizer use was estimated by calculating the percent change (increase or decrease) in fertilizer use from January through June 2005 to July through December 2005. This percent change was then multiplied by the January through June 2006 data to estimate July through December 2006 fertilizer use. State-level estimates of CO_2 emissions from the application of urea to agricultural soils were summed to estimate total emissions for the entire United States.

Table 7-26: Applied Urea (Million Metric Tons)

	1990	1995	2000	2001	2002	2003	2004	2005	2006
Urea Fertilizer[1]	3.30	3.62	4.38	4.66	4.87	5.02	4.98	4.78	4.96

Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

[1]These numbers represent amounts applied to all agricultural land, including *Land Converted to Cropland, Grassland Remaining*

Grassland, and *Land Converted to Grassland*.

Uncertainty

Uncertainty estimates are presented in Table 7-27 for Urea Fertilization. A Tier 2 Monte Carlo analysis was completed. The largest source of uncertainty was the default emission factor, which assumes that 100 percent of the C applied to soils is ultimately emitted into the environment as CO_2. This factor does not incorporate the possibility that some of the C may be retained in the soil. The emission estimate is, thus, likely to be high. In addition, each urea consumption data point has an associated uncertainty. Urea for non-fertilizer use may be included in consumption totals; it was determined through personal communication with Fertilizer Regulatory Program Coordinator David L. Terry (2007), however, that amount is most likely very small. Lastly, there is uncertainty surrounding the assumptions behind the calculation that converts fertilizer years to calendar years. CO_2 emissions from Urea Fertilization of Agricultural Soils in 2006 were estimated to be between 2.5 and 4.5 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 31 percent below to 24 percent above the 2006 emission estimate of 3.6 Tg CO_2 Eq.

Table 7-27: Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Fertilization (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emissions Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emissions Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Fertilization	CO_2	3.6	2.5	4.5	-31%	24%

[a]Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
Note: These numbers represent amounts applied to all agricultural land, including *Land Converted to Cropland, Grassland Remaining Grassland*, and *Land Converted to Grassland*.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. Minor errors were found in these steps and corrective actions were taken, including a data point that was incorrectly transcribed. Inventory reporting forms and text were reviewed and revised as needed to correct transcription errors.

Recalculations Discussion

Emissions from Urea production and application were previously included in the Industrial Processes Chapter. That chapter has been modified to only include emissions from Urea production.

Planned Improvements

Several improvements are planned for the urea fertilization inventory. The first improvement is to investigate using a Tier 2 or Tier 3 approach, which would utilize country-specific information to estimate a more precise emission factor. The second improvement is to investigate and quantify, if possible, the amount of urea that is currently included in urea consumption totals, but is used for non-agricultural practices such as deicing.

7.5. Land Converted to Cropland (IPCC Source Category 5B2)

Land Converted to Cropland includes all cropland in an inventory year that had been another land use in the past 20

years[35] 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, 2006) recommend reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[36]

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 7-28 and Table 7-29). The total rate of change in soil C stocks was 9.4 Tg CO_2 Eq. (2.6 Tg C) in 2006. Emissions from mineral soils were estimated at 6.7 Tg CO_2 Eq. (1.8 Tg C) in 2006, while drainage and cultivation of organic soils led to annual losses of 2.6 Tg CO_2 Eq. (0.7 Tg C) in 2006.

Table 7-28: Net CO_2 Flux from Soil C Stock Changes in *Land Converted to Cropland* (Tg CO_2 Eq.)

Soil Type	**1990**		**1995**		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Mineral Soils	12.3		6.7		6.7	6.7	6.7	6.7	6.7	6.7	6.7
Organic Soils	2.4		2.6		2.6	2.6	2.6	2.6	2.6	2.6	2.6
Total Net Flux	**14.7**		**9.4**		**9.4**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**	**9.4**

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 7-29: Net CO_2 Flux from Soil C Stock Changes in *Land Converted to Cropland* (Tg C)

Soil Type	**1990**		**1995**		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Mineral Soils	3.4		1.8		1.8	1.8	1.8	1.8	1.8	1.8	1.8
Organic Soils	0.7		0.7		0.7	0.7	0.7	0.7	0.7	0.7	0.7
Total Net Flux	**4.0**		**2.6**		**2.6**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**

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.

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 7-7 and Figure 7-8. 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 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.

Figure 7-7: Net C Stock Change for Mineral Soils in *Land Converted to Cropland*, 2006

[Figures will be included after public review.]

[35] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification was based on less than 20 years of recorded land-use history for the time series from 1982 to 2001.

[36] CO_2 emissions associated with liming are also estimated but included in a separate section of the report.

Figure 7-8: Net C Stock Change for Organic Soils in *Land Converted to Cropland*, 2006

[Figures will be included after public review.]

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).[37] 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 through 1984, 1985 through 1989, 1990 through 1994 and 1995 through 2000. NRI points were classified as *Land Converted to Cropland* for an inventory time period (e.g., 1990 through 1994 and 1995 through 2000) if the land use was cropland in the respective inventory time period but had been another use during the previous 20 years.[38] 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. Soil C stock changes on the remaining soils were estimated with the IPCC Tier 2 method (Ogle et al. 2003), including land used to produce vegetable, tobacco, perennial/horticultural crops, and rice; land on very gravelly, cobbly or shaley soils (greater than 35 percent by volume); and land converted from forest or federal ownership[39].

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).

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[37] More recent NRI land use survey data are available and will be incorporated by the public review.

[38] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification was based on less than 20 years of recorded land-use history for the time series from 1982 to 2001.

[39] 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).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Cropland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), with U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. The final estimates included a measure of uncertainty as determined from the Monte Carlo 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 2006.

Uncertainty

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 approaches were based on the same method described for *Cropland Remaining Cropland*, except that the uncertainty inherent in the structure of the Century model was not addressed. The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Cropland* was estimated using the Tier 2 approach, as described in the *Cropland Remaining Cropland* Section.

Uncertainty estimates are presented in Table 7-30 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) 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), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The combined uncertainty for soil C stocks in *Land Converted to Cropland* was estimated to be 25 percent below and 22 percent above the inventory estimate of 9.4 Tg CO_2 Eq.

Table 7-30: Quantitative Uncertainty Estimates[1] for C Stock Changes occurring within *Land Converted to Cropland* (Tg CO_2 Eq. and Percent)

Source	2006 Flux Estimate[1] (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[1] (Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: *Land Converted to Cropland*, Tier 3 Inventory Methodology	2.6	2.0	3.1	-21%	21%
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 Flux associated with Soil Carbon Stock Change in *Land Converted to Cropland*	**9.4**	**7.0**	**11.4**	**-25%**	**22%**

[1] Flux estimates based on soil C stock change.

QA/QC and Verification

See QA/QC and Verification Section under *Cropland Remaining Cropland*.

Recalculations Discussion

Two changes were implemented in the current inventory that led to a change in the time series. First, there was a modification in the land use classification. The classification is based on the land use in a specific year of the inventory and the previous 20 years. However, in the 1990 through 2005 inventory, each point was only classified once based on the entire NRI time series of the land-use history. This approach led to incorrect classifications for the early 1990s. For example, a NRI point may have been grassland in 1982, 1987 and 1992, but converted to

cropland in 1997. In the previous inventory, the NRI point would be classified as *Land Converted to Cropland* for the entire inventory from 1990 through 2005. This is incorrect for the early 1990s because the point was *Grassland Remaining Grassland* during those years. Second, the time series for manure N between 1990 through 2006, which was used to adjust manure applications relative to 1997, was based on manure N available for application rather than manure N production. Overall, these recalculations resulted in an average annual increase in emissions of 3.3 Tg CO_2 Eq. for soil C stock changes in *Land Converted to Cropland* over the time series from 1990 through 2005, compared to the previous inventory.

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. This improvement will produce a more rigorous assessment of uncertainty. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.6. Grassland Remaining Grassland (IPCC Source Category 5C1)

Grassland Remaining Grassland includes all grassland in an inventory year that had been grassland for the previous 20 years[40] 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. The IPCC/UNEP/OECD/IEA (1997) and IPCC (2003, 2006) recommend reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[41]

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. Organic soils lost about the same amount of C in each year of the inventory. Due to the pattern for mineral soils, the overall trend shifted from small increases in soil C during 1990 to decreases in soil C during the latter years of the inventory, estimated at 16.2 Tg CO_2 Eq. (4.4 Tg C) in 2006. Overall, flux rates changed by 18.1 Tg CO_2 Eq. (4.9 Tg C) from 1990 to 2006.

Table 7-31: Net CO_2 Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (Tg CO_2 Eq.)

Soil Type	**1990**		**1995**		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Mineral Soils	(5.7)		12.9		12.8	12.7	12.7	12.7	12.6	12.6	12.5
Organic Soils	3.9		3.7		3.7	3.7	3.7	3.7	3.7	3.7	3.7
Total Net Flux	**(1.9)**		**16.6**		**16.4**	**16.4**	**16.4**	**16.4**	**16.3**	**16.3**	**16.2**

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.

Table 7-32: Net CO2 Flux from Soil C Stock Changes in Grassland Remaining Grassland (Tg C)

Soil Type	**1990**		**1995**		**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Mineral Soils	(1.6)		3.5		3.5	3.5	3.5	3.5	3.4	3.4	3.4

[40] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification was based on less than 20 years of recorded land-use history for the time series from 1982 to 2001.

[41] CO_2 emissions associated with liming are also estimated but included in a separate section of the report.

Organic Soils	1.1		1.0		1.0	1.0	1.0	1.0	1.0	1.0	1.0
Total Net Flux	**(0.5)**		**4.5**		**4.5**	**4.5**	**4.5**	**4.5**	**4.5**	**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.

The spatial variability in annual CO_2 flux associated with C stock changes in mineral and organic soils is displayed in Figure 7-9 and Figure 7-10. 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 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.

Figure 7-9: Net Soil C Stock Change for Mineral Soils in *Grassland Remaining Grassland*, 2006

[Figures will be included after public review.]

Figure 7-10: Net Soil C Stock Change for Organic Soils in *Grassland Remaining Grassland*, 2006

[Figures will be included after public review.]

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).[42] 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 through 1984, 1985 through 1989, 1990 through 1994 and 1995 through 2000. NRI points were classified as *Grassland Remaining Grassland* for an inventory time period (e.g., 1990 through 1994 and 1995 through 2000) if the land use was grassland in the inventory time period and had been grassland for the previous 20 years.[43] 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

An IPCC Tier 3 model-based approach was used to estimate C stock changes for most mineral soils in *Grassland*

[42] More recent NRI land use survey data are available and will be incorporated by the public review.

[43] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification was based on less than 20 years of recorded land-use history for the time series from 1982 to 2001.

Remaining Grassland. The C stock changes for the remaining soils were estimated with an IPCC Tier 2 method (Ogle et al. 2003), including gravelly, cobbly or shaley soils (greater than 35 percent by volume) and additional stock changes associated with sewage sludge amendments.

Tier 3 Approach

Mineral soil organic C stocks and stock changes for *Grassland Remaining Grassland* were estimated using the 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 estimates of manure available for application in other years of the inventory. Specifically, county-scale ratios of manure available in other years relative to 1997 were used to adjust the area amended with manure (see Annex 3.13 for further details). Greater availability of managed manure N relative to 1997 was, thus, assumed to increase the urea amended with manure, while reduced availability of manure N relative to 1997 was assumed to reduce the amended area.

The amount of manure produced by each livestock type was calculated for managed and unmanaged waste management systems. Managed systems include feedlots or other housing (which requires manure to be collected and managed); unmanaged systems include daily spread, pasture, range, and paddock systems. 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. Population data used for cattle, swine, and sheep were downloaded from the USDA NASS Population Estimates Database (USDA 2007a). Poultry population data were obtained from USDA NASS reports (USDA 1995a, 1995b, 1998a, 1999, 2004a, 2004b, 2006a, 2006b, 2007b, 2007c). Horse population data were obtained from the FAOSTAT database (FAO 2007). Goat population data for 1992, 1997, and 2002 were obtained from the *Census of Agriculture* (USDA 2005); 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, 1997, and 2002 *Census of Agriculture* (USDA 2005).

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 an external input into the model). Manure amendments were an input to the Century Model based on manure N available for application from all other managed or unmanaged systems. Data on the county-level N available for application were estimated for managed systems based on the total amount of N excreted in manure minus N losses and including the addition of N from bedding materials. Nitrogen losses include direct nitrous oxide emissions, volatilization of ammonia and NOx, and runoff and leaching. More information on these losses is available in the description of the Manure Management source category. Animal-specific bedding factors were set equal to IPCC default factors (IPCC 2006). For unmanaged systems, it is assumed that no N losses or additions occur. 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 2006 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, in dry mass units, were obtained from an EPA report (EPA 1999) and estimates for 2004 were obtained from an independent national biosolids survey (NEBRA 2007). These values were linearly interpolated to estimate values for the intervening years. N application rates from Kellogg et al. (2000) were used to determine the amount of area receiving sludge amendments. Although sewage sludge can be added to land managed for other land uses, it was assumed that agricultural amendments occur in grassland. Cropland is assumed to rarely be amended with sewage sludge due to the high metal content and other pollutants in human waste. The soil C storage rate was estimated at 0.38 metric tons C per hectare per year for sewage sludge amendments to grassland. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.13 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Grassland Remaining Grassland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. Emissions were based on the 1992 and 1997 *Grassland Remaining Grassland* areas from the *1997 National Resources Inventory* (USDA-NRCS 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 2006.

Uncertainty

Uncertainty estimates are presented in Table 7-33 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). 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 Guidelines (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The combined uncertainty for soil C stocks in *Grassland Remaining Grassland* was estimated to be 18 percent below and 15 percent above the inventory estimate of 16.2 Tg CO_2 Eq.

Table 7-33: Quantitative Uncertainty Estimates[1] for C Stock Changes occurring within *Grassland Remaining Grassland* (Tg CO2 Eq. and Percent)

Source	2006 Flux Estimate[1] (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[1] (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	12.5	15.3	-10%	10%
Mineral Soil C Stocks: *Grassland Remaining Grassland*, Tier 2 Inventory Methodology	(0.2)	(0.3)	0.0	-89%	127%
Mineral Soil C Stocks: *Grassland Remaining Grassland* (Change in Soil C due to Sewage Sludge Amendments)	(1.2)	(1.7)	(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 Flux Associated with Agricultural Soil Carbon Stock Change in *Grassland Remaining Grassland*	**16.2**	**13.4**	**18.6**	**-18%**	**15%**

[1] Flux estimates based on soil C stock changes.

Uncertainties in Mineral Soil Carbon Stock Changes

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.

A ±50 percent uncertainty was assumed for additional adjustments to the soil C stocks between 1990 and 2006 to account for additional C stock changes associated with amending grassland soils with sewage sludge.

Uncertainties in Soil Carbon Stock Changes for Organic Soils

Uncertainty in C emissions from organic soils was estimated using country-specific factors and a Monte Carlo analysis. Probability distribution functions 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. The manure amendment records were not recorded correctly in a subset of the Century model output; corrective actions were taken to resolve this error.

Recalculations Discussion

Two changes were implemented in the current inventory that led to a change in the time series. First, there was a modification in the land use classification. The classification is based on the land use in a specific year of the inventory and the previous 20 years. However, in the previous inventory, each point was only classified once based on the entire NRI time series of the land-use history. This approach led to incorrect classifications for the early 1990s. For example, a NRI point may have been grassland in 1982, 1987 and 1992, but converted to cropland in 1997. In the previous inventory, the NRI point would be classified as *Land Converted to Cropland* for the entire inventory from 1990 through 2005. This is incorrect for the early 1990s because the point was *Grassland Remaining Grassland* during those years. Second, the time series for manure N between 1990 through 2006, which was used to adjust manure applications relative to 1997, was based on manure N available for application rather than manure N production. Overall, the recalculations resulted in an average annual decrease in emissions of 0.5 Tg CO_2 Eq. for the time series over the period from 1990 through 2005, compared to the previous inventory.

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. This improvement will produce a more rigorous assessment of uncertainty. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.7. Land Converted to Grassland (IPCC Source Category 5C2)

Land Converted to Grassland includes all grassland in an inventory year that had been in another land use during the previous 20 years[44] 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 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) and IPCC (2003, 2006) recommend reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and

[44] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification was based on less than 20 years of recorded land-use history for the time series from 1982 to 2001.

management activities on organic soils.[45]

Land-use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil C stocks from 1990 through 2006, which was largely caused by annual cropland converted into pasture (see Table 7-34 and Table 7-35). Stock change rates over the time series varied from -14.7 to -17.2 Tg CO_2 Eq./yr (4 to 5 Tg C). Drainage of organic soils for grazing management led to losses varying from 0.5 to 0.9 Tg CO_2 Eq./yr (0.1 to 0.2 Tg C).

Table 7-34: Net CO2 Flux from Soil C Stock Changes for *Land Converted to Grassland* (Tg CO2 Eq.)

Soil Type	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Mineral Soils[1]	(14.7)	(17.2)	(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	0.9
Total Net Flux	**(14.3)**	**(16.3)**	**(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.
[1] Stock changes due to application of sewage sludge are reported in *Grassland Remaining Grassland*.

Table 7-35: Net CO2 Flux from Soil C Stock Changes for *Land Converted to Grassland* (Tg C)

Soil Type	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Mineral Soils[1]	(4.0)	(4.7)	(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	0.2
Total Net Flux	**(3.9)**	**(4.5)**	**(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.
[1] Stock changes due to application of sewage sludge in *Land Converted to Grassland* are reported in *Grassland Remaining Grassland*.

The spatial variability in annual CO_2 flux associated with C stock changes in mineral soils is displayed in Figure 7-11 and Figure 7-12. Soil C stock increased in most states 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.

Figure 7-11: Net Soil C Stock Change for Mineral Soils in *Land Converted to Grassland*, 2006

[Figures will be included after public review.]

Figure 7-12: Net Soil C Stock Change for Organic Soils in *Land Converted to Grassland*, 2006

[Figures will be included after public review.]

Methodology

This section includes a brief description of the methodology used to estimate changes in soil C stocks due to

[45] CO_2 emissions associated with liming are also estimated but included in a separate section of the report.

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 the USDA NRI survey (USDA-NRCS 2000).[46] Land use and some management information (e.g., legume pastures, crop type, soil attributes, and irrigation) was collected for each NRI point on a 5-year cycle beginning in 1982, and was subdivided into four inventory time periods, 1980 through 1984, 1985 through 1989, 1990 through 1994 and 1995 through 2000. NRI points were classified as *Land Converted to Grassland* for an inventory time period (e.g., 1990 through 1994 and 1995 through 2000) if the land use was grassland at the end of the respective inventory time period but had been another use in the previous 20 years.[47] Grassland includes pasture and rangeland used for grass forage production, where the primary use is livestock grazing. Rangeland typically includes extensive areas of native grassland that are not intensively managed, while pastures are often seeded grassland, possibly following tree removal, that may or may not be improved with practices such as irrigation and interseeding legumes. 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

An IPCC Tier 3 model-based approach was used to estimate C stock changes for *Land Converted to Grassland* on most mineral soils. C stock changes on the remaining soils were estimated with an IPCC Tier 2 approach (Ogle et al. 2003), including prior cropland used to produce vegetables, tobacco, perennial/horticultural crops, and rice; land areas with very gravelly, cobbly or shaley soils (greater than 35 percent by volume); and land converted from forest or federal ownership.[48] 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 the USDA Economic Research Service Cropping Practices Survey (ERS 1997) and the 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 (2003, 2006), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. Emissions were based on the 1992 and 1997 *Land Converted to Grassland* areas from the *1997 National Resources Inventory* (USDA-NRCS 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 2006.

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[46] More recent NRI land use survey data are available and will be incorporated by the public review.

[47] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification was based on less than 20 years of recorded land-use history for the time series from 1982 to 2001.

[48] 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 analysis for mineral soil C stock changes using the Tier 3 and Tier 2 approaches were based on the same method described in *Cropland Remaining Cropland*, except that the uncertainty inherent in the structure of the Century model was not addressed. The uncertainty or annual C emission estimates from drained organic soils in *Land Converted to Grassland* was estimated using the Tier 2 approach, as described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 7-36 for each subsource (i.e., mineral soil C stocks and organic soil C stocks), disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). 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), (i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities). The combined uncertainty for soil C stocks in *Land Converted to Grassland* ranged from 13 percent below and 14 percent above the 2006 estimate of 16.3 Tg CO_2 Eq.

Table 7-36: Quantitative Uncertainty Estimates[1] for C Stock Changes occurring within *Land Converted to Grassland* (Tg CO_2 Eq. and Percent)

Source	2006 Flux Estimate[1] (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[1] (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 Flux associated with Agricultural Soil Carbon Stocks in *Land Converted to Grassland*	**(16.3)**	**(18.4)**	**(14.0)**	**-13%**	**14%**

[1] Flux estimates based on soil C stock changes.

QA/QC and Verification

See the QA/QC and Verification section under *Grassland Remaining Grassland*.

Recalculations Discussion

Two changes were implemented in the current inventory that led to a change in the time series. First, there was a modification in the land use classification. The classification is based on the land use in a specific year of the inventory and the previous 20 years. However, in the 1990 through 2005 inventory, each point was only classified once based on the entire NRI time series of the land-use history. This approach led to incorrect classifications for the early 1990s. For example, a NRI point may have been cropland in 1982, 1987 and 1992, but converted to grassland in 1997. In the previous inventory, the NRI point would be classified as *Land Converted to Grassland* for the entire inventory from 1990 through 2005. This is incorrect for the early 1990s because the point was *Cropland Remaining Cropland* during those years. Second, the time series for manure N between 1990 through 2006, which was used to adjust manure applications relative to 1997, was based on manure N available for application rather than manure N production. Overall, the recalculations resulted in an average annual decrease in emissions of 0.1 Tg CO_2 Eq. for the time series from 1990 through 2005, compared to the previous inventory.

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. This improvement will produce a more rigourous assessment of uncertainty. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.8. 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 percent, urban areas account for approximately 3 percent of total tree cover in the continental United States (Nowak et al. 2001). Trees in urban areas of the United States were estimated to account for an average annual net sequestration of 78.1 Tg CO_2 Eq. (21 Tg C) over the period from 1990 through 2006. Total sequestration increased by 57 percent between 1990 and 2006 due to increases in urban land area. Data on C storage and urban tree coverage were collected since the early 1990s and have been applied to the entire time series in this report. Annual estimates of CO_2 flux were developed based on periodic U.S. Census data on urban area (Table 7-37). Net C flux from urban trees in 2006 was estimated to be -95.5 Tg CO_2 Eq. (-26 Tg C).

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).

Table 7-37: Net C Flux from Urban Trees (Tg CO_2 Eq. and Tg C)

Year	Tg CO_2 Eq.	Tg C
1990	(60.6)	(16.5)
1995	(71.5)	(19.5)
2000	(82.4)	(22.5)
2001	(84.6)	(23.1)
2002	(86.8)	(23.7)
2003	(88.9)	(24.3)
2004	(91.1)	(24.9)
2005	(93.3)	(25.4)
2006	(95.5)	(26.0)

Note: Parentheses indicate net sequestration.

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 (2006), although sufficient data are not yet available to determine interannual gains and losses in C stocks in the living biomass of urban trees. Annual changes in net C flux from urban trees are based solely on changes in total urban area in the United States.

Most of the field data were analyzed using the U.S. Forest Service's Urban Forest Effects (UFORE) model.[49] The UFORE model is a computer model that uses standardized field data from random plots and local air pollution and meteorological data to quantify urban forest structure, values of the urban forest, and environmental effects, including total C stored and annual C sequestration (Nowak et al. 2007a).

Nowak and Crane (2002) developed estimates of annual gross C sequestration from tree growth and annual gross C emissions from decomposition for 15 U.S. cities: Atlanta, GA; Baltimore, MD; Boston, MA; Chicago, IL; Freehold, NJ; Jersey City, NJ; Minneapolis, MN; Moorestown, NJ; New York, NY; Oakland, CA; Philadelphia, PA; San Francisco, CA; Syracuse, NY; Washington, DC; and Woodbridge, NJ. The gross C sequestration estimates were derived from field data that were collected in these 15 cities during the period from 1989 through 2006, 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 15 cities, some of which are unpublished (Nowak 2007c), are described in Nowak and Crane (2002), Nowak et al. (2007a), 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). Tree growth rates were taken from existing literature. Average diameter growth was based on the following sources: estimates for trees in forest stands came from Smith and Shifley (1984); estimates for trees on land uses with a park-like structure came from deVries (1987); and estimates for more open-grown trees came from Nowak (1994). Formulas from Fleming (1988) formed the basis for average height growth calculations. Growth rates were adjusted to account for tree condition. Growth factors for Atlanta, Boston, Chicago, Freehold, Jersey City, Moorestown, New York, Oakland, Philadelphia, and Woodbridge were adjusted based on the typical growth conditions of different land-use categories (e.g., forest stands, park-like stands). Growth factors for the more recent studies in Baltimore, Minneapolis, San Francisco, Syracuse, and Washington were adjusted using an updated methodology based on the condition of each individual tree, which is determined using tree competition factors (depending on whether it is open grown or suppressed) (Nowak 2007b).

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 calculated based on estimates of gross and net sequestration from 13 of the 15 cities (Table 7-38), and urban area and urban tree cover data for the United States. Annual net C sequestration estimates were derived for 13 cities by subtracting the annual gross emission estimates from the annual gross sequestration estimates.[50]T 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

[49] Oakland and Chicago estimates were based on prototypes to the UFORE model.

[50] Two cities did not have net estimates.

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 (0.31 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 (0.72). The urban tree cover estimates for each of the 15 cities and the United States were obtained from Dwyer et al. (2000), Nowak et al. (2002), and Nowak (2007a). The urban area estimates were taken from Nowak et al. (2005).

Table 7-38: C Stocks (Metric Tons C), Annual C Sequestration (Metric Tons C/yr), Tree Cover (Percent), and Annual C Sequestration per Area of Tree Cover (kg C/m^{2}cover-yr) for 15 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
Atlanta, GA	1,219,256	42,093	32,169	36.7%	0.34	0.26
Baltimore, MD	541,589	14,696	9,261	21.0%	0.35	0.22
Boston, MA	289,392	9,525	6,966	22.3%	0.30	0.22
Chicago, IL	NA	NA	NA	11.0%	0.61	NA
Freehold, NJ	18,144	494	318	34.4%	0.28	0.18
Jersey City, NJ	19,051	807	577	11.5%	0.18	0.13
Minneapolis, MN	226,796	8,074	4,265	26.4%	0.20	0.11
Moorestown, NJ	106,141	3,411	2,577	28.0%	0.32	0.24
New York, NY	1,224,699	38,374	20,786	20.9%	0.23	0.12
Oakland, CA	NA	NA	NA	21.0%	NA	NA
Philadelphia, PA	480,808	14,606	10,530	15.7%	0.27	0.20
San Francisco, CA	175,994	4,627	4,152	11.9%	0.33	0.29
Syracuse, NY	156,943	4,917	4,270	23.1%	0.33	0.29
Washington, DC	477,179	14,696	11,661	28.6%	0.32	0.26
Woodbridge, NJ	145,150	5,044	3,663	29.5%	0.28	0.21

NA = not analyzed.
Sources: Nowak and Crane (2002) and Nowak (2007a,c).

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 15 U.S. cities. A 10 percent uncertainty was associated with urban area estimates while a 5 percent uncertainty was associated with percent urban tree coverage. Both of these uncertainty estimates were based on expert judgment. Uncertainty associated with estimates of gross and net C sequestration for the 15 U.S. cities was based on standard error estimates for each of the city-level sequestration estimates reported by Nowak (2007c). These estimates are based on field data collected in 15 U.S. cities, and uncertainty in these estimates increases as they are scaled up to the national level.

Additional uncertainty is associated with the biomass equations, conversion factors, and decomposition assumptions used to calculate C sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil C stocks, and there may be some overlap between the urban tree C estimates and the forest tree C estimates. Due to data limitations, urban soil flux is not quantified as part of this analysis, while reconciliation of urban tree and forest tree estimates will be addressed through the land representation effort described at the beginning of this chapter.

A Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-39. The net C flux from changes in C stocks in urban trees was estimated to be between -112.1 and -76.5 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 17 percent below and 20 percent above the 2006 flux estimate of -95.5 Tg CO_2 Eq.

Table 7-39: 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	2006 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Changes in C Stocks in Urban Trees	CO_2	(95.5)	(112.1)	(76.5)	-17%	20%

Note: Parentheses indicate negative values or net sequestration.

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 this correspondence, the methods used to collect the urban tree sequestration and area data were further clarified and the use of these data in the inventory was reviewed and validated (Nowak 2002a, 2007b).

Recalculations Discussion

New data was added for six U.S. cities: Freehold, NJ; Minneapolis, MN; Moorestown, NJ; San Francisco, CA; Washington, DC; and Woodbridge, NJ. Data for Sacramento, CA was removed from the urban trees estimates because it was analyzed using a different methodology. These changes brought the total number of included cities to 15, providing a better median estimate of net and gross sequestration than the previous inventory estimate based on data from 10 U.S. cities.

There was also a slight change in the methodology for adjusting urban tree growth rates to account for tree condition. Some of the older studies used average growth rates based on the typical growth conditions of different land-use categories. In contrast, some of the newer studies adjust growth factors based on the condition of the tree, which is determined using tree competition factors (depending on whether it is open grown or suppressed) for each individual tree. The cities that use each of these methodologies are identified above in the Methodology section. The difference that resulted from this change in methodological approach is very small and likely washes out on average (Nowak 2007b).

These changes resulted in changes in the estimates of net annual C sequestration by urban trees for the time period 1990 through 2005. On average, estimates of net annual C sequestration by urban trees increased by 5.3 percent over the period from 1990 to 2005 relative to the previous report.

Planned Improvements

A consistent representation of the managed land base in the United States is being developed. A component of this effort, which is discussed at the beginning of the LULUCF chapter, will involve reconciling the overlap between urban forest and non-urban forest greenhouse gas 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 inventory. Planned improvements to the FIA program include the development of a long-term dataset that will define urban area boundaries and make it possible to identify what area is forested. Once those data become available, they will

be incorporated into estimates of net C flux resulting from urban trees.

Urban forest data for additional cities is expected in the near term, and the use of this data will further refine the estimated median sequestration value. It may also be possible to report C losses and gains separately in the future. It is currently not possible, since existing studies estimate rather than measure natality or mortality; net sequestration estimates are based on assumptions about whether dead trees are being removed, burned, or chipped. There is an effort underway to develop long-term data on permanent plots in at least two cities, which would allow for direct calculation of C losses and gains from observed rather than estimated natality and mortality of trees.

Direct N_2O Fluxes from Settlement Soils (IPCC Source Category 5E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 3 percent are currently applied to 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 2006, N_2O emissions from this source were 1.8 Tg CO_2 Eq. (5.9 Gg). There was an overall increase of 74 percent over the period from 1990 through 2006 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 7-40.

Table 7-40: N_2O Fluxes from Soils in *Settlements Remaining Settlements* (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.0	3.4
1995	1.4	4.4
2000	1.5	5.0
2001	1.8	5.7
2002	1.8	5.8
2003	1.9	6.0
2004	1.9	6.1
2005	1.8	5.9
2006	1.8	5.9

Note: These estimates include direct N_2O emissions from N fertilizer additions only. Indirect N_2O emissions from fertilizer additions are reported in the Agriculture chapter. These estimates include emissions from both *Settlements Remaining Settlements* and from *Land Converted to Settlements*.

Methodology

For soils within *Settlements Remaining Settlements,* the IPCC Tier 1 approach was used to estimate soil N_2O emissions from synthetic N fertilizer and sewage sludge additions. Estimates of direct N_2O emissions from soils in settlements were based on the amount of N in synthetic commercial fertilizers applied to settlement soils and the amount of N in sewage sludge applied to non-agricultural land and in surface disposal of sewage sludge.

Nitrogen applications to settlement soils are estimated using data compiled by the USGS (Ruddy, et al. 2006). The USGS estimated on-farm and non-farm fertilizer use based on sales records at the county level from 1982 through 2001 (Ruddy, et al. 2006). Non-farm N fertilizer was assumed to be applied to settlements and values for 2001 were used for 2002 through 2006. Sewage sludge applications were derived from national data on sewage sludge generation, disposition, and N content (see Annex 3.11 for further detail). The total amount of N resulting from these sources was multiplied by the IPCC default emission factor for applied N (1 percent) to estimate direct N_2O emissions (IPCC 2006). The volatilized and leached/runoff 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 N_2O

Emissions from 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 does not incorporate any of these variables and only accounts for variations in fertilizer N and sewage sludge application rates. All settlement soils are treated equivalently under this methodology.

Uncertainties exist in both the fertilizer N and sewage sludge application rates in addition to the emission factors. Uncertainty in fertilizer N application was assigned a default level[51] of ±50 percent. Uncertainty in the amounts of sewage sludge applied to non-agricultural lands and used in surface disposal was derived from variability in several factors, including: (1) N content of sewage sludge; (2) total sludge applied in 2000; (3) wastewater existing flow in 1996 and 2000; and (4) the sewage sludge disposal practice distributions to non-agricultural land application and surface disposal. Uncertainty in the emission factors was provided by the IPCC (2006)

A simple error propagation method (IPCC 2006) was used to combine the uncertainties and results are summarized in Table 7-41. N_2O emissions from soils in *Settlements Remaining Settlements* in 2006 were estimated to be between 0.4 and 6.9 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 79 percent below to 280 percent above the 2006 emission estimate of 1.8 Tg CO_2 Eq.

Table 7-41: Tier 2 Quantitative Uncertainty Estimates of N_2O Emissions from Soils in *Settlements Remaining Settlements* (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emissions (Tg CO_2 Eq.)	Uncertainty Range Relative to 2006 Emission Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Settlements Remaining Settlements:						
N_2O Fluxes from Soils	N_2O	1.8	0.4	6.9	-79%	280%

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

A new data source was used for N fertilization in the current inventory. Instead of assuming settlement soils receive 10 percent of total synthetic N fertilizer applied in the United States, fertilization data were based on county-scale non-farm application amounts from a database compiled by the USGS (Ruddy, et al. 2006). According to the USGS data, approximately 1.7 percent of synthetic fertilizer N was applied to settlements in 1990 and this gradually increased to 3.1 percent in 2001. This change resulted in a 68 percent decrease in the emission estimates for 2005 and an average decrease of about 74 percent over the period from 1990 to 2005.

Planned Improvements

The key planned improvement is to estimate emissions using the process-based DAYCENT model instead of the IPCC default methodology. DAYCENT has been used to estimate N_2O emissions from agricultural soils, reducing bias and improving precision in estimates for the cropland and grassland soils. Applying the DAYCENT model is

[51] No uncertainty is provided with the USGS application data (Ruddy et al. 2006) so a conservative ±50% was used in the analysis.

also anticipated to reduce uncertainties in the estimated emissions from settlement soils. In addition, this planned improvement would incorporate state-level settlement area data from the National Resource Inventory.

7.9. 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.

7.10. Other (IPCC Source Category 5G)

Changes in Yard Trimming and Food Scrap Carbon 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.

Carbon storage estimates are associated with particular land uses. For example, harvested wood products are accounted for under *Forest Land Remaining Forest Land* because these wood products are a component of the forest ecosystem. The wood products serve as reservoirs to which C resulting from photosynthesis in trees is transferred, but the removals in this case occur in the forest. C stock changes in yard trimmings and food scraps are associated with settlements, but removals in this case do not occur within settlements. To address this complexity, yard trimming and food scrap C storage is therefore reported under the "Other" source category.

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, over 51 million metric tons (wet weight) of yard trimmings and food scraps were generated (i.e., put at the curb for collection to be taken to disposal sites or to composting facilities) (EPA 2007; Schneider 2007). Since then, programs banning or discouraging disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent 7 percent decrease in the amount of yard trimmings generated (i.e., collected for composting or disposal). 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 31 percent in 2006. The net effect of the reduction in generation and the increase in composting is a 60 percent decrease in the quantity of yard trimmings disposed in landfills since 1990. Food scraps generation has grown by 50 percent since 1990, but the proportion of food scraps discarded in landfills has decreased slightly from 81 percent in 1990 to 80 percent in 2006. Overall, the decrease in the yard trimmings landfill disposal rate has more than compensated for the increase in food scrap disposal in landfills, and the net result is a decrease in annual landfill C storage from 22.8 Tg CO_2 Eq. in 1990 to 9.8 Tg CO_2 Eq. in 2006 (Table 7-42 and Table 7-43).

Table 7-42: 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	2006
Yard Trimmings	**(20.3)**	**(11.8)**	**(7.5)**	**(7.8)**	**(7.9)**	**(6.4)**	**(5.5)**	**(5.8)**	**(6.1)**
Grass	(2.4)	(1.2)	(0.8)	(0.9)	(0.9)	(0.7)	(0.6)	(0.7)	(0.7)
Leaves	(8.2)	(4.7)	(3.0)	(3.0)	(3.1)	(2.5)	(2.1)	(2.2)	(2.3)
Branches	(9.7)	(5.8)	(3.7)	(3.9)	(3.9)	(3.2)	(2.8)	(2.9)	(3.0)
Food Scraps	**(2.5)**	**(1.6)**	**(3.3)**	**(3.2)**	**(3.1)**	**(2.9)**	**(3.4)**	**(3.5)**	**(3.7)**
Total Net Flux	**(22.8)**	**(13.3)**	**(10.8)**	**(10.9)**	**(11.0)**	**(9.4)**	**(8.9)**	**(9.3)**	**(9.8)**

Note: Totals may not sum due to independent rounding.

Table 7-43: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg C)

Carbon Pool	1990	1995	2000	2001	2002	2003	2004	2005	2006
Yard Trimmings	**(5.5)**	**(3.2)**	**(2.0)**	**(2.1)**	**(2.2)**	**(1.7)**	**(1.5)**	**(1.6)**	**(1.7)**
Grass	(0.6)	(0.3)	(0.2)	(0.2)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)
Leaves	(2.2)	(1.3)	(0.8)	(0.8)	(0.8)	(0.7)	(0.6)	(0.6)	(0.6)
Branches	(2.6)	(1.6)	(1.0)	(1.1)	(1.1)	(0.9)	(0.8)	(0.8)	(0.8)
Food Scraps	**(0.7)**	**(0.4)**	**(0.9)**	**(0.9)**	**(0.8)**	**(0.8)**	**(0.9)**	**(0.9)**	**(1.0)**
Total Net Flux	**(6.2)**	**(3.6)**	**(2.9)**	**(3.0)**	**(3.0)**	**(2.6)**	**(2.4)**	**(2.5)**	**(2.7)**

Note: Totals may not sum due to independent rounding.

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). 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 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: 2006 Facts and Figures* (EPA 2007), which provides data for 1960, 1970, 1980, 1990, 2000, 2002, and 2004 through 2006. To provide data for some of the missing years, detailed backup data was obtained from Schneider (2007). Remaining years in the time series for which data were not provided were estimated using linear interpolation. The report does not subdivide discards of individual materials into volumes landfilled and combusted, although it provides an estimate of the proportion of overall waste stream discards managed in landfills 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 7-44).

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. 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 7-44).

The modeling approach applied to simulate U.S. landfill C flows builds on the findings of Barlaz (1998, 2005). The

proportion of C stored is assumed to persist in landfills. The remaining portion is assumed to degrade, resulting in emissions of CH_4 and CO_2 (the CH_4 emissions resulting from decomposition of yard trimmings and food scraps are accounted for in the *Waste* chapter). The degradable portion of the C is assumed to decay according to first order kinetics. Food scraps are assumed to have a half-life of 3.7 years; grass is assumed to have a half-life of 5 years; leaves are assumed to have a half-life of 20 years; and branches are assumed to have a half-life of 23.1 years. The half-life of food scraps is consistent with analysis for landfill CH_4 in the *Waste* chapter.

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 (year),
- i = Waste type for which C stocks are being estimated (grass, leaves, branches, food scraps),
- $LFC_{i,t}$ = Stock of C in landfills in year *t*, for waste *i* (metric tons),
- $W_{i,n}$ = Mass of waste *i* disposed in landfills in year *n* (metric tons, wet weight),
- n = Year in which the waste was disposed (year, where 1960 U≤U n U≤U t),
- MC_i = Moisture content of waste *i* (percent of water),
- CS_i = Proportion of initial C that is stored for waste *i* (percent),
- ICC_i = Initial C content of waste *i* (percent),
- e = Natural logarithm, and
- k = First order rate constant for waste *i*, which is equal to 0.693 divided by the half-life for decomposition ($year^{-1}$).

For a given year *t*, the total stock of C in landfills ($TLFC_t$) is the sum of stocks across all four materials. 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 (2006). For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of C. Of this amount, 16 percent (179,000 metric tons) is persistent; the remaining 84 percent (956,000 metric tons) is degradable. By 1964, more than half of the degradable portion (500,000 metric tons) decomposes, leaving a total of 635,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2006, the total food scraps C originally disposed in 1960 had declined to 179,000 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 2006), the total landfill C from food scraps in 2006 was 29.5 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 2006, yielding a value of 224.5 million metric tons (as shown in Table 7-45). 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 7-43) 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 2006 shown in Table 7-43 (2.7 Tg C) is equal to the stock in 2006 (224.5 Tg C) minus the stock in 2005 (221.8 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 $CH_4\text{-}C = CO_2\text{-}C$.[52] 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.

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 ($2 \times CH_4\text{-}C$). This adjustment reduced the C storage value from the 71 percent reported by Barlaz (1998) to 68 percent (as shown in Table 7-44).

The resulting C stocks are shown in Table 7-45.

Table 7-44: Moisture Content (%), C Storage Factor, Proportion of Initial C Sequestered (%), Initial C Content (%), and Half-Life (years) for Landfilled Yard Trimmings and Food Scraps in Landfills

	Yard Trimmings			Food Scraps
Variable	**Grass**	**Leaves**	**Branches**	
Moisture Content (% H_2O)	70	30	10	70
CS, proportion of initial C stored (%)	68	72	77	16
Initial C Content (%)	45	42	49	51
Half-life (years)	5	20	23	4

Table 7-45: C Stocks in Yard Trimmings and Food Scraps in Landfills (Tg C)

Carbon Pool	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Yard Trimmings	**150.4**	**172.5**	**184.2**	**186.3**	**188.4**	**190.2**	**191.7**	**193.3**	**195.0**
Grass	18.2	20.7	21.9	22.2	22.4	22.6	22.8	23.0	23.2
Leaves	61.3	70.2	74.8	75.7	76.5	77.2	77.8	78.4	79.0
Branches	70.9	81.6	87.4	88.4	89.5	90.4	91.2	91.9	92.8
Food Scraps	**17.9**	**20.6**	**24.1**	**25.0**	**25.8**	**26.6**	**27.6**	**28.5**	**29.5**
Total Carbon Stocks	**168.3**	**193.0**	**208.3**	**211.3**	**214.3**	**216.8**	**219.3**	**221.8**	**224.5**

Note: Totals may not sum due to independent rounding.

Uncertainty

The uncertainty analysis for landfilled yard trimmings and food scraps includes an evaluation of the effects of uncertainty for the following data and factors: disposal in landfills per year (tons of C), initial C content, moisture

[52] 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.

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 respective uncertainties associated with each of these factors.

The uncertainty ranges were assigned based on expert judgment and are assumed to be normally distributed around the inventory estimate, except for the values for decomposition rate, proportion of C stored, and moisture content for branches. The uncertainty ranges associated with these values are highlighted separately in this section.

The uncertainty range selected for input variables for the proportions of both grass and leaves in yard trimmings was 20 to 60 percent. The initial C content for grass, leaves, and food scraps (all expressed as percentages in the calculations for the inventory) were plus or minus 10 percent. For the moisture content of branches (where the inventory estimate is 10 percent), the uncertainty range was assumed to be 5 to 30 percent, within a lognormal distribution.

The uncertainty ranges associated with the disposal of grass, leaves, branches, and food scraps were bound at 50 percent to 150 percent of the inventory estimates. The half-life of grass was assumed to range from 1 to 15 years, the half-life of food scraps was assumed to range from 1 to 20 years, the half-life of leaves was assumed to range from 2 to 30 years, and the half life of branches was assumed to range from 5 to 50 years. Finally, the proportion of C stored in grass, leaves, branches, and food scraps was assumed to vary plus or minus 20 percent from the best estimate, with a uniform distribution. The proportion of C stored in food scraps was truncated at a lower bound of 2 percent.

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 7-46. Total yard trimmings and food scraps CO_2 flux in 2006 was estimated to be between -19.1 and -5.8 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 41 percent above the 2006 flux estimate of -9.8 Tg CO_2 Eq.

Table 7-46: Tier 2 Quantitative Uncertainty Estimates for CO_2 Flux from Yard Trimmings and Food Scraps in Landfills (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	(9.8)	(19.1)	(5.8)	-94%	+41%

[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.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation.

Recalculations Discussion

The half lives of branches and food scraps were updated to be consistent with recommended values for food scraps and woody materials provided in IPCC (2006) for analyzing landfill CH_4.

The current inventory uses detailed unpublished backup data (Schneider 2007) for some years not previously shown in the MSW Facts and Figures reports (EPA 1999, 2003, 2005, 2005a, 2006, 2007). This data included updated generation, materials recovery, composting, combustion, and discard data for 1960, 1970, 1980, and 1990 through 2005. This newly available data allowed several previous interpolations to be replaced with the complete time series of data used to create the MSW Facts and Figures reports (EPA 1999, 2003, 2005, 2005a, 2006).

These changes resulted in a 1 percent increase in stocks over the previous inventory, and a 5 percent change in the stocks for 2005.

Planned Improvements

Future work may evaluate the potential contribution of inorganic C, primarily in the form of carbonates, 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.

To Be Inserted

Figure 7-1. Regional variation in area of Forest Land, Cropland, Grassland, Wetlands and Settlements within the United States during 2006 (million hectares)

To Be Inserted

Figure 7-2: Forest Sector Carbon Pools and Flows

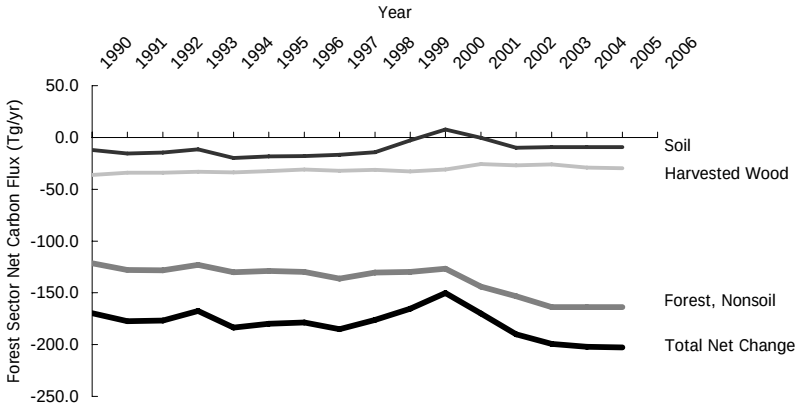

Figure 7-3: Estimates of Net Annual Changes in Carbon Stocks for Major Carbon Pools

To Be Inserted

Figure 7-4: Average C Density in the Forest Tree Pool in the Conterminous United States During 2006

To Be Inserted

Figure 7-5: Net C Stock Change for Mineral Soils in *Cropland Remaining Cropland*, 2006

To Be Inserted

Figure 7-6: Net C Stock Change for Organic Soils in *Cropland Remaining Cropland*, 2006

To Be Inserted

Figure 7-7: Net C Stock Change for Mineral Soils in *Land Converted to Cropland*, 2006

To Be Inserted

Figure 7-8: Net C Stock Change for Organic Soils in *Land Converted to Cropland*, 2006

To Be Inserted

Figure 7-9: Net Soil C Stock Change for Mineral Soils in *Grassland Remaining Grassland*, 2006

To Be Inserted

Figure 7-10: Net Soil C Stock Change for Organic Soils in *Grassland Remaining Grassland*, 2006

To Be Inserted

Figure 7-11: Net Soil C Stock Change for Mineral Soils in *Land Converted to Grassland*, 2006

To Be Inserted

Figure 7-12: Net Soil C Stock Change for Organic Soils in *Land Converted to Grassland*, 2006

8. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 8-1). Landfills accounted for approximately 23 percent of total U.S. anthropogenic methane (CH_4) emissions in 2006,[1] the second largest contribution of any CH_4 source in the United States. Additionally, wastewater treatment and composting of organic waste accounted for approximately 4 percent and less than 1 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions from the discharge of wastewater treatment effluents into aquatic environments were estimated, as were N_2O emissions from the treatment process itself. N_2O emissions from composting were also estimated. Together, these waste activities account for less than 2 percent of total U.S. N_2O emissions. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are emitted by waste activities, and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 8-1 and Table 8-2.

Figure 8-1: 2006 Waste Chapter Greenhouse Gas Sources

Overall, in 2006, waste activities generated emissions of 161.2 Tg CO_2 Eq., or just over 2 percent of total U.S. greenhouse gas emissions.

Table 8-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH_4	**172.9**	**169.1**	**146.7**	**143.0**	**145.5**	**151.0**	**148.1**	**149.0**	**151.3**
Landfills	149.6	144.0	120.8	117.6	120.1	125.6	122.6	123.7	125.7
Wastewater Treatment	23.0	24.3	24.6	24.2	24.1	23.9	24.0	23.8	23.9
Composting	0.3	0.7	1.3	1.3	1.3	1.5	1.6	1.6	1.6
N_2O	**6.6**	**7.7**	**8.9**	**9.2**	**9.0**	**9.3**	**9.6**	**9.7**	**10.0**
Domestic Wastewater Treatment	6.3	6.9	7.6	7.8	7.6	7.7	7.8	8.0	8.1
Composting	0.4	0.8	1.4	1.4	1.4	1.6	1.7	1.7	1.8
Total	**179.6**	**176.8**	**155.6**	**152.1**	**154.5**	**160.3**	**157.7**	**158.7**	**161.2**

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	2006
CH_4	**8,235**	**8,052**	**6,983**	**6,808**	**6,928**	**7,190**	**7,053**	**7,096**	**7,202**
Landfills	7,124	6,859	5,751	5,598	5,720	5,981	5,838	5,890	5,985
Wastewater Treatment	1,096	1,158	1,173	1,150	1,148	1,140	1,141	1,131	1,136
Composting	15	35	60	60	61	69	74	75	75
N_2O	**21**	**25**	**29**	**30**	**29**	**30**	**31**	**31**	**32**
Domestic Wastewater Treatment	20	22	24	25	25	25	25	26	26
Composting	1	3	4	5	5	5	6	6	6

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.

8.1. Landfills (IPCC Source Category 6A1)

In 2006, landfill CH_4 emissions were approximately 125.7 Tg CO_2 Eq. (5,985 Gg of CH_4), representing the second largest source of CH_4 emissions in the United States, behind enteric fermentation. 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 88 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 or longer.

From 1990 to 2006, net CH_4 emissions from landfills decreased by approximately 16 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 CH_4 generation 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 waste in MSW landfills, which is related to total waste landfilled annually; (2) the characteristics of landfills receiving waste (i.e., composition of waste-in-place, size, climate); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized in landfills instead of being released into the atmosphere. The estimated annual quantity of waste placed in MSW landfills increased from about 209 Tg in 1990 to 307 Tg in 2006, an increase of 47 percent (see Annex 3.14). During this period, the estimated CH_4 recovered and combusted from MSW landfills increased as well. In 1990, for example, approximately 888 Gg of CH_4 were recovered and combusted (i.e., used for energy or flared) from landfills, while in 2006, 5,958 Gg CH_4 was combusted. In 2006, an estimated 26 new landfill gas-to-energy (LFGTE) projects and 41 new flares began operation, resulting in a 4.4 percent increase in the quantity of CH_4 recovered and combusted from 2005 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 continue to increase as a result of 1996 federal regulations that require large municipal solid waste landfills to collect and combust landfill gas (see 40 CFR Part 60, Subpart Cc 2005 and 40 CFR Part 60, Subpart WWW 2005), voluntary programs encouraging CH_4 recovery and use such as EPA's Landfill Methane Outreach Program (LMOP), and federal and state incentives that promote renewable energy (e.g. tax credits, low interest loans, and Renewable Portfolio Standards).

Table 8-3: CH_4 Emissions from Landfills (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
MSW Landfills	172.6	191.8	206.9	211.4	225.8	225.8	233.7	241.2	248.6

[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.

Industrial Landfills	12.3	13.6	15.2	15.5	15.8	15.8	16.0	16.1	16.2
Recovered									
Gas-to-Energy	(13.6)	(23.4)	(51.3)	(56.1)	(57.2)	(57.2)	(60.6)	(62.2)	(65.3)
Flared	(5.1)	(22.0)	(36.7)	(40.3)	(44.9)	(44.9)	(52.7)	(57.7)	(59.8)
Oxidized[a]	(16.6)	(16.0)	(13.4)	(13.1)	(14.0)	(14.0)	(13.6)	(13.7)	(14.0)
Total	**149.6**	**144.0**	**120.8**	**117.6**	**120.1**	**125.6**	**122.6**	**123.7**	**125.7**

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**	**2006**
MSW Landfills	8,219	9,132	9,854	10,068	10,367	10,754	11,127	11,486	11,838
Industrial Landfills	585	649	725	739	746	754	760	760	770
Recovered									
Gas-to-Energy	(646)	(1,113)	(2,441)	(2,670)	(2,721)	(2,723)	(2,888)	(2,961)	(3,110)
Flared	(242)	(1,047)	(1,747)	(1,917)	(2,037)	(2,140)	(2,512)	(2,748)	(2,848)
Oxidized[a]	(792)	(762)	(639)	(622)	(636)	(665)	(649)	(654)	(665)
Total	**7,124**	**6,859**	**5,751**	**5,598**	**5,720**	**5,981**	**5,838**	**5,890**	**5,985**

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.
[a] Includes oxidation at municipal and industrial landfills.

Methodology

A detailed description of the methodology used to estimate CH_4 emissions from landfills can be found in Annex 3.14.

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
$CH_{4,MSW}$ = CH_4 generation from municipal solid waste landfills,
$CH_{4,ind}$ = 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 2006 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 (2007) 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. For calculations in this inventory, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in landfills (MCF of 1) and those disposed in dumps (MCF of 0.6). Please see the Recalculations Discussion section and Annex 3.14 for more details.

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 2007), and a database maintained by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007). The three databases were carefully compared to identify landfills that were in two or all three of the databases to avoid double-counting reductions. Based on the information provided by the EIA and flare vendor databases, the CH_4 combusted by flares in operation from 1990 to 2006 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. As over 99 percent of the organic waste placed in industrial landfills originated from the food processing (meat, vegetables, fruits) and pulp and paper industries, estimates of industrial landfill emissions focused on these two sectors (EPA 1993). The amount of CH_4 oxidized by the landfill cover at both municipal and industrial landfills was assumed to be ten percent of the CH_4 generated that is not recovered (IPCC 2006, Mancinelli and McKay 1985, Czepiel et al. 1996). To calculate net CH_4 emissions, both CH_4 recovered and CH_4 oxidized were subtracted from CH_4 generated at municipal and industrial landfills.

Uncertainty

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. Furthermore, the 2006 IPCC Guidelines (IPCC 2006) did not include a methodology for estimating N_2O emissions from solid waste disposal sites "because they are not significant." Therefore, any uncertainty or bias caused by not including N_2O emissions from landfills is expected to be minimal.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 8-5. Landfill CH_4 emissions in 2006 were estimated to be between 74.7 and 168.5 Tg CO_2 Eq., which indicates a range of 41 percent below to 34 percent above the 2006 emission estimate of 127.5 Tg CO_2 Eq.

Table 8-5. Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (Tg CO_2 Eq. and Percent)

Source	Gas	2006 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	125.7	74.7	168.5	-41%	+34%

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

Recalculations Discussion

In developing the 1990 to 2006 inventory, the proportion of waste disposed of in managed landfills versus open dumps prior to 1980 was re-evaluated. Based on the historical data presented by Minz et al. (2003), a timeline was developed for the transition from the use of open dumps for solid waste disposed to the use of managed landfills. Based on this timeline, 6 percent of the waste that was land disposed in 1940 was disposed of in managed landfills and 94 percent was managed in open dumps. Between 1940 and 1980, the fraction of waste land disposed transitioned towards managed landfills until 100 percent of the waste was disposed of in managed landfills in 1980. Although this timeline was based primarily on information about MSW disposal, a similar trend in disposal practices was expected for industrial landfills; therefore, this same time line was applied to the industrial landfills. For wastes disposed of in dumps, a methane correction factor (MCF) of 0.6 was used based on the recommended IPCC default value for uncharacterized land disposal (IPCC 2006); this MCF is equivalent to assuming 50 percent of the open dumps are deep and 50 percent are shallow. The recommended IPCC default value for the MCF for managed landfills of 1 was used for the managed landfills (IPCC 2006). This recalculation reduced the MSW landfill CH_4 generation rate for the 1990 to 2005 time series by 5.6 percent, and it reduced the industrial landfill CH_4 generation rate for the 1990 to 2005 time series by 1.8 percent.

Another significant recalculation, which affected estimates of CH_4 recovery, was associated with updating the EIA, LMOP, and flare vendor databases. The estimates of gas recovery by LFGTE projects for 1990 to 2005 increased because more landfills with operational gas recovery projects were identified and included in the LFGTE database. However, many of these LFGTE projects did not have a corresponding flare in the flare vendor database. The gas recovery and combustion estimates from the flare database were adjusted by deducting the recovery and combustion estimates associated with these LFGTE projects with unmatched flares from the flare combustion totals. This results in a decrease in the estimates for flaring. For the 1990 to 2005 time series, the recalculation resulted in an average increase of 1.4 percent in the amount of CH_4 recovered and destroyed by gas-to-energy projects and a net decrease of 0.5 percent in the estimated CH_4 emissions.

Overall, these recalculations resulted in an average decrease of 7.8 percent in emissions across the time series relative to the previous inventory.

Planned Improvements

For future inventories, additional efforts will be made to improve the estimates of the amount of waste placed in MSW landfills. Improvements to the flare database will be investigated, and an effort will be made to identify additional landfills that have flares.

[Begin Text Box]

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).

[End Box]

8.2. Wastewater Treatment (IPCC Source Category 6B)

Wastewater treatment processes can produce anthropogenic CH_4 and N_2O emissions. Wastewater from domestic (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,[4] 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 2007b).

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

[4]Package plants are treatment plants assembled in a factory, skid mounted, and transported to the treatment site.

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 2006, CH_4 emissions from domestic wastewater treatment were 16.0 Tg CO_2 Eq. (762 Gg). Emissions gradually increased from 1990 through 1997, but have decreased since 1998 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 2006, CH_4 emissions from industrial wastewater treatment were estimated to be 7.9 Tg CO_2 Eq. (374 Gg). Industrial emission sources have increased across the time series through 1999 and then fluctuated up and down in keeping with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, and starch-based ethanol production industries.[5] 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 2006 emissions of N_2O from centralized wastewater treatment processes and from effluent were estimated to be 0.3 Tg CO_2 Eq. (1 Gg) and 7.8 Tg CO_2 Eq. (25 Gg), respectively. Total N_2O emissions from domestic wastewater were estimated to be 8.1 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.

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	2006
CH_4	**23.0**	**24.3**	**24.6**	**24.2**	**24.1**	**23.9**	**24.0**	**23.8**	**23.9**
Domestic	16.4	16.9	16.8	16.6	16.5	16.4	16.3	16.2	16.0
Industrial*	6.6	7.4	7.8	7.5	7.6	7.6	7.7	7.6	7.9
N_2O	**6.3**	**6.9**	**7.6**	**7.8**	**7.6**	**7.7**	**7.8**	**8.0**	**8.1**
Domestic	6.3	6.9	7.6	7.8	7.6	7.7	7.8	8.0	8.1
Total	**29.3**	**31.2**	**32.2**	**32.0**	**31.7**	**31.6**	**31.8**	**31.8**	**32.0**

* Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, and starch-based ethanol production 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	2006
CH_4	**1,096**	**1,158**	**1,173**	**1,150**	**1,148**	**1,140**	**1,141**	**1,131**	**1,136**
Domestic	782	804	802	792	786	780	775	770	762
Industrial*	314	355	371	358	362	360	366	361	374
N_2O	**20**	**22**	**24**	**25**	**25**	**25**	**25**	**26**	**26**
Domestic	20	22	24	25	25	25	25	26	26

* Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, and starch-based ethanol production industries.
Note: Totals may not sum due to independent rounding.

[5] Other industrial sectors include organic chemicals, starch production, alcohol refining, creameries, and textiles; however, emissions from these sectors are considered to be insignificant.

Methodology

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems, such as publicly owned treatment works (POTWs). Within these centralized systems, CH_4 emissions can arise from aerobic systems that are not well managed, 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 relative percentage of wastewater facilities with primary treatment, the percentage of BOD_5 treated after primary treatment (67.5 percent), the maximum CH_4-producing capacity of domestic wastewater (0.6), and the relative MCFs for aerobic (zero or 0.3) and anaerobic (0.8) systems. 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 (0.65), the density of CH_4 (662 g CH_4/m^3 CH_4), and the destruction efficiency associated with burning the biogas in an energy/thermal device (0.99)[6] 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) × (% aerobic w/out primary) + (% collected) × (total BOD_5 produced) × (% aerobic) × (% aerobic w/primary) × (1-% BOD removed in prim. treat.)] × (% operations not well managed) × (B_o) × (MCF-aerobic_not_well_man) × 1/10^6

Emissions from Centrally Treated Anaerobic Systems = C
= [(% collected) × (total BOD_5 produced) × (% anaerobic) × (% anaerobic w/out primary) + (% collected) × (total BOD_5 produced) × (% anaerobic) × (% anaerobic w/primary) × (1-%BOD removed in prim. treat.)] × (B_o) × (MCF-anaerobic) × 1/10^6

Emissions from Anaerobic Digesters = D
= [(POTW_flow_AD) × (digester gas)/ (per capita flow)] × conversion to m^3 × (FRAC_CH_4) × (365.25) × (density of CH_4) × (1-DE) × 1/10^9

Total CH_4 Emissions (Gg) = A + B + C + D

Where:

% onsite =	Flow to septic systems / total flow
% collected =	Flow to POTWs / total flow
% aerobic =	Flow to aerobic systems / total flow to POTWs
% anaerobic =	Flow to anaerobic systems / total flow to POTWs
% aerobic w/out primary =	Percent of aerobic systems that do not employ primary treatment
% aerobic w/primary =	Percent of aerobic systems that emply primary treatment
% BOD removed in prim. treat. =	32.5 %
% operations not well managed =	Percent of aerobic systems that are not well managed and in which

[6] Anaerobic digesters at wastewater treatment plants generated 798 Gg CH_4 in 2006, 790 Gg of which was combusted in flares or energy devices (assuming a 99% destruction efficiency).

	Some anaerobic degradation occurs
% anaerobic w/out primary =	Percent of anaerobic systems that do not employ primary treatment
% anaerobic w/primary =	Percent of anaerobic systems that employ primary treatment
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)
conversion to m^3=	Conversion factor, ft^3 to m^3 (0.0283)
FRAC_CH_4 =	Proportion CH_4 in biogas (0.65)
density of CH_4 =	662 (g CH_4/m^3 CH_4)
1/10^9 =	Conversion factor, g to Gg

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2007a) 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 2006. The proportions of domestic wastewater treated onsite versus at centralized treatment plants were based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, and 2005 American Housing Surveys conducted by the U.S. Census Bureau (U.S. Census 2007b), 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 (EPA 1992, 1996, 2000, and 2004a).[7] Data for intervening years were obtained by linear interpolation. The BOD_5 production rate (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 MCFs were taken from IPCC (2006). The CH_4 destruction efficiency, 99 percent, was selected based on the range of efficiencies (98-100 percent) recommended for flares in *AP-42 Compilation of Air Pollutant Emission Factors, Chapter 2.4* (EPA 1998), efficiencies used to establish new source performance standards (NSPS) for landfills, and in recommendations for closed flares used by LMOP. The cubic feet of digester gas produced per person per day (1.0 ftP^3/person/day) and the proportion of CH_4 in biogas (0.65) come from Metcalf and Eddy (1991). The wastewater flow to a POTW (100 gal/person/day) was taken from the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, "Recommended Standards for Wastewater Facilities (Ten-State Standards)" (2004).

Table 8-8. U.S. Population (Millions) and Domestic Wastewater BOD_5 Produced (Gg)

Year	Population	BOD_5
1990	254	8,350
1995	271	8,895

[7] 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.

2000	287	9,419
2001	289	9,509
2002	292	9,597
2003	295	9,685
2004	297	9,774
2005	300	9,864
2006	303	9,954

Source: U.S. Census Bureau (2006a); Metcalf & Eddy 1991 and 2003.

Industrial Wastewater CH_4 Emission Estimates

CH_4 emissions estimates from industrial wastewater were developed according to the methodology described in IPCC (2006). Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified. High volumes of wastewater generated and a high organic wastewater load were the main criteria. The top four industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; and starch-based ethanol production. Table 8-9 contains production data for these industries.

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	Ethanol
1990	128.9	27.3	14.6	38.7	2.7
1995	140.9	30.8	18.9	46.9	4.2
2000	142.8	32.1	22.2	50.9	4.9
2001	134.3	31.6	22.8	45.0	5.3
2002	132.7	32.7	23.5	47.7	6.4
2003	131.9	32.3	23.7	44.8	8.4
2004	136.4	31.2	24.4	47.8	10.2
2005	131.4	31.4	25.1	43.3	11.7
2006	137.4	32.5	25.5	42.6	14.5

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 EPA (1997a) and used to estimate COD loadings. The B_o value used for all industries is the IPCC default value of 0.25 kg CH_4/kg COD (IPCC 2006). 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 CH_4 emissions from industrial wastewater (kg/year)
P	= Industry output (metric tons/year)
W	= Wastewater generated (m^3/metric ton of product)
COD	= Organics loading in wastewater (kg /m^3)
TA	= Percent of wastewater treated anaerobically on site
B_o	= Maximum CH_4 producing potential of industrial wastewater (default value of 0.25 kg CH_4/kg COD)
MCF	= CH_4 correction factor, indicating the extent to which the organic content (measured as COD) degrades anaerobically

Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation,

and flotation/hydrocycloning to remove solids (World Bank 1999, Nemerow and Dasgupta 1991). Secondary treatment (storage, settling, and biological treatment) mainly consists of lagooning. In determining the percent that degrades anaerobically, both primary and secondary treatment were considered. In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993b). The vast majority of pulp and paper mills with on-site treatment systems use mechanical clarifiers to remove suspended solids from the wastewater. About 10 percent of pulp and paper mills with treatment systems use settling ponds for primary treatment and these are more likely to be located at mills that do not perform secondary treatment (EPA 1993b). However, because the vast majority of primary treatment operations at U.S. pulp and paper mills use mechanical clarifiers, and less than 10 percent of pulp and paper wastewater is managed in primary settling ponds that are not expected to have anaerobic conditions, negligible emissions are assumed to occur during primary treatment.

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. No anaerobic activity is assumed to occur in activated sludge systems or aerated stabilization basins (note: although IPCC recognizes that some CH_4 can be emitted from anaerobic pockets, they recommend an MCF of zero). However, about 25 percent of the wastewater treatment systems used in the United States are non-aerated stabilization basins. These basins are typically 10 to 25 feet deep. These systems are classified as anaerobic deep lagoons (MCF = 0.8). Therefore, the pulp and paper CH_4 emission calculation is:

$$\text{Methane} = \text{Production} \times \text{Flow} \times \text{BOD} \times 42\% \times \text{COD:BOD Ratio} \times \%\text{TA} \times \text{Bo} \times \text{MCF}$$

Where:

Production	= metric tons of pulp, paper, and paperboard production
Flow	= cubic meters of wastewater generated per ton production
BOD	= BOD concentration in influent (4000 mg/L)
42%	= Percent of BOD entering secondary treatment
COD:BOD	= COD to BOD ratio (for pulp and paper, COD:BOD = 2)
%TA	= estimated percent of wastewater treated anaerobically on site (25%)
Bo	= maximum methane producing capacity (0.25 mg CH4/mg COD)
MCF	= methane conversion factor for anaerobic deep lagoons (0.80)

A time series of CH_4 emissions for 1990 through 2001 was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post 2002). Published data from the American Forest and Paper Association, data published by Paper Loop, and other published statistics were used to estimate production for 2002 through 2006 (Pulp and Paper 2005, 2006 and monthly reports from 2003 through 2006; Paper 360◦ 2007). The overall wastewater outflow was estimated to be 85 m^3/metric ton, and the average BOD concentrations in raw wastewater was estimated to be 0.4 gram BOD/liter (EPA 1997b, EPA 1993b, 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 2007a). Data collected by EPA's Office of Water provided estimates for wastewater flows into anaerobic lagoons: 5.3 and 12.5 mP^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. The IPCC default B_o of 0.25 kg COD/kg CH_4 and default MCF of 0.8 for anaerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems. The USDA National Agricultural Statistics Service (USDA 2007a) 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 EPA (1975) 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	8.86	0.813
Fruit		
Apples	3.66	1.371
Citrus	10.11	0.317
Non-citrus	12.42	1.204
Grapes (for wine)	2.783	1.831

Ethanol, or ethyl alcohol, is produced primarily for use as a fuel component, but is also used in industrial applications and in the manufacture of beverage alcohol. Ethanol can be produced from the fermentation of sugar-based feedstocks (e.g., molasses and beets), starch- or grain-based feedstocks (e.g., corn, sorghum, and beverage waste), and cellulosic biomass feedstocks (e.g., agricultural wastes, wood, and bagasse). Ethanol can also be produced synthetically from ethylene or hydrogen and carbon monoxide. However, synthetic ethanol comprises only about 2 percent of ethanol production, and although the Department of Energy predicts cellulosic ethanol to greatly increase in the coming years, currently it is only in an experimental stage in the United States. According to the Renewable Fuels Association, 82 percent of ethanol production facilities use corn as the sole feedstock and 7 percent of facilities use a combination of corn and another starch-based feedstock. The fermentation of corn is the principal ethanol production process in the United States and is expected to increase for at least the next 6 years, and potentially more; therefore, emissions associated with wastewater treatment at starch-based ethanol production facilities were estimated (ERG 2006).

Ethanol is produced from corn (or other starch-based feedstocks) primarily by two methods: wet milling and dry milling. Historically, the majority of ethanol was produced by the wet milling process, but now the majority is produced by the dry milling process. The wastewater generated at ethanol production facilities is handled in a variety of ways. Dry milling facilities often combine the resulting evaporator condensate with other process wastewaters, such as equipment wash water, scrubber water, and boiler blowdown and anaerobically treat this wastewater using various types of digesters. Wet milling facilities often treat their steepwater condensate in anaerobic systems followed by aerobic polishing systems. Wet milling facilities may treat the stillage (or processed stillage) from the ethanol fermentation/distillation process separately or together with steepwater and/or wash water. CH_4 generated in anaerobic digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006).

Available information was compiled from the industry on wastewater generation rates, which ranged from 1.25 gallon per gallon ethanol produced (for dry milling) to 10 gallons per gallon ethanol produced (for wet milling) (Ruocco 2006a,b; Merrick 1998; Donovan 1996; and NRBP 2001). COD concentrations were also found to be about 3 g/L (Ruocco 2006a; Merrick 1998; White and Johnson 2003). The amount of wastewater treated anaerobically was estimated, along with how much of the methane is recovered through the use of biomethanators (ERG 2006). CH_4 emissions were then estimated as follows:

$$\text{Methane} = [\text{Production} \times \text{Flow} \times \text{COD} \times \%\ \text{TA} \times \text{Bo} \times \text{MCF} \times \%\ \text{Not Recovered}] + [\text{COD} \times \%\text{TA} \times \text{Bo} \times \text{MCF} \times (\%\ \text{Recovered}) \times (1\text{-DE})]$$

Where:

Production	= million gallons ethanol produced
Flow	= gallons wastewater generated per gallon ethanol produced (1.25 dry milling, 10 wet milling)
COD	= COD concentration in influent (3 g/l)
% TA	= percent of wastewater treated anaerobically (for dry milling operations, this value is estimated separately for facilities using biomethanators with 100% recovery and facilities using other anaerobic systems)
Bo	= maximum methane producing capacity (0.25 mg CH4/mg COD)
MCF	= methane conversion factor (0.8 for anaerobic systems)
% Recovered	= percent of wastewater treated in system with emission recovery
% Not Recovered	= 1 - percent of wastewater treated in system with emission recovery
DE	= destruction efficiency of recovery system (99%)

A time series of CH_4 emissions for 1990 through 2006 was developed based on production data from the Renewable Fuels Association (RFA 2006).

Domestic Wastewater N_2O Emission Estimates

N_2O emissions from domestic wastewater (wastewater treatment) were estimated using the IPCC (2006) methodology, including calculations that take into account N removal with sewage sludge, non-consumption and industrial 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.[8]
- 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.[9] Furthermore, a significant quantity of industrial wastewater (N) is co-discharged with domestic wastewater. To account for this, a factor of 1.25 is used.[10]
- 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 intentional nitrification and denitrification (Scheehle and Doorn 2001) Analysis of the 2000 CWNS shows there are 88 treatment plants in the United States, serving a population of 2.6 million people, 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 analyses were completed for each year in the Inventory using data from CWNS on the amount of wastewater in centralized systems treated in denitrification units. Plants without intentional nitrification/denitrification are

[8] The methodology for estimating the quantity of sewage sludge N not entering aquatic environments is described in Annex 3.11

[9] 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.

[10] 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).

assumed to generate 3.2 grams N_2O per capita per year.

With the modifications described above, N_2O emissions from domestic wastewater were estimated using the following methodology:

$$N_2O_{TOTAL} = N_2O_{PLANT} + N_2O_{EFFLUENT}$$

$$N_2O_{PLANT} = N_2O_{NIT/DENIT} + N_2O_{WOUT\ NIT/DENIT}$$

$$N_2O_{NIT/DENIT} = [(US_{POPND}) \times EF_2 \times F_{IND\text{-}COM}] \times 1/10^9$$

$$N_2O_{WOUT\ NIT/DENIT} = \{[(US_{POP} \times WWTP) - US_{POPND} \times F_{IND\text{-}COM}] \times EF_1\} \times 1/10^9$$

$$N_2O_{EFFLUENT} = \{[(US_{POP} \times Protein \times F_{NPR} \times F_{NON\text{-}CON} \times F_{IND\text{-}COM}) - N_{SLUDGE}] \times EF_3 \times 44/28\} \times 1/10^6$$

where,

N_2O_{TOTAL} =	Annual emissions of N_2O (kg)
N_2O_{PLANT} =	N_2O emissions from centralized wastewater treatment plants (kg)
$N_2O_{NIT/DENIT}$ =	N_2O emissions from centralized wastewater treatment plants with nitrification/denitrification (kg)
$N_2O_{WOUT\ NIT/DENIT}$ =	N_2O emissions from centralized wastewater treatment plants without nitrification/denitrification (kg)
$N_2O_{EFFLUENT}$ =	N_2O emissions from wastewater effluent discharged to aquatic environments (kg)
US_{POP} =	U.S. population
US_{POPND} =	U.S. population that is served by biological denitrification (from CWNS)
WWTP =	Fraction of population using WWTP (as opposed to septic systems)
EF_1 =	Emission factor (3.2 g N_2O/person-year)
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 (1.4)
$F_{IND\text{-}COM}$ =	Factor for industrial and commercial co-discharged protein into the sewer system (1.25)
N_{SLUDGE} =	N removed with sludge, kg N/yr
EF_3 =	Emission factor (0.005 kg N_2O -N/kg sewage-N produced)
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 2007a) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. The fraction of the U.S. population using wastewater treatment plants is based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, and 2005 American Housing Survey (U.S. Census 2007b). Data for intervening years were obtained by linear interpolation. The emission factor (EF_1) to estimate emissions from wastewater treatment was taken from IPCC (2006). Data on annual per capita protein intake were provided by U.S. Department of Agriculture Economic Research Service (ERS 2006b). Protein consumption data for 2005 and 2006 were extrapolated from data for 1990 through 2004. 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 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). Sludge generation was obtained from EPA (1999) for 1988, 1996, and 1998 and from Beecher et al. (2007) for 2004. Intervening years were interpolated, and estimates for 2005 and 2006 were forecasted from the rest of the time series. 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. In 2006, 263 Tg N was removed with sludge.

Table 8-11. U.S. Population (Millions) and Average Protein Intake [kg/(person-year)]

Year	Population	Protein
1990	254	38.7

1995	271	39.8
2000	287	41.3
2001	289	42.0
2002	292	40.9
2003	295	40.9
2004	297	41.3
2005	300	41.7
2006	303	41.9

Source: U.S. Census Bureau 2006a, USDA ERS 2006b.

Uncertainty

The overall uncertainty associated with both the 2006 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 include that of numerous input variables used to model emissions from domestic wastewater, and wastewater from pulp and paper manufacture, meat and poultry processing, fruits and vegetable processing, and ethanol production. Uncertainty associated with the parameters used to estimate N_2O emissions include that of sewage sludge disposal, total U.S. population, average protein consumed per person, fraction of N in protein, non-consumption nitrogen factor, emission factors per capita and per mass of sewage-N, and for the percentage of total population using centralized wastewater treatment plants.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 8-12. CH_4 emissions from wastewater treatment were estimated to be between 15.0 and 35.2 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 37 percent below to 48 percent above the 2006 emissions estimate of 23.9 Tg CO_2 Eq. N_2O emissions from wastewater treatment were estimated to be between 1.8 and 16.4 Tg CO_2 Eq., which indicates a range of approximately 78 percent below to 101 percent above the actual 2006 emissions estimate of 8.1 Tg CO_2 Eq.

Table 8-12. Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Wastewater Treatment (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2006 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**	**23.9**	**15.0**	**35.2**	**-37%**	**+48%**
Domestic	CH_4	16.0	7.9	26.6	-51%	+66%
Industrial	CH_4	7.9	4.5	12.8	-43%	+62%
Domestic Wastewater Treatment	**N_2O**	**8.1**	**1.8**	**16.2**	**-78%**	**+100%**

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

Recalculations Discussion

The 2006 estimates for CH_4 emissions from domestic wastewater include one major methodological refinement and one major data change. First, for centralized wastewater treatment systems, CH_4 emissions were estimated based on the total BOD_5 available for biological treatment rather than the total BOD_5 entering wastewater treatment plants. Metcalf and Eddy (1991) estimate that 25-40 percent of BOD_5 at aerobic and anaerobic plants is removed through primary sedimentation, meaning that not all of the BOD_5 entering treatment plants has the potential to generate methane during biological treatment. This change resulted in a decrease of methane emissions from centrally treated

anaerobic systems of 20 percent, and an overall reduction in methane emissions of 4.5 to 5.5 percent. The major data adjustment for the current inventory estimates involved the adjustment of the 1995 AHS data (US Census Bureau 2007b) that indicates the percent of wastewater treated onsite versus the percent collected. The previous Inventory indicated a total percent of wastewater treated onsite and collected of 97.6 percent for 1995, while all other years had a total of approximately 99.5 percent. Reevaluation of the 1995 AHS data resulted in an updated total percent of 99.5 percent.

For industrial wastewater, the 2006 estimates include a change in calculation methodology for pulp and paper, and the inclusion of wastewater emissions from U.S. starch-based ethanol production. First, the types of primary treatment in place at pulp and paper operations were evaluated and it was concluded that due to the majority of operations using mechanical clarifiers, negligible emissions of CH_4 occur during primary treatment. The estimate of BOD treated anaerobically during secondary treatment was also updated based on the number of operations expected to have non-aerated stabilization basins. These systems were reclassified as anaerobic deep lagoons, and CH_4 emissions were revised. These changes resulted in a decrease in emissions from pulp and paper wastewater treatment of 18.5 percent across the time series.

Next, emissions associated with ethanol production were estimated, as described earlier. The addition of this industrial sector increased industrial wastewater emission estimates by 0.4 to 0.9 percent across the time series.

Flow and BOD data for fruits and vegetable processing wastewater were updated to reflect commodity-specific data, which had minimal impact on the emissions. Overall, the CH_4 emission estimates for wastewater treatment are on average 6 percent lower than the previous inventory.

For N_2O emissions from domestic wastewater, one major data source adjustment was made along with two minor changes to account for co-discharged industrial and commercial wastewater and to update the values used for the nitrogen composition of sludge. The 2006 estimates utilize protein consumption data from the U.S. Department of Agriculture Economic Research Service (USDA 2006b). The previous inventory report used UN FAO protein consumption data. The protein data changed on average approximately one percent for each year in the timeseries. The 2006 estimates also apply a factor for co-discharged industrial and commercial wastewater to the emission factors for direct N_2O emissions from centralized wastewater treatment plants. This resulted in a N_2O emission factor from centralized treatment plants that have intentional nitrification/denitrification unit operations of 8.75 g N_2O/person-year (7 g N_2O/person-year × 1.25) and a N_2O emission factor from centralized wastewater treatment plants that do not have intentional nitrification/denitrification unit operations of 4 g N_2O/person-year (3.2 g N_2O/person-year × 1.25). In addition, the nitrogen composition of sludge was updated to 3.9 percent, representing an average nitrogen composition, rather than the previous value of 3.3 percent which represented a median value. The sludge generation estimates across the time series changed slightly based on the inclusion of a new reference for sludge generation in 2004.

Overall, emissions from wastewater treatment and discharge (CH_4 and N_2O) decreased by an average of approximately 5 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 reflecting emissions from various types of municipal treatment systems are currently being pursued.

Available data on wastewater treatment emissions at petroleum refineries will be reviewed to determine if this is a significant source to be included in future versions of the inventory.

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 there is uncertainty associated with the N_2O emission factors for direct emissions from centralized wastewater treatment facilities. Efforts to gain greater confidence in these emission factors are currently being pursued.

8.3. Composting (IPCC Source Category 6D)

Composting of organic waste, such as food waste, garden (yard) and park waste and sludge, is common in the United States. Advantages of composting include reduced volume in the waste material, stabilization of the waste, and destruction of pathogens in the waste material. The end products of composting, depending on its quality, can be recycled as fertilizer and soil amendment, or be disposed in a landfill.

Composting is an aerobic process and a large fraction of the degradable organic carbon in the waste material is converted into carbon dioxide (CO_2). Methane (CH_4) is formed in anaerobic sections of the compost, but it is oxidized to a large extent in the aerobic sections of the compost. Anaerobic sections are created in composting piles when there is excessive moisture or inadequate aeration (or mixing) of the compost pile. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few per cent of the initial carbon content in the material (IPCC 2006). Composting can also produce emissions of nitrous oxide (N_2O). The range of the estimated emissions varies from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006).

From 1990 to 2006, the amount of material composted in the United States has increased from 3,810 Gg to 18,852 Gg, an increase of almost 400 percent. Emissions of CH_4 and N_2O from composting have increased by the same percentage (see Table 8-13 and Table 8-14). In 2006, CH_4 emissions from composting were 1.6 Tg CO_2 Eq. (75 Gg), and N_2O emissions from composting were 1.8 Tg CO_2 Eq. (6 Gg). The wastes that are composted include primarily yard trimmings (grass, leaves, tree and brush trimmings) and food scraps from residences and commercial establishments (such as grocery stores, restaurants, and school and factory cafeterias). The composting waste quantities reported here do not include backyard composting. The growth in composting is attributable primarily to two factors: (1) steady growth in population and residential housing and (2) state and local governments started enacting legislation that discouraged the disposal of yard trimmings in landfills. In 1992, 11 states and the District of Columbia had legislation in effect that banned or discouraged disposal of yard trimmings in landfills. In 2005, 21 states and the District of Columbia, representing about 50 percent of the nation's population, had enacted such legislation (EPA 2006).

Table 8-13: CH_4 and N_2O Emissions from Composting (Tg CO_2 Eq.)

Activity	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
CH_4	0.3	0.7	1.3	1.3	1.3	1.5	1.6	1.6	1.6
N_2O	0.4	0.8	1.4	1.4	1.4	1.6	1.7	1.7	1.8
Total	**0.7**	**1.5**	**2.6**	**2.7**	**2.7**	**3.1**	**3.3**	**3.3**	**3.3**

Table 8-14: CH_4 and N_2O Emissions from Composting (Gg)

Activity	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
CH_4	15	35	60	60	61	69	74	75	75
N_2O	1	3	4	5	5	5	6	6	6

Methodology

CH_4 and N_2O emissions from composting depend on factors such as the type of waste composted, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content and aeration during the process.

The emissions shown in Table 8-13 and Table 8-14 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006), which is the product of an emission factor and the mass of organic waste composted (note: no CH_4 recovery is expected to occur at composting operations):

$$E_i = M \times EF_i$$

where,

E_i = CH_4 or N_2O emissions from composting, Gg CH_4 or N_2O,
M = mass of organic waste composted in Gg,
EF_i = emission factor for composting, 4 g CH_4/kg of waste treated (wet basis) and 0.3 g N_2O/kg of waste treated (wet basis), and
i = designates either CH_4 or N_2O.

Estimates of the quantity of waste composted (M) are presented in Table 8-15. Estimates of the quantity composted for 1990, 1995, 2001, and 2002 were taken from EPA's *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2003* (EPA 2005); estimates of the quantity composted for 2003 through 2005 were taken from EPA's *Municipal Solid Waste In The United States: 2005 Facts and Figures* (EPA 2006). The quantity composted estimate for 2006 was taken from the "2006 MSW Characterization Data Tables" associated with EPA's *Municipal Solid Waste In The United States: 2006 Facts and Figures* (EPA 2007).

Table 8-15: U.S. Waste Composted (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Waste Composted	3,810	8,682	14,923	15,014	15,187	17,309	18,570	18,643	18,852

Source: EPA 2005, EPA 2006, and EPA 2007.

Uncertainty

The estimated uncertainty from the 2006 IPCC Guidelines is ±50 percent for the Tier 1 methodology. Emissions from composting in 2006 were estimated to be between 1.7 and 5.0 Tg CO_2 Eq., which indicates a range of 50 percent below to 50 percent above the actual 2006 emission estimate of 3.3 Tg CO_2 Eq. (see Table 8-16).

Table 8-16 : Tier 1 Quantitative Uncertainty Estimates for Emissions from Composting (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
Composting	CH_4, N_2O	3.3	1.7	5.0	-50%	+50%

Recalculations Discussion

No recalculations were performed because this is the first year that composting has been included in the inventory.

Planned Improvements

For future inventories, additional efforts will be made to improve the estimates of CH_4 and N_2O emissions from composting. For example, a literature search may be conducted to determine if emission factors specific to various composting systems and composted materials are available.

8.4. 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 2006 are provided in Table 8-17.

Table 8-17: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
NO_x	**+**	**1**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Landfills	+	1	2	2	2	2	2	2	2
Wastewater Treatment	+	+	+	+	+	+	+	+	+
Miscellaneous[a]	+	1	+	+	+	+	+	+	+
CO	**1**	**2**	**8**	**8**	**7**	**7**	**7**	**7**	**7**
Landfills	1	2	7	7	6	6	6	6	6
Wastewater Treatment	+	+	1	1	+	+	+	+	+
Miscellaneous[a]	+	1	+	+	+	+	+	+	+
NMVOCs	**673**	**731**	**119**	**122**	**115**	**114**	**112**	**111**	**110**
Wastewater Treatment	57	61	23	23	22	22	21	21	21
Miscellaneous[a]	557	602	51	53	50	49	48	48	47
Landfills	58	68	46	46	44	43	43	42	42

[a] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.
Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.5 Gg.

Methodology

These emission estimates were obtained from preliminary data (EPA 2008), 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.

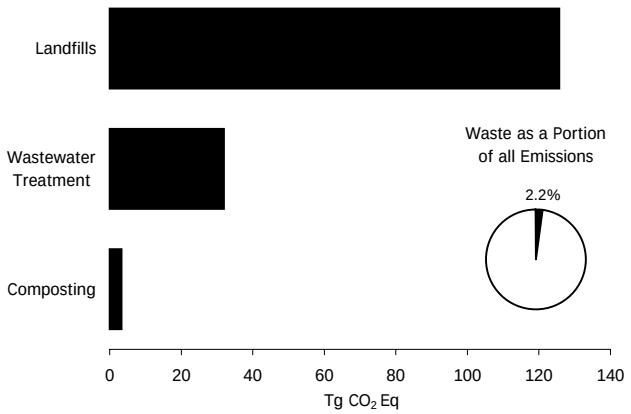

Figure 8-1: 2006 Waste Chapter Greenhouse Gas Sources

9. Other

The United States does not report any greenhouse gas emissions under the Intergovernmental Panel on Climate Change (IPCC) “Other” sector.

10. Recalculations and Improvements

Each year, emission and sink estimates are recalculated and revised for all years in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks,* as attempts are made to improve both the analyses themselves, through the use of better methods or data, and the overall usefulness of the report. In this effort, the United States follows the 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 2005 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:

- CO_2 emissions from Cropland remaining Cropland, which include CO_2 emissions from agricultural liming and urea fertilization;
- CO_2 emissions from Petroleum Systems, which account for vented, fugitive and process upset emissions sources from 29 activities for crude oil production field operations; and
- CH_4 and N_2O emissions from Composting.

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 2005) 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 2005, 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 incorporating state-level N fertilizer application data for on-farm use as opposed to regional data, revising assumptions of manure N availability for land application, and revising DAYCENT parameterization for sorghum. Overall, changes resulted in an average annual increase in N_2O emissions from Agricultural Soil Management of 67.4 Tg CO_2 Eq. (18.3 percent) for the period 1990 through 2005.
- *Net CO_2 Flux from Land Use, Land-Use Change, and Forestry*. Forest Land Remaining Forest Land is the principal section contributing to the change in net CO_2 flux from Land Use, Land-Use Change, and Forestry sector. The addition of newly available forest inventory data as well as some refinements in previously existing data were the principal factors contributing to the changes. Changes for the period 1990 through 2005, as compared to the estimates presented in the previous inventory, are based on the cumulative effects of (1) incorporating and updating state and sub-state inventory data, and (2) including a portion of Alaska forest for the first time. Minor refinements to the harvested wood product contribution included (1) shorter half-life for decay in dumps and (2) separation of decay in dumps from decay in landfills. Overall, these changes, in combination with adjustments in the other sources/sinks within the sector, resulted in an average annual increase in net flux of CO_2 to the atmosphere from the Land Use, Land-Use Change, and Forestry sector of 20.9 Tg CO_2 Eq. (2.6 percent) for the period 1990 through 2005.

- *Landfills*. For municipal solid waste landfills, changes to historical data resulted from revising the proportion of waste disposed of in managed landfills versus open dumps prior to 1980 and from using the recommended IPCC (2006) default value for uncharacterized land disposal. Additionally, Energy Information Administration, Landfill Methane Outreach Program, 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 11.4 Tg CO_2 Eq. (7.8 percent) for the period 1990 through 2005.

- *Enteric Fermentation.* Changes in the estimates of CH_4 emissions resulting from Enteric Fermentation occurred as a result of (1) modifying the Cfi coefficient based on the revised IPCC equations (IPCC 2006), (2) updating the C factor in accordance with the revised IPCC Guidelines (IPCC 2006), (3) revising the equation for net energy of growth (NEg), (4) modifying the Cattle Enteric Fermentation Model to output at the state level and include more detailed data inputs, (5) incorporating revised FAO horse population estimates for 2001 through 2005, and (6) including revised USDA estimates of swine population for 2005. Overall, changes resulted in an average annual increase in CH_4 emissions from Enteric Fermentation of 11.4 Tg CO_2 Eq. (9.9 percent) from 1990 through 2005.

- *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 decrease in hydrofluorocabon (HFC) emissions from the Substitution of Ozone Depleting Substances of 8.1 Tg CO_2 Eq. (12.6 percent) for the period 1990 through 2005.

- *Settlements Remaining Settlements.* The data source used for N fertilization was updated for N_2O Emissions from Settlement Soils. This fertilization data is based on county-scale non-farm application amounts from a USGS database. Overall, changes resulted in an average annual decrease in N_2O emissions from Settlements Remaining Settlements of 4.1 Tg CO_2 Eq. (73.9 percent) for the period 1990 through 2005.

- *Manure Management.* Several changes were made in this section. First, a major change in the N_2O emission calculations is that emissions are now calculated from the "bottom-up" such that emissions are calculated for each animal group, manure management system, and state. These values are then summed to calculate the total greenhouse gas emissions from manure management in the United States. Second, dairy heifers and beef on feed now have one WMS distribution that represents managed and unmanaged systems, and emissions are calculated for each WMS using the EF for that system, and not using a state average EF. Third, the inventory now includes indirect N_2O emissions in the manure management sector associated with N losses from volatilization of nitrogen as ammonia (NH_3), nitrogen oxides (NOx), and leaching and runoff. Fourth, the days per year used in N_2O calculations was changed from 365 to 365.25 to include leap years and to be consistent with the CH_4 inventory calculations. Fifth, changes were also made to the current calculations involving animal population data. Overall, the changes resulted in an average annual increase in N_2O emissions from Manure Management of 4.0 Tg CO_2 Eq. (43.1 percent) for the period 1990 through 2005.

- *Coal Mining.* Three changes were made across the coal mining sector. First, recalculations of emissions avoided at three JWR coal mines in Alabama were performed as the mining company reported and filed data for 1991 through 2005; data was also provided for 2006. Secondly, the gas content values assigned to each coal basin in the surface mine emissions component of the inventory were changed to reflect recent work carried out by U.S. EPA. Third, the conversion factor used to convert from mmcf of methane was updated to be consistent across the inventory. Overall, the changes resulted in an average annual increase in CH_4 emissions from Coal Mining of 3.7 Tg CO_2 Eq. (6.2 percent) for the period 1990 through 2005.

- *Ammonia Manufacture and Urea Consumption*. CO_2 emissions estimates were revised for all years to incorporate a new methodology that estimates urea production and consumption based on urea consumed as fertilizer. The new methodology allocated CO_2 emissions associated with urea applied as fertilizer to the Land Use, Land-Use Change, and Forestry chapter. Overall, the changes resulted in an average annual decrease in CO_2 emissions from Ammonia Manufacture and Urea Consumption of 3.0 Tg CO_2 Eq. (15.8 percent) for the period (1990 through 2005).

- *Wastewater Treatment.* For domestic centralized wastewater systems, CH_4 emissions were revised to be based

on the total BOD_5 entering wastewater treatment plants. Additionally, a major data change included adjusting US Census Bureau American Housing Survey data. For industrial wastewater, the 2006 estimates include a change in calculation methodology for pulp and paper, and the inclusion of wastewater emissions from U.S. starch-based ethanol production. Finally, emissions associated with ethanol production were estimated and included in this sector. Overall, the changes resulted in an average annual decrease in CH_4 emissions from Wastewater Treatment of 1.6 Tg CO_2 Eq. (6.4 percent) for the period (1990 through 2005).

Table 10-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CO_2	**5.5**	**8.1**	**(1.7)**	**1.8**	**14.5**	**18.6**	**(8.4)**	**3.9**
Fossil Fuel Combustion	+	2.4	(7.8)	(4.3)	7.6	12.4	(12.5)	0.3
Non-Energy Use of Fuels	(0.1)	+	0.4	0.5	0.5	0.4	(1.3)	(3.3)
Natural Gas Systems	+	+	+	+	+	+	(0.1)	1.3
Cement Manufacture	NC	NC	NC	NC	NC	NC	NC	NC
Lime Manufacture	0.7	1.2	1.5	1.4	1.3	1.4	1.4	1.5
Limestone and Dolomite Use	NC	NC	NC	NC	NC	NC	NC	NC
Soda Ash Manufacture and Consumption	NC	NC	NC	NC	NC	NC	NC	NC
Carbon Dioxide Consumption	+	+	+	+	+	+	+	+
Municipal Solid Waste Combustion	NC	NC	(0.4)	(0.4)	(0.1)	(0.4)	+	(0.2)
Titanium Dioxide Production	(0.1)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Aluminum Production	NC	NC	NC	NC	NC	NC	NC	+
Iron and Steel Production	NC	NC	NC	NC	NC	NC	NC	NC
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC	NC
Ammonia Manufacture and Urea Consumption	(2.4)	(2.7)	(3.2)	(3.4)	(3.6)	(3.7)	(3.7)	(3.5)
Phosphoric Acid Production	NC	NC	NC	NC	NC	NC	NC	NC
Petrochemical Production	NC	NC	NC	NC	NC	NC	NC	(0.1)
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC	NC
Lead Production	NC	NC	NC	+	+	NC	+	+
Zinc Production	NC	NC	NC	NC	NC	NC	NC	NC
Cropland Remaining Cropland[a]	7.1	7.0	7.5	7.8	8.5	8.3	7.6	7.9
Petroleum Systems[a]	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Land-Use, Land-Use Change, and Forestry (Sink)	(23.8)	54.3	83.8	17.9	(14.1)	(48.4)	(48.2)	(49.4)
International Bunker Fuels	+	+	NC	NC	NC	NC	2.7	4.9
Wood Biomass and Ethanol Consumption	+	+	(1.0)	NC	NC	(0.1)	NC	20.9
CH_4	**(0.4)**	**(0.5)**	**5.6**	**7.7**	**7.8**	**9.5**	**5.3**	**(0.3)**
Stationary Combustion	(0.6)	(0.6)	(0.7)	(0.6)	(0.6)	(0.6)	(0.6)	(0.4)
Mobile Combustion	+	+	(0.1)	0.1	(0.1)	(0.1)	(0.1)	(0.1)
Coal Mining	2.2	0.6	4.5	4.8	4.8	4.8	5.2	4.7
Abandoned Underground Coal Mines	+	+	+	+	+	+	+	+
Natural Gas Systems	0.2	(0.1)	(0.1)	(0.1)	(0.1)	(0.4)	(5.1)	(8.7)
Petroleum Systems	(0.6)	0.9	2.4	2.8	3.1	3.4	3.3	(0.2)
Petrochemical Production	NC	NC	NC	NC	NC	NC	NC	NC
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production	NC	NC	+	+	+	+	NC	NC
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC	NC
Enteric Fermentation	11.2	11.7	11.1	11.1	11.2	11.6	11.9	12.4
Manure Management	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.5

Rice Cultivation	NC	NC	NC	NC	NC	NC	NC	+
Field Burning of Agricultural Residues	+	+	+	+	+	+	+	+
Forest Land Remaining Forest Land	NC	NC	NC	NC	NC	NC	NC	NC
Landfills	(11.4)	(13.0)	(11.1)	(10.1)	(10.3)	(9.3)	(9.5)	(8.3)
Wastewater Treatment	(1.8)	(0.8)	(1.8)	(1.7)	(1.7)	(1.7)	(1.7)	(1.6)
Composting[a]	0.3	0.7	1.3	1.3	1.3	1.5	1.6	1.6
International Bunker Fuels	NC	NC	NC	NC	NC	NC	+	+
N_2O	**62.9**	**74.9**	**56.4**	**72.9**	**65.1**	**59.1**	**71.1**	**69.2**
Stationary Combustion	0.5	0.6	0.6	0.6	0.6	0.7	0.7	1.0
Mobile Combustion	(0.2)	(0.2)	(0.7)	0.2	(1.2)	(1.3)	(1.4)	(1.5)
Adipic Acid Production	0.1	0.1	0.2	0.2	0.2	0.2	0.2	(0.1)
Nitric Acid Production	(0.9)	(1.0)	(1.0)	(0.8)	(0.9)	(1.4)	(0.8)	0.1
Manure Management	3.4	3.8	4.1	4.2	4.3	4.3	4.4	4.4
Agricultural Soil Management	63.7	74.9	55.8	70.6	64.4	59.0	70.4	67.4
Field Burning of Agricultural Residues	+	+	+	+	+	+	+	+
Wastewater Treatment	(0.1)	+	+	0.2	+	(0.1)	(0.1)	+
N_2O from Product Uses	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Municipal Solid Waste Combustion	NC	NC	NC	NC	NC	NC	NC	NC
Settlements Remaining Settlements	(4.1)	(4.2)	(4.1)	(3.7)	(3.8)	(3.9)	(4.1)	(4.0)
Forest Land Remaining Forest Land	NC	NC	NC	NC	NC	NC	NC	NC
Composting[a]	0.4	0.8	1.4	1.4	1.4	1.6	1.7	1.7
International Bunker Fuels	NC	NC	NC	NC	NC	NC	+	+
HFCs, PFCs, and SF_6	**(0.4)**	**(3.4)**	**(11.1)**	**(11.8)**	**(13.2)**	**(15.2)**	**(17.3)**	**(19.5)**
Substitution of Ozone Depleting Substances	+	(3.1)	(10.9)	(12.3)	(13.9)	(15.7)	(17.9)	(21.0)
Aluminum Production	NC	NC	NC	NC	NC	NC	+	NC
HCFC-22 Production	NC	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	+	+	+	+	+	(0.4)	0.1
Electrical Transmission and Distribution	(0.4)	(0.4)	(0.1)	+	0.1	+	0.3	0.8
Magnesium Production and Processing	+	+	+	0.5	0.6	0.6	0.6	0.6
Net Change in Total Emissions[b]	**67.7**	**79.1**	**49.2**	**70.6**	**74.2**	**72.1**	**50.7**	**53.3**
Percent Change	**0.8%**	**2.3%**	**2.1%**	**1.4%**	**1.0%**	**0.4%**	**0.0%**	**0.1%**

+ Absolute value does not exceed 0.05 Tg CO_2 Eq. or 0.05 percent.
NC (No Change)
[a] New source category relative to previous inventory.
[b] Excludes net CO_2 flux from Land Use, Land-Use Change, and Forestry, and emissions from International Bunker Fuels and Wood Biomass and Ethanol Consumption.
Note: Totals may not sum due to independent rounding.

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**	**2005**
Forest Land Remaining Forest Land	(23.1)	57.6	87.9	22.3	(9.2)	(43.9)	(44.1)	(44.9)
Cropland Remaining Cropland	(1.9)	(2.0)	(1.9)	(2.0)	(2.6)	(2.2)	(1.5)	(1.6)
Land Converted to Cropland	6.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Grassland Remaining Grassland	(2.0)	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Land Converted to Grassland	0.3	NC	NC	NC	NC	NC	NC	NC
Settlements Remaining Settlements	(3.1)	(3.7)	(4.3)	(4.4)	(4.5)	(4.6)	(4.7)	(4.8)
Other	NC	NC	(0.3)	(0.3)	(0.2)	+	(0.2)	(0.5)

Net Change in Total Flux	**(23.8)**		**54.3**		**83.8**	**17.9**	**(14.1)**	**(48.4)**	**(48.2)**	**(49.4)**
Percent Change	**-3.3%**		**6.6%**		**11.1%**	**2.3%**	**-1.7%**	**-6.0%**	**-5.8%**	**-6.0%**

+ Absolute value does not exceed 0.05 Tg CO_2 Eq. or 0.05 percent.
NC (No Change)
Note: Numbers in parentheses indicate a decrease in estimated net flux of CO_2 to the atmosphere, or an increase in net sequestration.
Note: Totals may not sum due to independent rounding.

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