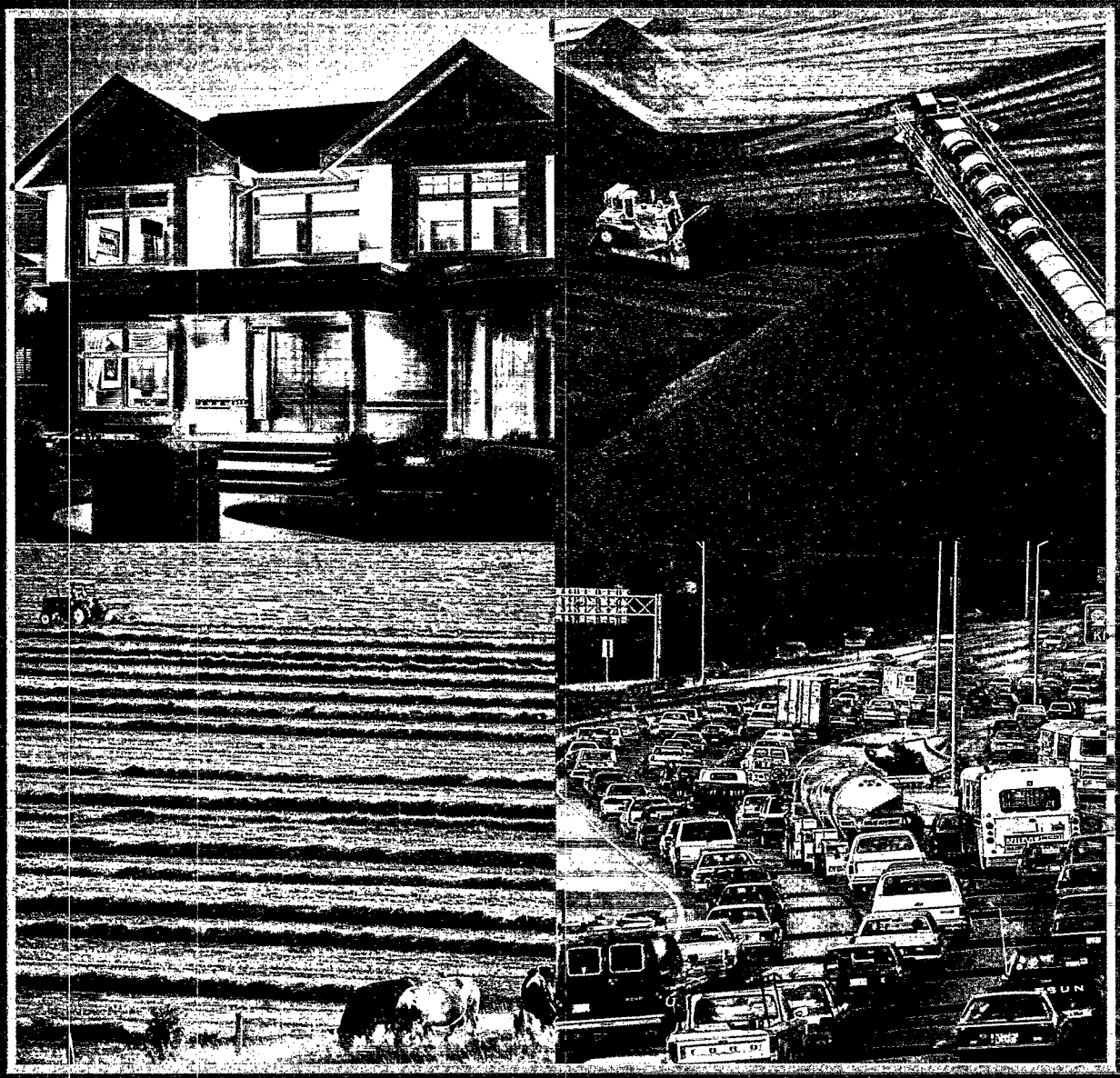
EPA

# Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2000



## How to Obtain Copies

You can electronically download this document on the U.S. EPA's homepage at http://www.epa.gov/globalwarming/publications/emissions. To request free copies of this report, call the National Service Center for Environmental Publications (NSCEP) at (800) 490-9198, or visit the web site above and click on order "online" after selecting an edition.

All data tables of this document are available for the full time series 1990 through 2000, inclusive, at the web site mentioned above.

## FOR FURTHER INFORMATION

Contact Mr. Michael Gillenwater, Environmental Protection Agency, (202) 564-4092, ghginventory@epa.gov.
For more information regarding climate change and greenhouse gas emissions see EPA web side at http://www.epa.gov/globalwarming.

Released for printing: April 2002

## Emissions by Economic Sectors

The photographs on the front and back cover of this report represent the six major economic sectors into which emissions have been allocated for analytical purposes. The six economic sectors are Electricity Generation, Transportation, Industry, Agriculture, Residential, and Commercial. The economic sectors represent an alternative method of allocating U.S. greenhouse gas emissions, different from the sectors defined by the IPCC and used in this report for international reporting and standardized methodological reasons (i. e. Energy, Industrial Processes, Solvent Use, Agriculture, Land-Use Change and Forestry, and Waste).

**Residential:** Residential sector greenhouse gas emissions are dominated by $CO_2$ from fossil fuel combustion, used to heat and supply electricity to homes. Emissions also result from landfills, wastewater treatment, waste combustion, human sewage, stationary combustion, and leaks from the use of refrigerants.

**Coal for Electricity Generation:** Coal is a fossil fuel that is combusted to indirectly generate electricity. In coal fueled combustors (i.e. boilers) the heat generated from burning coal is used to produce high-pressure steam. The high-pressure steam is then used to turn turbines and generate electricity. Carbon dioxide is the predominant greenhouse gas emitted from coal-fired boilers in Electricity Generation.

**Agriculture:** This is the only economic sector from which the majority of emissions are not from fossil fuel combustion. Nitrous oxide emissions from agricultural soils dominate this sector, followed by emissions from livestock due to enteric fermentation and manure management, and then $CO_2$ from fossil fuel combustion. Smaller quantities of methane and nitrous oxide emissions are derived from rice cultivation, agricultural residue burning, and mobile and stationary combustion.

**Motor Vehicle Transportation:** Petroleum-based products supplied almost all of the energy consumed for transportation, with nearly two-thirds related to gasoline consumption in automobiles and other highway vehicles. Motor vehicle emissions consist of $CO_2$, $CH_4$ and $N_2O$ from the internal combustion engines and HFCs from motor vehicle air-conditioners and refrigerated transport.

**UNITED STATES ENVIRONMENTAL PROTECTION AGENCY**
WASHINGTON, D.C. 20460

April 2002

The U.S. Environmental Protection Agency, in cooperation with other federal agencies, has prepared the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000.* The estimates of emissions and removals contained in this report, along with future updates, will be used to monitor and track the progress of the United States in meeting our commitments under the United Nations Framework Convention on Climate Change (UNFCCC).

In accordance with a decision of the Conference of Parties to the UNFCCC (Decision 3/CP.5), this inventory complies with the UNFCCC Reporting Guidelines on Annual Inventories (FCCC/CP/1999/7). Adherence to these guidelines ensures that national inventories are well documented, consistently prepared, and as accurate and complete as possible. The assumptions and methodologies used in this report have been clearly explained, and are based on the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* and the *IPCC Report on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.*

Each year, advances in scientific understanding and availability of underlying data allow us to improve the quality and comprehensiveness of the inventory. A section entitled "Changes in this Year's U.S. Greenhouse Gas Inventory Report," guides readers to specific areas where methods have been improved or new data has been collected.

One of this year's advances is a new analysis that allocates emissions to "economic sectors," which is intended to communicate more intuitively the emissions from broad categories of economic activity. A "comprehensive electric power industry sector" has been evaluated for the first time, as well as emissions from industrial wastewater and carbon sequestration in urban trees. A series of improvements were also made to the estimates of $CO_2$ emissions and carbon storage from the non-energy use of fossil fuels for industrial feedstocks. Finally, newly reported data on $SF_6$ emissions from magnesium production and processing and electric power transmission and distribution systems has been incorporated.

We hope that these improvements make this document more useful, and appreciate the comments and suggestions we have received from numerous reviewers in both the scientific community and the general public.

Sincerely,

Jeffrey R. Holmstead
Assistant Administrator
Office of Air and Radiation

**Recycled/Recyclable** • Printed with Vegetable Oil Based Inks on 100% Recycled Paper (20% Postconsumer)

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

# 1990 — 2000

## April 15, 2002

**U.S. Environmental Protection Agency**
**Office of Atmospheric Programs (6202N)**
**1200 Pennsylvania Avenue, NW**
**Washington, DC 20460**
**USA**

# Acknowledgments

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

In particular, we wish to acknowledge the efforts of the Energy Information Administration and the Department of Energy for providing detailed statistics and insightful analysis on numerous energy-related topics; the U.S. Forest Service for preparing the forest carbon inventory, and the Department of Agriculture's Agricultural Research Service for their work on nitrous oxide emissions from soils; and to the Department of Agriculture's Agriculture Research Service and the Natural Resource Ecology Laboratory at Colorado State University for their work on carbon in agricultural soils.

Within the EPA, many Offices contributed data, analysis and technical review for this report. The EPA Office of Atmospheric Programs developed methodologies and provided detailed emission estimates for numerous source categories, particularly for methane, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. The Office of Transportation and Air Quality and the Office of Air Quality Planning and Standards provided analysis and review for several of the source categories addressed in this report. The Office of Solid Waste and the Office of Research and Development also contributed analysis and research.

Other government agencies have contributed data as well, including the U.S. Geological Survey, the Federal Highway Administration, the Department of Transportation, the Bureau of Transportation Statistics, the Department of Commerce, the National Agricultural Statistics Service, the Federal Aviation Administration, and the Department of Defense.

Michael Gillenwater has directed the analytical development and writing of this report. Work on fuel combustion and industrial process emissions was also directed by Michael Gillenwater. Work on energy and waste sector methane emissions was directed by Elizabeth Scheehle, while work on agriculture sector emissions was directed by Tom Wirth and Joe Mangino. Land-Use Change and Forestry sector analysis was directed by Tom Wirth. Work on emissions of HFCs, PFCs, and $SF_6$ was directed by Deborah Schafer and Alicia Karspeck. Adam Chambers helped direct the review process for this report.

We would especially like to thank Marian Martin, Randall Freed, and their staff at ICF Consulting's Global Environmental Practice, including John Venezia, Kim Raby, Katrin Peterson, Barbara Braatz, Leonard Crook, Payton Deeks, Susan Brown, Diana Pape, Bill Cowart, Anne Choate, Noam Glick, and Jeffrey King for synthesizing this report and preparing many of the individual analyses. Eastern Research Group, Raven Ridge Resources, and Arcadis also provided significant analytical support.

# Preface

The United States Environmental Protection Agency (EPA) prepares the official *U.S. Inventory of Greenhouse Gas Emissions and Sinks* to comply with existing commitments under the United Nations Framework Convention on Climate Change (UNFCCC).[1] Under a decision of the UNFCCC Conference of the Parties, national inventories for most 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 page.[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. The EPA's policy is to allow at least 60 days for public review and comment when proposing new regulations or documents supporting regulatory development – unless statutory or judicial deadlines make a shorter time necessary – and 30 days for non-regulatory documents of an informational nature such as the Inventory document.

[1] See http://www.unfccc.de

[2] See http://www.epa.gov/globalwarming/emissions/national

# Table of Contents


**Acknowledgments** ..... i

**Preface** ..... ii

**Table of Contents** ..... iii

**List of Tables, Figures, and Boxes** ..... vi

Tables ..... vi
Figures ..... ix
Boxes ..... xi

**Executive Summary** ..... ES-1

Recent Trends in U.S. Greenhouse Gas Emissions ..... ES-2
Emissions by Economic Sector ..... ES-8
Global Warming Potentials ..... ES-9
Carbon Dioxide Emissions ..... ES-11
Methane Emissions ..... ES-17
Nitrous Oxide Emissions ..... ES-20
HFC, PFC, and SF6 Emissions ..... ES-22
Ambient Air Pollutant Emissions ..... ES-25

**Changes in This Year's Inventory Report** ..... Changes-1

Methodological Changes ..... Changes-3
Changes in Historical Data ..... Changes-11

**1. Introduction** ..... 1-1

What is Climate Change? ..... 1-2
Greenhouse Gases ..... 1-2
Global Warming Potentials ..... 1-7
Recent Trends in U.S. Greenhouse Gas Emissions ..... 1-10
Emissions by Economic Sectors ..... 1-16
Methodology and Data Sources ..... 1-21
Uncertainty in and Limitations of Emission Estimates ..... 1-24
Organization of Report ..... 1-26

**2. Energy** ..... 2-1

Carbon Dioxide Emissions from Fossil Fuel Combustion ..... 2-3
Carbon Stored in Products from Non-Energy Uses of Fossil Fuels ..... 2-19
Stationary Combustion (excluding $CO_2$) ..... 2-21
Mobile Combustion (excluding $CO_2$) ..... 2-25
Coal Mining ..... 2-30
Natural Gas Systems ..... 2-33
Petroleum Systems ..... 2-35
Municipal Solid Waste Combustion ..... 2-37
Natural Gas Flaring and Ambient Air Pollutant Emissions from Oil and Gas Activities ..... 2-41
Indirect $CO_2$ from $CH_4$ Oxidation ..... 2-42
International Bunker Fuels ..... 2-45
Wood Biomass and Ethanol Consumption ..... 2-50

## 3. Industrial Processes ..... 3-1

Iron and Steel Production ..... 3-2
Cement Manufacture ..... 3-5
Ammonia Manufacture ..... 3-7
Lime Manufacture ..... 3-9
Limestone and Dolomite Use ..... 3-11
Soda Ash Manufacture and Consumption ..... 3-14
Ferroalloy Production ..... 3-15
Titanium Dioxide Production ..... 3-16
Carbon Dioxide Consumption ..... 3-18
Petrochemical Production ..... 3-19
Silicon Carbide Production ..... 3-20
Adipic Acid Production ..... 3-21
Nitric Acid Production ..... 3-23
Substitution of OzoneDepleting Substances ..... 3-24
Aluminum Production ..... 3-26
HCFC-22 Production ..... 3-29
Semiconductor Manufacture ..... 3-30
Electrical Transmission and Distribution ..... 3-32
Magnesium Production and Processing ..... 3-33
Industrial Sources of Ambient Air Pollutants ..... 3-35

## 4. Solvent Use ..... 4-1

## 5. Agriculture ..... 5-1

Enteric Fermentation ..... 5-2
Manure Management ..... 5-5
Rice Cultivation ..... 5-10
Agricultural Soil Management ..... 5-14
Agricultural Residue Burning ..... 5-19

## 6. Land-Use Change and Forestry ..... 6-1

Changes in Forest Carbon Stocks ..... 6-2
Changes in Carbon Stocks in Urban Trees ..... 6-9
Changes in Agricultural Soil Carbon Stocks ..... 6-11
Changes in Yard Trimming Carbon Stocks in Landfills ..... 6-21

## 7. Waste ..... 7-1

Landfills ..... 7-1
Wastewater Treatment ..... 7-5
Human Sewage ..... 7-8
Waste Sources of Ambient Air Pollutants ..... 7-9

## 8. References ..... 8-1

Executive Summary ..... 8-1
Changes in this Year's Inventory ..... 8-2
Introduction ..... 8-6
Energy ..... 8-7
Industrial Processes ..... 8-14
Solvent Use ..... 8-19
Agriculture ..... 8-19
Land-Use Change and Forestry ..... 8-31
Waste ..... 8-34

## Annexes


ANNEX A: Methodology for Estimating Emissions of $CO_2$ from Fossil Fuel Combustion ..... A-1
ANNEX B: Methodology for Estimating Carbon Stored in Products from Non-Energy Uses of Fossil Fuels ..... B-1
ANNEX C: Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Ambient Air Pollutants from Stationary Combustion ..... C-1
ANNEX D: Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Ambient Air Pollutants from Mobile Combustion ..... D-1
ANNEX E: Methodology for Estimating $CH_4$ Emissions from Coal Mining ..... E-1
ANNEX F: Methodology for Estimating $CH_4$ Emissions from Natural Gas Systems ..... F-1
ANNEX G: Methodology for Estimating $CH_4$ Emissions from Petroleum Systems ..... G-1
ANNEX H: Methodology for Estimating $CO_2$ Emissions from Municipal Solid Waste Combustion ..... H-1
ANNEX I: Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military ..... I-1
ANNEX J: Methodology for Estimating HFC, and PFC Emissions from Substitution of Ozone Depleting Substances ..... J-1
ANNEX K: Methodology for Estimating $CH_4$ Emissions from Enteric Fermentation ..... K-1
ANNEX L: Methodology for Estimating $CH_4$ and $N_2O$ Emissions from Manure Management ..... L-1
ANNEX M: Methodology for Estimating $N_2O$ Emissions from Agricultural Soil Management ..... M-1
ANNEX N: Methodology for Estimating Net Changes in Forest Carbon Stocks ..... N-1
ANNEX O: Methodology for Estimating $CH_4$ Emissions from Landfills ..... O-1
ANNEX P: Key Source Analysis ..... P-1
ANNEX Q: Global Warming Potential Values ..... Q-1
ANNEX R: Ozone Depleting Substance Emissions ..... R-1
ANNEX S: Sulfur Dioxide Emissions ..... S-1
ANNEX T: Complete List of Source Categories ..... T-1
ANNEX U: IPCC Reference Approach for Estimating $CO_2$ Emissions from Fossil Fuel Combustion ..... U-1
ANNEX V: Sources of Greenhouse Gas Emissions Excluded ..... V-1
ANNEX W: Constants, Units, and Conversions ..... W-1
ANNEX X: Abbreviations ..... X-1
ANNEX Y: Chemical Formulas ..... Y-1
ANNEX Z: Glossary ..... Z-1

# List of Tables, Figures, and Boxes

## Tables


Table ES-1: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Tg $CO_2$ Eq.) ..... ES-3
Table ES-2: Annual Change in $CO_2$ Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (Tg $CO_2$ Eq. and Percent) ..... ES-5
Table ES-3: Recent Trends in Various U.S. Data (Index 1990 = 100) ..... ES-7
Table ES-4: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg $CO_2$ Eq. and Percent of Total in 2000) ..... ES-8
Table ES-5: U.S Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (Tg $CO_2$ Eq.) ..... ES-9
Table ES-6: Comparison of 100 Year GWPs ..... ES-10
Table ES-7: Global Warming Potentials (100 Year Time Horizon) ..... ES-11
Table ES-8: U.S. Sources of $CO_2$ Emissions and Sinks (Tg $CO_2$ Eq.) ..... ES-13
Table ES-9: $CO_2$ Emissions from Fossil Fuel Combustion by End-Use Sector (Tg $CO_2$ Eq.) ..... ES-15
Table ES-10: U.S. Sources of Methane Emissions (Tg $CO_2$ Eq.) ..... ES-18
Table ES-11: U.S. Sources of Nitrous Oxide Emissions (Tg $CO_2$ Eq.) ..... ES-21
Table ES-12: Emissions of HFCs, PFCs, and SF6 (Tg $CO_2$ Eq.) ..... ES-23
Table ES-13: Emissions of Ozone Depleting Substances (Gg) ..... ES-24
Table ES-14: Emissions of NOx, CO, NMVOCs, and $SO_2$ (Gg) ..... ES-26

Table Changes-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO2 Eq.) ..... Changes-2
Table Changes-2: Revisions to Net $CO_2$ Sequestration from Land-Use Change and Forestry (Tg $CO_2$ Eq.) ..... Changes-3

Table 1-1: Global atmospheric concentration (ppm unless otherwise specified), rate of concentration change (ppb/year) and atmospheric lifetime (years) of selected greenhouse gases ..... 1-4
Table 1-2: Global Warming Potentials and Atmospheric Lifetimes (Years) ..... 1-7
Table 1-3: Comparison of 100 Year GWPs ..... 1-8
Table 1-4: Effects on U.S. Greenhouse Gas Emission Trends Using IPCC SAR and TAR GWP Values (Tg $CO_2$ Eq.) Change from 1990 to 2000 Revisions to Annual Estimates ..... 1-9
Table 1-5: Comparison of Emissions by Sector using IPCC SAR and TAR GWP Values (Tg $CO_2$ Eq.) ..... 1-9
Table 1-6: Annual Change in $CO_2$ Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (Tg $CO_2$ Eq. and Percent) ..... 1-11
Table 1-7: Recent Trends in Various U.S. Data (Index 1990 = 100) ..... 1-13
Table 1-8: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Tg $CO_2$ Eq.) ..... 1-14
Table 1-9: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Gg) ..... 1-15
Table 1-10: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (Tg $CO_2$ Eq.) ..... 1-16
Table 1-11: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg $CO_2$ Eq. and Percent of Total in 2000) ..... 1-18
Table 1-12: U.S Greenhouse Gas Emissions by "Economic Sector" and Gas with Electricity-Related Emissions Distributed (Tg $CO_2$ Eq.) and Percent of Total in 2000 ..... 1-20
Table 1-13: Electricity Generation-Related Greenhouse Gas Emissions (Tg $CO_2$ Eq.) ..... 1-21
Table 1-14: Transportation-Related Greenhouse Gas Emissions (Tg $CO_2$ Eq.) ..... 1-22
Table 1-15: IPCC Sector Descriptions ..... 1-24
Table 1-16: List of Annexes ..... 1-25
Table 2-1: Emissions from Energy (Tg $CO_2$ Eq.) ..... 2-2
Table 2-2: Emissions from Energy (Gg) ..... 2-2
Table 2-3: $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type and Sector (Tg $CO_2$ Eq.) ..... 2-4

Table 2-4: Fossil Fuel Carbon in Products (Tg $CO_2$ Eq.) ..... 2-7
Table 2-5: $CO_2$ Emissions from International Bunker Fuels (Tg $CO_2$ Eq.) ..... 2-7
Table 2-6: $CO_2$ Emissions from Fossil Fuel Combustion by End-Use Sector (Tg $CO_2$ Eq.) ..... 2-8
Table 2-7: $CO_2$ Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (Tg $CO_2$ Eq.) .... 2-10
Table 2-8: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (Tg $CO_2$ Eq./EJ) ..... 2-15
Table 2-9: Carbon Intensity from Energy Consumption by Sector (Tg $CO_2$ Eq./EJ) ..... 2-15
Table 2-10: Change in $CO_2$ Emissions from Direct Fossil Fuel Combustion Since 1990 (Tg $CO_2$ Eq.) ..... 2-16
Table 2-11: 2000 Non-Energy Fossil Fuel Consumption, Storage, and Emissions (Tg $CO_2$ Eq. unless otherwise noted) ..... 2-20
Table 2-12: Storage and Emissions from Non-Energy Fossil Fuel Consumption (Tg $CO_2$ Eq.) ..... 2-20
Table 2-13: $CH_4$ Emissions from Stationary Combustion (Tg $CO_2$ Eq.) ..... 2-23
Table 2-14: $N_2O$ Emissions from Stationary Combustion (Tg $CO_2$ Eq.) ..... 2-23
Table 2-15: $CH_4$ Emissions from Stationary Combustion (Gg) ..... 2-24
Table 2-16: $N_2O$ Emissions from Stationary Combustion (Gg) ..... 2-24
Table 2-17: $NO_x$, CO, and NMVOC Emissions from Stationary Combustion in 2000 (Gg) ..... 2-25
Table 2-18: $CH_4$ Emissions from Mobile Combustion (Tg CO2 Eq.) ..... 2-26
Table 2-19: $N_2O$ Emissions from Mobile Combustion (Tg CO2 Eq.) ..... 2-26
Table 2-20: $CH_4$ Emissions from Mobile Combustion (Gg) ..... 2-27
Table 2-21: $N_2O$ Emissions from Mobile Combustion (Gg) ..... 2-27
Table 2-22: $NO_x$, CO, and NMVOC Emissions from Mobile Combustion in 2000 (Gg) ..... 2-28
Table 2-23: $CH_4$ Emissions from Coal Mining (Tg CO2 Eq.) ..... 2-31
Table 2-24: $CH_4$ Emissions from Coal Mining (Gg) ..... 2-31
Table 2-25: Coal Production (Thousand Metric Tons) ..... 2-33
Table 2-26: $CH_4$ Emissions from Natural Gas Systems (Tg $CO_2$ Eq.) ..... 2-34
Table 2-27: $CH_4$ Emissions from Natural Gas Systems (Gg) ..... 2-34
Table 2-28: $CH_4$ Emissions from Petroleum Systems (Tg $CO_2$ Eq.) ..... 2-36
Table 2-29: $CH_4$ Emissions from Petroleum Systems (Gg) ..... 2-36
Table 2-30: Uncertainty in CH4 Emissions from Production Field Operations (Gg) ..... 2-38
Table 2-31: $CO_2$ and $N_2O$ Emissions from Municipal Solid Waste Combustion (Tg $CO_2$ Eq.) ..... 2-39
Table 2-32: $CO_2$ and $N_2O$ Emissions from Municipal Solid Waste Combustion (Gg) ..... 2-39
Table 2-33: Municipal Solid Waste Generation (Metric Tons) and Percent Combusted ..... 2-40
Table 2-34: U.S. Municipal Solid Waste Combusted by Data Source (Metric Tons) ..... 2-41
Table 2-35: $CO_2$ Emissions from Natural Gas Flaring ..... 2-42
Table 2-36: $NO_x$, NMVOCs, and CO Emissions from Oil and Gas Activities (Gg) ..... 2-42
Table 2-37: Total Natural Gas Reported Vented and Flared (Million Ft3) and Thermal Conversion Factor (Btu/Ft3) ..... 2-42
Table 2-38: $CH_4$ Emissions from Non-Combustion Fossil Sources (Gg) ..... 2-43
Table 2-39: Indirect $CO_2$ Emissions from Non-Combustion Fossil Methane Sources (Gg) ..... 2-44
Table 2-40: Indirect $CO_2$ Emissions from Non-Combustion Fossil Methane Sources (Tg $CO_2$ Eq.) ..... 2-44
Table 2-41: Emissions from International Bunker Fuels (Tg $CO_2$ Eq.) ..... 2-47
Table 2-42: Emissions from International Bunker Fuels (Gg) ..... 2-47
Table 2-43: Aviation Jet Fuel Consumption for International Transport (Million Gallons) ..... 2-48
Table 2-44: Marine Fuel Consumption for International Transport (Million Gallons) ..... 2-48
Table 2-45: $CO_2$ Emissions from Wood Consumption by End-Use Sector (Tg $CO_2$ Eq.) ..... 2-50
Table 2-46: $CO_2$ Emissions from Wood Consumption by End-Use Sector (Gg) ..... 2-50
Table 2-47: $CO_2$ Emissions from Ethanol Consumption ..... 2-51
Table 2-48: Woody Biomass Consumption by Sector (Trillion Btu) ..... 2-51
Table 2-49: Ethanol Consumption ..... 2-51

Table 3-1: Emissions from Industrial Processes (Tg $CO_2$ Eq.) ..... 3-3
Table 3-2: Emissions from Industrial Processes (Gg) ..... 3-4
Table 3-3: $CO_2$ Emissions from Iron and Steel Production ..... 3-4
Table 3-4: $CO_2$ Emissions from Cement Production ..... 3-6
Table 3-5: Cement Production (Gg) ..... 3-7
Table 3-6: $CO_2$ Emissions from Ammonia Manufacture ..... 3-8

Table 3-7: Ammonia Manufacture ..... 3-8
Table 3-8: $CO_2$ Emissions from Lime Manufacture ..... 3-9
Table 3-9: $CO_2$ Emissions from Lime Manufacture (Gg) ..... 3-9
Table 3-10: Lime Production and Lime Use for Sugar Refining and PCC (Thousand Metric Tons) ..... 3-10
Table 3-11: Hydrated Lime Production (Thousand Metric Tons) ..... 3-10
Table 3-12: $CO_2$ Emissions from Limestone & Dolomite Use (Tg $CO_2$ Eq.) ..... 3-12
Table 3-13: $CO_2$ Emissions from Limestone & Dolomite Use (Gg) ..... 3-12
Table 3-14: Limestone and Dolomite Consumption (Thousand Metric Tons) ..... 3-13
Table 3-15: Dolomitic Magnesium Metal Production Capacity (Metric Tons) ..... 3-13
Table 3-16: $CO_2$ Emissions from Soda Ash Manufacture and Consumption ..... 3-14
Table 3-17: $CO_2$ Emissions from Soda Ash Manufacture and Consumption (Gg) ..... 3-14
Table 3-18: Soda Ash Manufacture and Consumption (Thousand Metric Tons) ..... 3-15
Table 3-19: $CO_2$ Emissions from Ferroalloy Production ..... 3-16
Table 3-20: Production of Ferroalloys (Metric Tons) ..... 3-17
Table 3-21: $CO_2$ Emissions from Titanium Dioxide ..... 3-17
Table 3-22: Titanium Dioxide Production ..... 3-18
Table 3-23: $CO_2$ Emissions from Carbon Dioxide Consumption ..... 3-19
Table 3-24: Carbon Dioxide Consumption ..... 3-19
Table 3-25: $CH_4$ Emissions from Petrochemical Production ..... 3-20
Table 3-26: Production of Selected Petrochemicals (Thousand Metric Tons) ..... 3-20
Table 3-27: $CH_4$ Emissions from Silicon Carbide Production ..... 3-20
Table 3-28: Production of Silicon Carbide ..... 3-21
Table 3-29: $N_2O$ Emissions from Adipic Acid Production ..... 3-22
Table 3-30: Adipic Acid Production ..... 3-22
Table 3-31: $N_2O$ Emissions from Nitric Acid Production ..... 3-23
Table 3-32: Nitric Acid Production ..... 3-24
Table 3-33: Emissions of HFCs and PFCs from ODS Substitution (Tg $CO_2$ Eq.) ..... 3-24
Table 3-34: Emissions of HFCs and PFCs from ODS Substitution (Mg) ..... 3-25
Table 3-35: $CO_2$ Emissions from Aluminum Production ..... 3-26
Table 3-36: PFC Emissions from Aluminum Production (Tg $CO_2$ Eq.) ..... 3-26
Table 3-37: PFC Emissions from Aluminum Production (Gg) ..... 3-27
Table 3-38: Production of Primary Aluminum ..... 3-28
Table 3-39: HFC-23 Emissions from HCFC-22 Production ..... 3-29
Table 3-40: HCFC-22 Production ..... 3-29
Table 3-41: PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacture (Tg $CO_2$ Eq.) ..... 3-31
Table 3-42: PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacture (Mg) ..... 3-31
Table 3-43: $SF_6$ Emissions from Electrical Transmission and Distribution ..... 3-32
Table 3-44: $SF_6$ Emissions from Magnesium Production and Processing ..... 3-33
Table 3-45: 2000 Potential and Actual Emissions of HFCs, PFCs, and SF6 from Selected Sources (Tg $CO_2$ Eq.) ..... 3-34
Table 3-46: $NO_x$, CO, and NMVOC Emissions from Industrial Processes (Gg) ..... 3-35

Table 4-1: Emissions of $NO_x$, CO, and NMVOC from Solvent Use (Gg) ..... 4-2

Table 5-1: Emissions from Agriculture (Tg $CO_2$ Eq.) ..... 5-2
Table 5-2: Emissions from Agriculture (Gg) ..... 5-2
Table 5-3: $CH_4$ Emissions from Enteric Fermentation (Tg $CO_2$ Eq.) ..... 5-3
Table 5-4: $CH_4$ Emissions from Enteric Fermentation (Gg) ..... 5-3
Table 5-5: $CH_4$ and $N_2O$ Emissions from Manure Management (Tg $CO_2$ Eq.) ..... 5-7
Table 5-6: $CH_4$ and $N_2O$ Emissions from Manure Management (Gg) ..... 5-7
Table 5-7: $CH_4$ Emissions from Rice Cultivation (Tg $CO_2$ Eq.) ..... 5-12
Table 5-8: $CH_4$ Emissions from Rice Cultivation (Gg) ..... 5-12
Table 5-9: Rice Areas Harvested (Hectares) ..... 5-12
Table 5-10: $N_2O$ Emissions from Agricultural Soil Management (Tg $CO_2$ Eq.) ..... 5-15
Table 5-11: $N_2O$ Emissions from Agricultural Soil Management (Gg) ..... 5-15

Table 5-12: Direct $N_2O$ Emissions from Managed Soils (Tg CO2 Eq.) ..... 5-16
Table 5-13: Direct $N_2O$ Emissions from Pasture, Range, and Paddock Livestock Manure (Tg $CO_2$ Eq.) ..... 5-16
Table 5-14: Indirect $N_2O$ Emissions (Tg $CO_2$ Eq.) ..... 5-16
Table 5-15: Emissions from Agricultural Residue Burning (Tg $CO_2$ Eq.) ..... 5-20
Table 5-16: Emissions from Agricultural Residue Burning (Gg) ..... 5-21
Table 5-17: Agricultural Crop Production (Thousand Metric Tons of Product) ..... 5-22
Table 5-18: Percentage of Rice Area Burned by State ..... 5-22
Table 5-19: Percentage of Rice Area Burned in California ..... 5-22
Table 5-20: Key Assumptions for Estimating Emissions from Agricultural Residue Burning ..... 5-23
Table 5-21: Greenhouse Gas Emission Ratios ..... 5-23

Table 6-1: Net $CO_2$ Flux from Land-Use Change and Forestry (Tg $CO_2$ Eq.) ..... 6-2
Table 6-2: Net $CO_2$ Flux from Land-Use Change and Forestry (Tg C) ..... 6-2
Table 6-3: Net $CO_2$ Flux from U.S. Forests (Tg $CO_2$ Eq.) ..... 6-5
Table 6-4: Net $CO_2$ Flux from U.S. Forests (Tg C) ..... 6-5
Table 6-5: U.S. Forest Carbon Stock Estimates (Tg C) ..... 6-8
Table 6-6: Net $CO_2$ Flux From Urban Trees (Tg $CO_2$ Eq.) ..... 6-9
Table 6-7: Carbon Storage (Metric Tons C), Carbon Sequestration (Metric Tons C/yr), and Tree Cover (%) for Ten U.S. Cities ..... 6-10
Table 6-8: Annual Sequestration per Area of Tree Cover (kg C/$m^2$ cover-year) ..... 6-10
Table 6-9: Net $CO_2$ Flux From Agricultural Soils (Tg $CO_2$ Eq.) ..... 6-12
Table 6-10: Mineral Soil Areas by Land-Use Category and IPCC Climatic Region (million hectares)a ..... 6-15
Table 6-11: Mineral Soil Areas by Land-Use Category and IPCC Mineral Soil Category (thousand hectares)a ..... 6-16
Table 6-12: Tillage Percentages by Management Category and IPCC Climatic Zonea ..... 6-17
Table 6-13: Organic Soil Areas by IPCC Land-Use Category and Climatic Region (thousand hectares)a ..... 6-18
Table 6-14: Quantities of Applied Minerals (Thousand Metric Tons) ..... 6-18
Table 6-15: Net $CO_2$ Flux from Landfilled Yard Trimmings ..... 6-21
Table 6-16: Storage Factor (kg C/kg dry yard trimmings) Moisture Content (kg water/kg wet yard trimmings), Composition (percent) and Converted Storage Factor (kg C/kg wet yard trimmings) of Landfilled Yard Trimmings ..... 6-21
Table 6-17: Collection and Destination of Yard Trimmings (Million Metric Tons, wet) ..... 6-22

Table 7-1: Emissions from Waste (Tg $CO_2$ Eq.) ..... 7-2
Table 7-2: Emissions from Waste (Gg) ..... 7-2
Table 7-3: $CH_4$ Emissions from Landfills (Tg $CO_2$ Eq.) ..... 7-4
Table 7-4: $CH_4$ Emissions from Landfills (Gg) ..... 7-4
Table 7-6: $CH_4$ Emissions from Domestic and Industrial Wastewater Treatment (Gg) ..... 7-6
Table 7-5: $CH_4$ Emissions from Domestic and Industrial Wastewater Treatment (Tg $CO_2$ Eq.) ..... 7-6
Table 7-7: U.S. Population (Millions) and Wastewater BOD Produced (Gg) ..... 7-7
Table 7-8: U.S. Pulp and Paper, Meat and Poultry, and Vegetables, Fruits and Juices Production (Million Metric Tons) ..... 7-7
Table 7-9: $N_2O$ Emissions from Human Sewage ..... 7-8
Table 7-10: U.S. Population (Millions) and Average Protein Intake (kg/Person/Year) ..... 7-9
Table 7-11: Emissions of $NO_x$, CO, and NMVOC from Waste (Gg) ..... 7-10

## Figures

Figure ES-1: U.S. GHG Emissions by Gas ..... ES-2
Figure ES-2: Annual Percent Change in U.S. GHG Emissions ..... ES-4
Figure ES-3: 2000 Greenhouse Gas Emissions by Gas ..... ES-4
Figure ES-4: Absolute Change in U.S. GHG Emissions Since 1990 ..... ES-4
Figure ES-5: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product ..... ES-7
Figure ES-6: Emissions Allocated to Economic Sectors ..... ES-8
Figure ES-7: Emissions with Electricity Distributed to Economic Sectors ..... ES-9

Figure ES-8: U.S. Carbon Flows for 2000 ..... ES-12
Figure ES-9: 2000 Sources of $CO_2$ 2000 U.S. Energy Consumption by Energy Source ..... ES-12
Figure ES-10: 2000 Sources of $CH_4$ ..... ES-12
Figure ES-11: U.S. Energy Consumption (Quadrillion Btu) ..... ES-13
Figure ES-12: 2000 $CO_2$ Emissions from Fossil Fuel Combustion by Sector and Fuel Type ..... ES-14
Figure ES-13: 2000 End-Use Sector Emissions of $CO_2$ from Fossil Fuel Combustion ..... ES-14
Figure ES-14: 2000 Sources of $CH_4$ ..... ES-18
Figure ES-15: 2000 Sources of $N_2O$ 2000 Sources of HFCs, PFCs, and $SF_6$ ..... ES-20
Figure ES-16: Sources of HFCs, PFCs, and $SF_6$ ..... ES-22

Figure 1-1: U.S. GHG Emissions by Gas ..... 1-10
Figure 1-2: Annual Percent Change in U.S. GHG Emissions ..... 1-11
Figure 1-3: Absolute Change in U.S. GHG Emissions Since 1990 ..... 1-11
Figure 1-4: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product ..... 1-13
Figure 1-5: U.S. GHG Emissions by Chapter/IPCC Sector ..... 1-16
Figure 1-6: Emissions Allocated to Economic Sectors, 1990-2000 ..... 1-17
Figure 1-7: U.S. Greenhouse Gas Emissions with Electricity Distributed to Economic Sectors, 1990-2000 .... 1-21

Figure 2-1: 2000 Energy Chapter GHG Sources ..... 2-1
Figure 2-2: 2000 U.S. Fossil Carbon Flows ..... 2-3
Figure 2-3: 2000 U.S. Energy Consumption by Energy Source ..... 2-5
Figure 2-4: U.S. Energy Consumption (Quadrillion Btu) ..... 2-5
Figure 2-5: 2000 $CO_2$ Emissions from Fossil Fuel Combustion by Sector and Fuel Type ..... 2-5
Figure 2-6: Annual Deviations from Normal Heating Degree Days for the United States (1949-2000) ..... 2-6
Figure 2-7: Annual Deviations from Normal Cooling Degree Days for the United States (1949-2000) ..... 2-6
Figure 2-8: Nuclear and Hydroelectric Power Plant Capacity Factors in the United States (1973-2000) ..... 2-7
Figure 2-9: 2000 End-Use Sector Emissions of $CO_2$ from Fossil Fuel Combustion ..... 2-9
Figure 2-10: Motor Gasoline Retail Prices (Real) ..... 2-9
Figure 2-11: Motor Vehicle Fuel Efficiency ..... 2-9
Figure 2-12: Industrial Production Indexes (Index 1992=100) ..... 2-11
Figure 2-13: Heating Degree Days ..... 2-12
Figure 2-14: Cooling Degree Days ..... 2-12
Figure 2-15: Electricity Generation Retail Sales by End-Use Sector ..... 2-13
Figure 2-16: Net Generation by Electric Utilities and Nonutilities ..... 2-13
Figure 2-17: U.S. Energy Consumption and Energy-Related $CO_2$ Emissions Per Capita and Per Dollar GDP 2-15
Figure 2-18: Change in $CO_2$ Emissions from Fossil Fuel Combustion Since 1990 by End-Use Sector ..... 2-15
Figure 2-19: Mobile Source $CH_4$ and $N_2O$ Emissions ..... 2-28

Figure 3-1: 2000 Industrial Processes Chapter GHG Sources ..... 3-1

Figure 5-1: 2000 Agriculture Chapter GHG Sources ..... 5-1
Figure 5-2: Direct and Indirect $N_2O$ Emissions from Agricultural Soils ..... 5-15

Figure 6-1: Forest Sector Carbon Pools and Flows ..... 6-3
Figure 6-2: Forest Carbon Stocks 1997 ..... 6-8
Figure 6-3: Net Annual $CO_2$ Flux From Mineral Soils Under Agricultural Management, 1990-1992 (metric ton C/ha) ..... 6-13
Figure 6-4: Net Annual $CO_2$ Flux From Mineral Soils Under Agricultural Management, 1993-1997 (metric ton C/ha) ..... 6-13
Figure 6-5: Net Annual $CO_2$ Flux From Organic Soils Under Agricultural Management, 1990-1992 (metric ton C/ha) ..... 6-14
Figure 6-6: Net Annual $CO_2$ Flux From Organic Soils Under Agricultural Management, 1993-2000 (metric ton C/ha) ..... 6-14

Figure 7-1: 2000 Waste Chapter GHG Sources ..... 7-1

## Boxes


Box ES-1: Recent Trends in Various U.S. Greenhouse Gas Emissions-Related Data ..... ES-7
Box ES-2: The IPCC Third Assessment Report and Global Warming Potentials ..... ES-10
Box ES-3: Emissions of Ozone Depleting Substances ..... ES-24
Box ES-4: Sources and Effects of Sulfur Dioxide ..... ES-25

Box 1-1: The IPCC Third Assessment Report and Global Warming Potentials ..... 1-8
Box 1-2: Recent Trends in Various U.S. Greenhouse Gas Emissions-Related Data ..... 1-13
Box 1-3: IPCC Good Practice Guidance ..... 1-23

Box 2-1: Weather and Non-Fossil Energy Effects on $CO_2$ from Fossil Fuel Combustion Trends ..... 2-6
Box 2-2: Sectoral Carbon Intensity Trends Related to Fossil Fuel and Overall Energy Consumption ..... 2-14
Box 2-3: Biogenic Emissions and Sinks of Carbon ..... 2-39

Box 3-1: Potential Emission Estimates of HFCs, PFCs, and $SF_6$ ..... 3-34

Box 6-1: Estimating Uncertainty Using a Revised IPCC Approach ..... 6-19
Box 6-2: Century Model Estimates of Soil Carbon Stock Changes on Cropland ..... 6-20

Box 7-1: Biogenic Emissions and Sinks of Carbon ..... 7-2
Box 7-2: Recycling and Greenhouse Gas Emissions and Sinks ..... 7-3

# Executive Summary

Central to any study of climate change is the development of an emissions inventory that identifies and quantifies a country's primary anthropogenic[1] sources and sinks of greenhouse gases. This inventory adheres to both 1) a comprehensive and detailed methodology for estimating sources and sinks of anthropogenic greenhouse gases, and 2) a common and consistent mechanism that enables signatory countries 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. Moreover, systematically and consistently estimating national and international emissions is a prerequisite for accounting for reductions and evaluating mitigation strategies.

In June of 1992, the United States signed, and later ratified in October, the UNFCCC. The objective of the UNFCCC is "to achieve...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[2]

By signing the Convention, Parties make commitments "to 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 this commitment.

This chapter summarizes the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 2000. To ensure that the U.S. emissions inventory is comparable to those of other UNFCCC signatory countries, 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) and the *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). For most source categories, the IPCC default methodologies were expanded, resulting in a more comprehensive and detailed estimate of emissions.

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). Because CFCs, HCFCs, and halons are stratospheric ozone depleting substances, they are covered under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. The UNFCCC

[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://www.unfccc.de>.

[3] Article 4 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change (also identified in Article 12). See <http://www.unfccc.de>.

defers to this earlier international treaty; consequently these gases are not included in national greenhouse gas inventories.[4] 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 do not have a direct global warming effect but indirectly affect terrestrial and/or solar radiation absorption by influencing the formation or destruction of other greenhouse gases, including tropospheric and stratospheric ozone. These gases include carbon monoxide (CO), oxides of nitrogen ($NO_x$), and nonmethane 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, their atmospheric concentrations have been affected by human activities. Since pre-industrial time (i.e., about 1750), concentrations of these greenhouse gases have increased by 31, 150, and 16 percent, respectively (IPCC 2001). According to the IPCC, the current concentration of $CO_2$ and $CH_4$ in the atmosphere has not been exceeded in the last 420,000 years. Additionally, the rate of increase of $CO_2$ in the atmosphere in the past century has been unprecedented in the last 20,000 years. This build-up has altered the chemical composition of the earth's atmosphere, and therefore effected the global climate system.

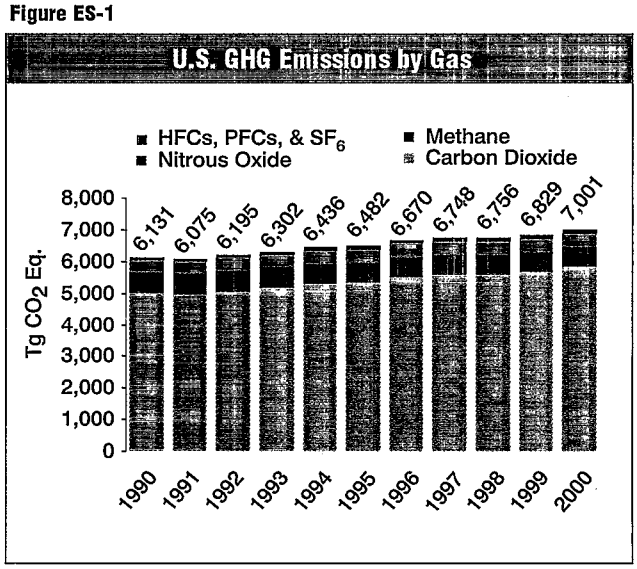
Beginning in the 1950s, the use of CFCs and other stratospheric ozone depleting substances (ODSs) increased by nearly 10 percent per year until the mid-1980s, when international concern about ozone depletion led to the signing of the *Montreal Protocol*. Since then, the production of ODSs is being phased out. In recent years, use of ODS substitutes such as HFCs and PFCs has grown as they begin to be phased in as replacements for CFCs and HCFCs. Accordingly, atmospheric concentrations of these substitutes have been growing (IPCC 2001).

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

In 2000, total U.S. greenhouse gas emissions rose to 7,001.2 teragrams of carbon dioxide equivalents (Tg $CO_2$ Eq.)[5] (14.2 percent above 1990 emissions). The single year increase in emissions from 1999 to 2000 was 2.5 percent (171.7 Tg $CO_2$ Eq.), which was greater than the average annual rate of increase for 1990 through 2000 (1.3 percent). The higher than average increase in emissions in 2000 was, in part, attributable to the following factors: 1) robust economic growth in 2000, leading to increased demand for electricity and transportation fuels, 2) cooler winter conditions compared to the previous two years, and 3) decreased output from hydroelectric dams. (See following section for an analysis of emission trends by general economic sectors).

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-1 provides a detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 2000.

**Figure ES-1**




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

[5] Estimates are presented in units of teragrams of carbon dioxide equivalents (Tg $CO_2$ Eq.), which weight each gas by its Global Warming Potential, or GWP, value. (See the following section on Global Warming Potentials, in Executive Summary or Chapter 1.)

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

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | **4,998.5** | **5,305.9** | **5,483.7** | **5,568.0** | **5,575.1** | **5,665.5** | **5,840.0** |
| Fossil Fuel Combustion | 4,779.8 | 5,085.0 | 5,266.6 | 5,339.6 | 5,356.2 | 5,448.6 | 5,623.3 |
| Iron and Steel Production | 85.4 | 74.4 | 68.3 | 76.1 | 67.4 | 64.4 | 65.7 |
| Cement Manufacture | 33.3 | 36.8 | 37.1 | 38.3 | 39.2 | 40.0 | 41.1 |
| Indirect $CO_2$ from $CH_4$ Oxidation | 30.9 | 29.5 | 28.9 | 28.4 | 28.2 | 27.0 | 26.3 |
| Waste Combustion | 14.1 | 18.6 | 19.6 | 21.3 | 20.3 | 21.8 | 22.5 |
| Ammonia Manufacture | 18.5 | 18.9 | 19.5 | 19.5 | 20.1 | 18.9 | 18.0 |
| Lime Manufacture | 11.2 | 12.8 | 13.5 | 13.7 | 13.9 | 13.5 | 13.3 |
| Limestone and Dolomite Use | 5.2 | 7.0 | 7.4 | 8.4 | 8.2 | 9.1 | 9.2 |
| Natural Gas Flaring | 5.5 | 8.7 | 8.2 | 7.6 | 6.3 | 6.7 | 6.1 |
| Aluminum Production | 6.3 | 5.3 | 5.6 | 5.6 | 5.8 | 5.9 | 5.4 |
| Soda Ash Manufacture and Consumption | 4.1 | 4.3 | 4.2 | 4.4 | 4.3 | 4.2 | 4.2 |
| Titanium Dioxide Production | 1.3 | 1.7 | 1.7 | 1.8 | 1.8 | 1.9 | 2.0 |
| Ferroalloys | 2.0 | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 | 1.7 |
| Carbon Dioxide Consumption | 0.8 | 1.0 | 1.1 | 1.3 | 1.4 | 1.6 | 1.4 |
| Land-Use Change and Forestry (Sink)[a] | (1,097.7) | (1,110.0) | (1,108.1) | (887.5) | (885.9) | (896.4) | (902.5) |
| International Bunker Fuels[b] | 113.9 | 101.0 | 102.3 | 109.9 | 112.9 | 105.3 | 100.2 |
| **$CH_4$** | **651.3** | **657.6** | **643.7** | **633.3** | **627.1** | **620.5** | **614.5** |
| Landfills | 213.4 | 216.6 | 211.5 | 206.4 | 201.0 | 203.1 | 203.5 |
| Enteric Fermentation | 127.9 | 133.2 | 129.6 | 126.8 | 124.9 | 124.5 | 123.9 |
| Natural Gas Systems | 121.2 | 125.7 | 126.6 | 122.7 | 122.2 | 118.6 | 116.4 |
| Coal Mining | 87.1 | 73.5 | 68.4 | 68.1 | 67.9 | 63.7 | 61.0 |
| Manure Management | 29.2 | 34.8 | 34.2 | 35.8 | 38.0 | 37.6 | 37.5 |
| Wastewater Treatment | 24.3 | 26.8 | 27.0 | 27.5 | 27.8 | 28.3 | 28.7 |
| Petroleum Systems | 26.4 | 24.2 | 24.0 | 24.0 | 23.4 | 22.3 | 21.9 |
| Stationary Sources | 7.9 | 8.2 | 8.4 | 7.5 | 7.0 | 7.3 | 7.5 |
| Rice Cultivation | 7.1 | 7.6 | 7.0 | 7.5 | 7.9 | 8.3 | 7.5 |
| Mobile Sources | 4.9 | 4.8 | 4.7 | 4.6 | 4.5 | 4.4 | 4.4 |
| Petrochemical Production | 1.2 | 1.5 | 1.6 | 1.6 | 1.6 | 1.7 | 1.7 |
| Agricultural Residue Burning | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 |
| Silicon Carbide Production | + | + | + | + | + | + | + |
| International Bunker Fuels[b] | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **$N_2O$** | **387.3** | **419.8** | **430.5** | **429.8** | **426.3** | **423.5** | **425.3** |
| Agricultural Soil Management | 267.1 | 283.4 | 292.6 | 297.5 | 298.4 | 296.3 | 297.6 |
| Mobile Sources | 50.9 | 60.4 | 60.1 | 59.7 | 59.1 | 58.7 | 58.3 |
| Nitric Acid | 17.8 | 19.9 | 20.7 | 21.2 | 20.9 | 20.1 | 19.8 |
| Manure Management | 16.0 | 16.4 | 16.8 | 17.1 | 17.1 | 17.1 | 17.5 |
| Stationary Sources | 12.8 | 13.5 | 14.1 | 14.2 | 14.3 | 14.6 | 14.9 |
| Human Sewage | 7.0 | 7.7 | 7.8 | 7.9 | 8.1 | 8.4 | 8.5 |
| Adipic Acid | 14.9 | 17.9 | 17.8 | 11.5 | 7.7 | 7.7 | 8.1 |
| Agricultural Residue Burning | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.4 | 0.5 |
| Waste Combustion | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 |
| International Bunker Fuels[b] | 1.0 | 0.9 | 0.9 | 1.0 | 1.0 | 0.9 | 0.9 |
| **HFCs, PFCs, and $SF_6$** | **93.6** | **98.5** | **111.9** | **116.9** | **127.7** | **120.0** | **121.3** |
| Substitution of Ozone Depleting Substances | 0.9 | 21.8 | 30.6 | 38.0 | 44.9 | 51.3 | 57.8 |
| HCFC-22 Production | 35.0 | 27.0 | 31.1 | 30.0 | 40.2 | 30.4 | 29.8 |
| Electrical Transmission and Distribution | 31.2 | 26.5 | 26.8 | 24.5 | 20.1 | 15.5 | 14.4 |
| Aluminum Production | 18.1 | 11.8 | 12.5 | 11.0 | 9.0 | 8.9 | 7.9 |
| Semiconductor Manufacture | 2.9 | 5.9 | 5.4 | 6.5 | 7.3 | 7.7 | 7.4 |
| Magnesium Production and Processing | 5.5 | 5.5 | 5.5 | 6.9 | 6.2 | 6.1 | 4.0 |
| **Total** | **6,130.7** | **6,481.8** | **6,669.8** | **6,748.1** | **6,756.2** | **6,829.5** | **7,001.2** |
| **Net Emissions (Sources and Sinks)** | **5,033.0** | **5,371.8** | **5,561.7** | **5,860.5** | **5,870.3** | **5,933.1** | **6,098.7** |

+ Does not exceed 0.05 Tg $CO_2$ Eq.

[a] Sinks are only included in net emissions total, and are based partially on projected activity data. Parentheses indicate negative values (or sequestration).

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

Note: Totals may not sum due to independent rounding.

Figure ES-2

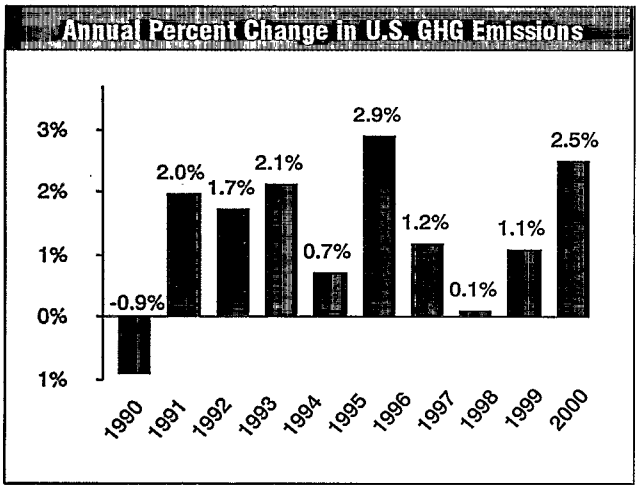



Figure ES-4

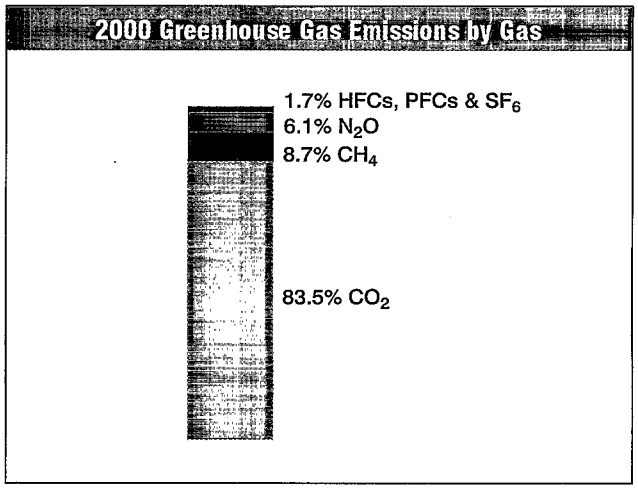



Figure ES-3

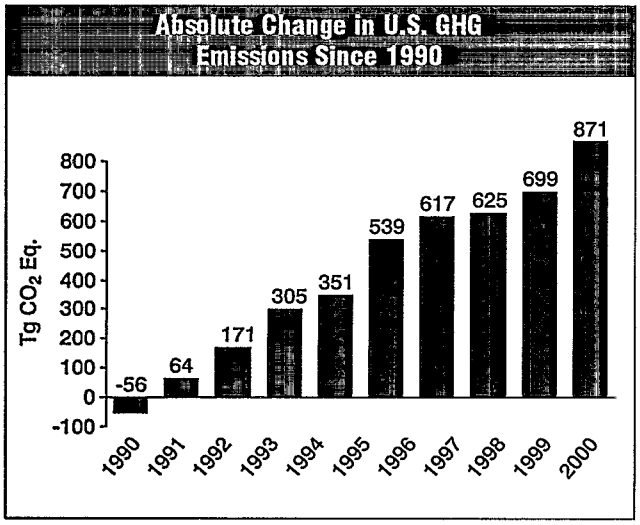



Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 2000. The primary greenhouse gas emitted by human activities in the United States was $CO_2$. The largest source of $CO_2$, and of overall greenhouse gas emissions, was fossil fuel combustion. Methane emissions resulted primarily from decomposition of wastes in landfills, enteric fermentation associated with domestic livestock, and natural gas systems. Emissions of $N_2O$ were dominated by agricultural soil management and mobile source fossil fuel combustion. 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 the majority of PFC emissions were a by-product of primary aluminum production.

As the largest source of U.S. greenhouse gas emissions, $CO_2$ from fossil fuel combustion accounted for a nearly constant 79 percent of global warming potential (GWP) weighted emissions from 1990 to 2000.[6] Emissions from this source category grew by 18 percent (843.4 Tg $CO_2$ Eq.) from 1990 to 2000 and were responsible for most of the increase in national emissions during this period. The annual increase in $CO_2$ emissions from fossil fuel combustion was 3.2 percent in 2000, double the source's average annual rate of 1.6 percent from 1990 through 2000. 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 and other countries generally fluctuates in response to changes in economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, 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 would be expected to have proportionally greater fossil fuel

[6] If a full accounting of emissions from fossil fuel combustion is made by including emissions from the combustion of international bunker fuels and $CH_4$ and $N_2O$ emissions associated with fuel combustion, then this percentage increases to a nearly constant 80 percent during the 1990s.

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

Energy-related $CO_2$ emissions are also a function of the type fuel or energy consumed and its carbon intensity. Producing heat or electricity using natural gas instead of coal, for example, can reduce the $CO_2$ emissions associated with energy consumption because of the lower carbon content of natural gas per unit of useful energy produced. Table ES-2 shows annual changes in emissions during the last few years of the 1990s for selected fuel types and sectors.

Carbon dioxide emissions from fossil fuel combustion grew rapidly in 1996, due primarily to two factors: 1) fuel switching by electric utilities from natural gas to more carbon intensive coal as colder winter conditions and the associated rise in demand for natural gas from residential and commercial customers for heating caused gas prices to rise sharply; and 2) higher consumption of petroleum fuels for transportation. Milder weather conditions in summer and winter moderated the growth in emissions in 1997; however, the shut-down of several nuclear power plants lead electric utilities to increase their consumption of coal and other fuels to offset the lost nuclear capacity.

In 1998, weather conditions were again a dominant factor in slowing the growth in emissions. Warm winter temperatures resulted in a significant drop in residential and commercial natural gas consumption. This drop in emissions from natural gas used for heating was primarily offset by two factors: 1) electric utility emissions, which increased in part due to a hot summer and its associated air conditioning demand; and 2) increased motor gasoline consumption for transportation.

In 1999, the increase in emissions from fossil fuel combustion was driven largely by growth in petroleum consumption for transportation. In addition, residential and commercial heating fuel demand partially recovered as winter temperatures dropped relative to 1998, although temperatures were still warmer than normal.[7] These increases were offset, in part, by a decline in emissions from electric power producers due primarily to: 1) an increase in net generation of electricity by nuclear plants to record levels, which reduced demand from fossil fuel plants; and 2) moderated summer temperatures compared to the previous year-thereby reducing electricity demand for air conditioning.

Emissions from fuel combustion increased considerably in 2000, due to several factors. The primary reason for the increase was the robust U.S. economy, which produced a

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

| Sector | Fuel Type | 1995 to 1996 | | 1996 to 1997 | | 1997 to 1998 | | 1998 to 1999 | | 1999 to 2000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Electricity Generation | Coal | 91.2 | 5.5% | 49.9 | 2.9% | 28.0 | 1.6% | 11.1 | 0.6% | 87.3 | 4.8% |
| Electricity Generation | Natural Gas | (24.3) | -8.8% | 17.9 | 7.1% | 32.4 | 12.0% | 7.5 | 2.5% | 31.5 | 10.2% |
| Electricity Generation | Petroleum | 5.0 | 7.8% | 8.9 | 12.9% | 28.1 | 35.8% | 1.2 | 1.2% | (12.5) | -11.6% |
| Transportation[a] | Petroleum | 38.7 | 2.5% | 7.6 | 0.5% | 32.7 | 2.1% | 68.0 | 4.2% | 59.6 | 3.5% |
| Residential | Natural Gas | 21.4 | 8.1% | (14.0) | -4.9% | (24.0) | -8.9% | 10.0 | 4.0% | 11.8 | 4.6% |
| Commercial | Natural Gas | 7.0 | 4.3% | 3.1 | 1.8% | (11.1) | -6.4% | 1.7 | 1.0% | 15.6 | 9.4% |
| Industrial | Coal | (5.7) | -4.4% | 1.4 | 1.1% | (5.6) | -4.4% | (4.4) | -3.6% | (14.1) | -12.1% |
| Industrial | Natural Gas | 16.3 | 4.1% | (5.2) | -1.3% | (31.6) | -7.7% | (5.0) | -1.3% | (1.6) | -0.4% |
| **All Sectors[b]** | **All Fuels[b]** | **181.6** | **3.6%** | **72.9** | **1.4%** | **16.6** | **0.3%** | **92.4** | **1.7%** | **174.7** | **3.2%** |

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

[7] Normal is calculated as the average of the years 1961 through 1990.

high demand for fuels—especially for petroleum in the transportation sector—despite increases in the price of both natural gas and petroleum. Colder winter conditions relative to the previous year triggered a rise in residential and commercial demand for heating. Structural and other economic changes taking place within U.S. industry—especially manufacturing—lead to lower coal consumption. Additionally, electricity generation became more carbon intensive as coal and natural gas consumption offset reduced hydropower output. In sum, emissions from fossil fuel combustion exhibited the second highest annual increase since 1990.

Overall, from 1990 to 2000, total emissions of $CO_2$ and $N_2O$ increased by 841.5 (17 percent) and 38.0 Tg $CO_2$ Eq. (10 percent), respectively, while $CH_4$ emissions decreased by 36.8 Tg $CO_2$ Eq. (6 percent). During the same period, aggregate weighted emissions of HFCs, PFCs, and $SF_6$ rose by 27.7 Tg $CO_2$ Eq. (30 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 and in landfilled carbon, which were estimated to be 13 percent of total emissions in 2000.

Other significant trends in emissions from additional source categories over the eleven year period from 1990 through 2000 included the following:

- Aggregate HFC and PFC emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) increased by 56.8 Tg $CO_2$ Eq. This increase was significantly offset, however, by reductions in PFC emissions from aluminum production (10.2 Tg $CO_2$ Eq. or 56 percent), reductions in emissions of HFC-23 from the production of HCFC-22 (5.2 Tg $CO_2$ Eq. or 15 percent), and reductions of $SF_6$ from electric power transmission and distribution systems (16.8 Tg $CO_2$ Eq. or 54 percent). Reductions in PFC emissions from aluminum production were the result of both industry emission reduction efforts and lower domestic aluminum production. HFC-23 emissions from the production of HCFC-22 decreased due to a reduction in the intensity of emissions from that source, despite increased HCFC-22 production. Reduced emissions of $SF_6$ from electric power transmission and distribution systems are primarily the result of higher purchase prices for $SF_6$ and efforts by industry to reduce emissions.
- Methane emissions from coal mining dropped by 26.2 Tg $CO_2$ Eq. (30 percent) as a result of the mining of less gassy coal from underground mines and the increased use of methane from degasification systems.
- Nitrous oxide emissions from agricultural soil management increased by 30.5 Tg $CO_2$ Eq. (11 percent) as fertilizer consumption and cultivation of nitrogen fixing crops rose.
- By 1998, all of the three major adipic acid producing plants had implemented $N_2O$ abatement technology, and as a result, emissions fell by 6.8 Tg $CO_2$ Eq. (46 percent). The majority of this decline occurred from 1997 to 1998, despite increased production.
- Carbon dioxide emissions from feedstock uses of coal coke for iron and steel production decreased by 19.7 Tg $CO_2$ Eq. (23 percent), as imports of steel have increased.
- Methane emissions from U.S. landfills decreased 5 percent, as the amount of landfill gas collected and combusted by landfill operators has increased.
- Emissions of $N_2O$ from mobile combustion rose by 7.4 Tg $CO_2$ Eq. (14 percent), primarily due to an increased average $N_2O$ generation rate for the U.S. highway vehicle fleet.

## Box ES-1: Recent Trends in Various U.S. Greenhouse Gas Emissions-Related Data

There are several ways to assess a nation's greenhouse gas emitting intensity. The basis for measures of intensity can be 1) per unit of aggregate energy consumption, because energy-related activities are the largest sources of emissions; 2) per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; 3) per unit of electricity consumption, because the electric power industry has been the largest source of U.S. greenhouse gas emissions in the United States; 4) per unit of total gross domestic product as a measure of national economic activity; or 5) on a per capita basis. Depending upon the measure used, the United States could appear to have reduced or increased its national greenhouse gas intensity during the 1990s.

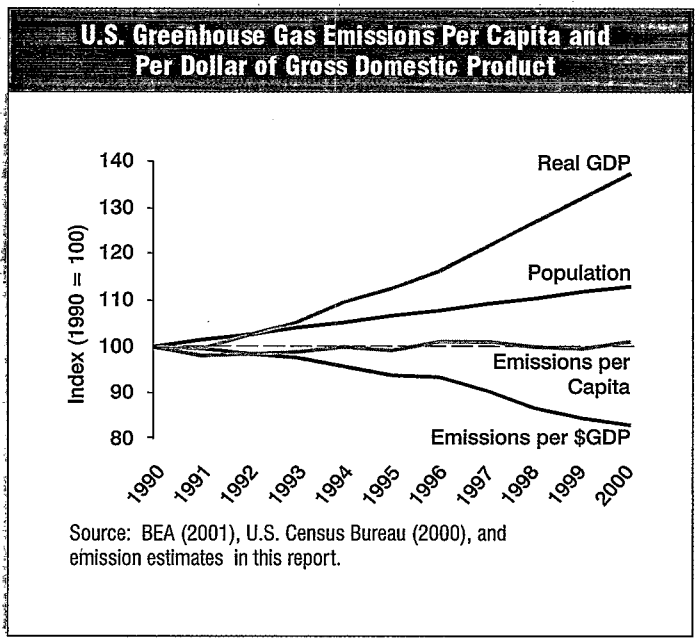
Table ES-3 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. Greenhouse gas emissions in the U.S. have grown at an average annual rate of 1.3 percent since 1990. This rate is slightly slower than that for total energy or fossil fuel consumption—thereby indicating an improved or lower greenhouse gas emitting intensity—and much slower than that for either electricity consumption or overall gross domestic product. At the same time, total U.S. greenhouse gas emissions have grown at about the same rate as national population during the last decade (see Figure ES-5). Overall, global atmospheric $CO_2$ concentrations—a function of many complex anthropogenic and natural processes—are increasing at 0.4 percent per year.

**Table ES-3: Recent Trends in Various U.S. Data (Index 1990 = 100)**

| Variable | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | Growth Rate[f] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GHG Emissions[a] | 99 | 101 | 103 | 105 | 106 | 109 | 110 | 110 | 111 | 114 | 1.3% |
| Energy Consumption[b] | 100 | 101 | 104 | 106 | 108 | 111 | 112 | 112 | 115 | 117 | 1.6% |
| Fossil Fuel Consumption[b] | 99 | 101 | 103 | 106 | 107 | 110 | 112 | 112 | 114 | 116 | 1.5% |
| Electricity Consumption[b] | 102 | 102 | 105 | 108 | 111 | 114 | 116 | 120 | 122 | 125 | 2.3% |
| GDP[c] | 100 | 103 | 105 | 110 | 112 | 116 | 122 | 127 | 132 | 138 | 3.2% |
| Population[d] | 101 | 103 | 104 | 105 | 107 | 108 | 109 | 110 | 112 | 113 | 1.2% |
| Global Atmospheric $CO_2$ Concentration[e] | 100 | 101 | 101 | 101 | 102 | 102 | 103 | 104 | 104 | 104 | 0.4% |

[a] GWP weighted values
[b] Energy content weighted values (EIA 2001)
[c] Gross Domestic Product in chained 1996 dollars (BEA 2000)
[d] (U.S. Census Bureau 2000)
[e] Mauna Loa Observatory, Hawaii (Keeling and Whorf 2000)
[f] Average annual growth rate

**Figure ES-5**

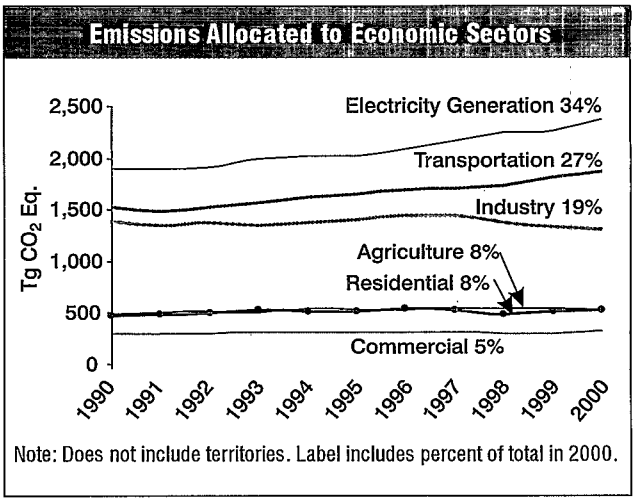



Source: BEA (2001), U.S. Census Bureau (2000), and emission estimates in this report.

## Emissions by Economic Sector

Throughout this report, emission estimates are grouped into six sectors (i.e., chapters) defined by the IPCC: Energy, Industrial Processes, Solvent Use, Agriculture, Land-Use Change and Forestry, and Waste. While it is important to use this characterization for methodological reasons, it is also useful to allocate emissions into sectoral categories that are more intuitive. This section reports emissions by the following economic sectors: Residential, Commercial, Industry, Transportation, Electricity Generation, and Agriculture, and U.S. Territories. Table ES-4 summarizes emissions from each of these sectors. Figure ES-6 shows the trend in emissions by sector from 1990 to 2000.

Figure ES-6




Note: Does not include territories. Label includes percent of total in 2000.

Using this categorization scheme, emissions from electricity generation accounted for the largest portion (34 percent) of U.S. greenhouse gas emissions. The 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 2000. In contrast to electricity generation and transportation, emissions from industry have declined over the past decade, as structural changes have occurred in the U.S. economy (i.e., shifts from a manufacturing base to a service-based economy), fuel switching has occurred, and efficiency improvements have been made. The remaining 20 percent of U.S. greenhouse gas emissions were contributed by the residential, agriculture, commercial, and U.S. territory economic sectors combined. Residences accounted for about 8 percent, and primarily consisted of carbon dioxide ($CO_2$) emissions from fossil fuel combustion. Activities related to agriculture accounted for roughly 8 percent of U.S. emissions, but unlike all other economic sectors these emissions were dominated by nitrous oxide ($N_2O$) emissions from agricultural soils instead of $CO_2$ from fossil fuel combustion. The commercial sector accounted for about 5 percent of emissions, while U.S. territories accounted for less than 1 percent of total emissions.

Carbon dioxide was also emitted and sequestered by a variety of activities related to land-use change and forestry.

**Table ES-4: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg $CO_2$ Eq. and Percent of Total in 2000)**

| Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | Percent[a] |
|---|---|---|---|---|---|---|---|---|
| Electricity Generation | 1,898.2 | 2,024.3 | 2,096.9 | 2,171.6 | 2,256.1 | 2,271.2 | 2,376.9 | 33.9% |
| Transportation | 1,527.7 | 1,652.4 | 1,695.2 | 1,708.5 | 1,737.4 | 1,813.3 | 1,877.0 | 26.8% |
| Industry | 1,393.9 | 1,400.9 | 1,447.6 | 1,442.7 | 1,385.9 | 1,341.1 | 1,314.6 | 18.8% |
| Agriculture | 494.7 | 533.3 | 533.3 | 544.2 | 545.1 | 544.9 | 535.5 | 7.6% |
| Residential | 484.6 | 522.7 | 549.0 | 531.1 | 494.3 | 516.0 | 531.6 | 7.6% |
| Commercial | 303.5 | 313.0 | 320.8 | 320.9 | 302.9 | 307.1 | 327.6 | 4.7% |
| U.S. Territories | 28.1 | 35.3 | 27.0 | 29.1 | 34.4 | 35.8 | 38.0 | 0.5% |
| **Total** | **6,130.7** | **6,481.8** | **6,669.8** | **6,748.1** | **6,756.2** | **6,829.5** | **7,001.2** | **100.0%** |
| Sinks | (1,097.7) | (1,110.0) | (1,108.1) | (887.5) | (885.9) | (896.4) | (902.5) | -- |
| Net Emissions (Sources and Sinks) | 5,033.0 | 5,371.8 | 5,561.7 | 5,860.5 | 5,870.3 | 5,933.1 | 6,098.7 | -- |

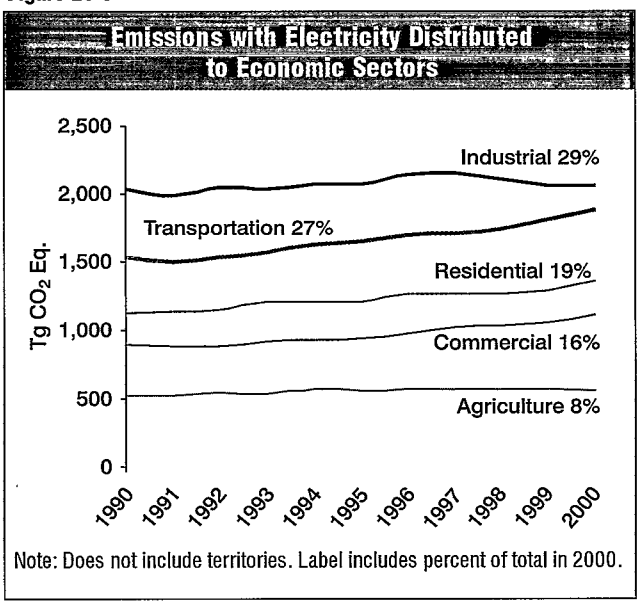
Note: Totals may not sum due to independent rounding. Includes all emissions of $CO_2$, $CH_4$, $N_2O$, HFCs, PFCs, and $SF_6$.
See Table 1-11 for more detailed data.
[a] Percent of total in 2000.

Table ES-5 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 electric generation were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity.[8] These three source categories include $CO_2$ from fossil fuel combustion, $CH_4$ and $N_2O$ from stationary sources, and $SF_6$ from electrical transmission and distribution.[9]

When emissions from electricity are distributed among these sectors, industry accounts for the largest share of U.S. greenhouse gas emissions (29 percent). Emissions from the residential and commercial sectors also increase substantially due to their relatively large share of electricity consumption. Transportation activities remain the second largest contributor to emissions. In all sectors except agriculture, $CO_2$ accounts for more than 75 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels. Figure ES-7 shows the trend in these emissions by sector from 1990 to 2000.

The following sections describe the concept of Global Warming Potentials (GWPs), present the anthropogenic sources and sinks of greenhouse gas emissions in the United States, briefly discuss emission pathways, further summarize the emission estimates, and explain the relative importance of emissions from each source category.

**Figure ES-7**




Note: Does not include territories. Label includes percent of total in 2000.

## Global Warming Potentials

Gases in the atmosphere can contribute to the greenhouse effect both directly and indirectly. Direct effects occur when the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformations of the original gas 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).[10] The concept of a Global Warming Potential (GWP) has been developed to compare the ability of each

**Table ES-5: U.S Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (Tg $CO_2$ Eq.)**

| Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Industry | 2,029.7 | 2,071.6 | 2,136.2 | 2,151.5 | 2,104.0 | 2,059.7 | 2,054.7 |
| Transportation | 1,530.5 | 1,655.1 | 1,697.9 | 1,711.2 | 1,740.2 | 1,816.0 | 1,879.7 |
| Residential | 1,131.2 | 1,213.1 | 1,270.1 | 1,265.6 | 1,266.3 | 1,293.5 | 1,357.4 |
| Commercial | 890.7 | 944.9 | 974.3 | 1,022.4 | 1,040.0 | 1,057.5 | 1,113.8 |
| Agriculture | 520.5 | 561.8 | 564.3 | 568.2 | 571.4 | 567.0 | 557.7 |
| U.S. Territories | 28.1 | 35.3 | 27.0 | 29.1 | 34.4 | 35.8 | 38.0 |
| **Total** | **6,130.7** | **6,481.8** | **6,669.8** | **6,748.1** | **6,756.2** | **6,829.5** | **7,001.2** |

Note: Totals may not sum due to independent rounding. Includes all emissions of $CO_2$, $CH_4$, $N_2O$, HFCs, PFCs, and $SF_6$.
See Table 1-12 for more detailed data.

[8] Emissions were not distributed to U.S. territories, since they do not consume electricity produced by the electricity generation sector.

[9] 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.

[10] Albedo is a measure of the Earth's reflectivity; see the Glossary (Annex Z) for definition.

### Box ES-2: The IPCC Third Assessment Report and Global Warming Potentials

The IPCC recently published its Third Assessment Report (TAR), providing the most current and comprehensive scientific assessment of climate change. Within this report, the global warming potentials (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 Second Assessment Report, 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 Second Assessment Report, 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 Second Assessment Report, 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 Second Assessment Report. Table ES-6 presents the new Global Warming Potentials, relative to those presented in the Second Assessment Report.

**Table ES-6: Comparison of 100 Year GWPs**

| Gas | SAR | TAR | Change | |
|---|---|---|---|---|
| | | | Absolute | Percent |
| Carbon dioxide ($CO_2$) | 1 | 1 | NC | NC |
| Methane ($CH_4$)* | 21 | 23 | 2 | 10% |
| Nitrous oxide ($N_2O$) | 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, 1996)
NC (No Change)
* The methane 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.

Although the GWPs have been updated by the IPCC, estimates of emissions presented in this Inventory will continue to use the GWPs from the Second Assessment Report. The guidelines under which this Inventory is developed, the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and the UNFCCC reporting guidelines for national inventories[11] were developed prior to the publication of the TAR. Therefore, to comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends (see Annex Q).

greenhouse gas to trap heat in the atmosphere relative to another gas. Carbon dioxide ($CO_2$) was chosen as the reference gas to be consistent with IPCC guidelines.

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, and have only indirect effects on radiative forcing (IPCC 1996).

[11] See FCCC/CP/1999/7 at <www.unfccc.de>.

The GWP of a greenhouse gas is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 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. Indirect radiative forcing occurs when chemical transformations involving the original gas produces 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 $CO_2$ equivalents (Tg $CO_2$ Eq.)[12] All gases in this executive summary are presented in units of Tg $CO_2$ Eq. The relationship between gigagrams (Gg) of a gas and Tg $CO_2$ Eq. can be expressed as follows:

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

While any time period can be selected, the 100 year GWPs recommended by the IPCC and employed by the United States for policy making and reporting purposes were used in this report (IPCC 1996). GWP values are listed below in Table ES-7.

**Table ES-7: Global Warming Potentials (100 Year Time Horizon)**

| Gas | GWP |
|---|---|
| Carbon dioxide ($CO_2$) | 1 |
| Methane ($CH_4$)* | 21 |
| Nitrous oxide ($N_2O$) | 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 methane 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.

## 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 (sinks) and are emitted to the atmosphere annually through natural processes (sources). When in equilibrium, carbon fluxes among these various reservoirs are roughly balanced. Since the Industrial Revolution, this equilibrium of atmospheric carbon has been altered. Atmospheric concentrations of $CO_2$ have risen about 31 percent (IPCC 2001), principally because of fossil fuel combustion, which accounted for 96 percent of total U.S. $CO_2$ emissions in 2000. Globally, approximately 23,300 Tg of $CO_2$ were added to the atmosphere through the combustion of fossil fuels at the end of the 1990s, of which the United States accounted for about 24 percent (see Figure ES-8).[13] Changes in land use and forestry practices can also emit $CO_2$ (e.g., through conversion of forest land to agricultural or urban use) or can act as a sink for $CO_2$ (e.g., through net additions to forest biomass).

Figure ES-9 and Table ES-8 summarize U.S. sources and sinks of $CO_2$. The remainder of this section then discusses $CO_2$ emission trends in greater detail.

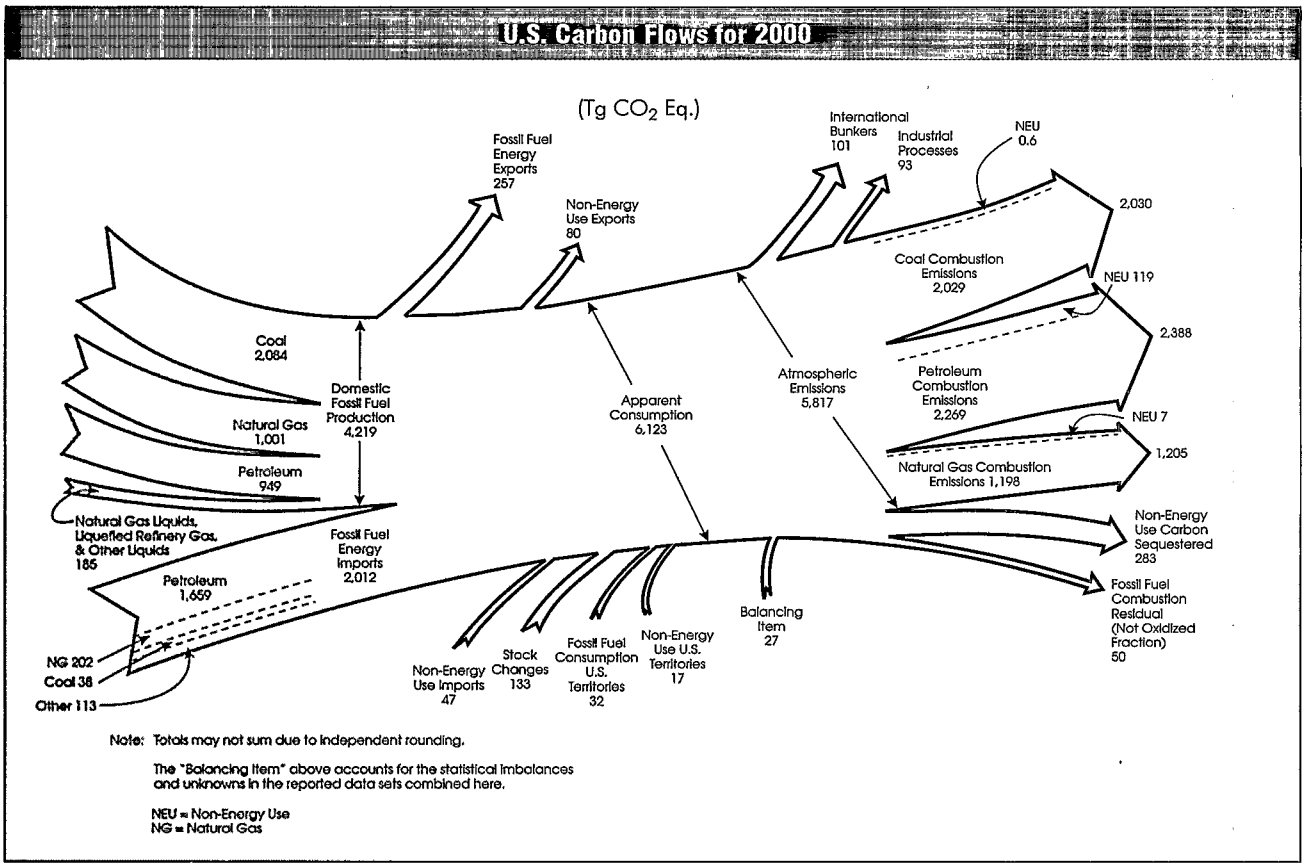
### Energy

Energy-related activities accounted for the vast majority of U.S. $CO_2$ emissions for the period of 1990 through 2000. Carbon dioxide from fossil fuel combustion was the dominant contributor. In 2000, approximately 85 percent of the energy consumed in the United States was produced through the combustion of fossil fuels. The remaining 15 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy (see Figure ES-10 and Figure ES-11). A discussion of specific trends related to $CO_2$ emissions from energy consumption is presented below.

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

[13] Global $CO_2$ emissions from fossil fuel combustion were taken from Marland et al. (2001). <http://cdiac.esd.ornl.gov/trends/emis/meth_reg.htm>

Figure ES-8




Note: Totals may not sum due to independent rounding.

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

NEU = Non-Energy Use
NG = Natural Gas

Figure ES-9

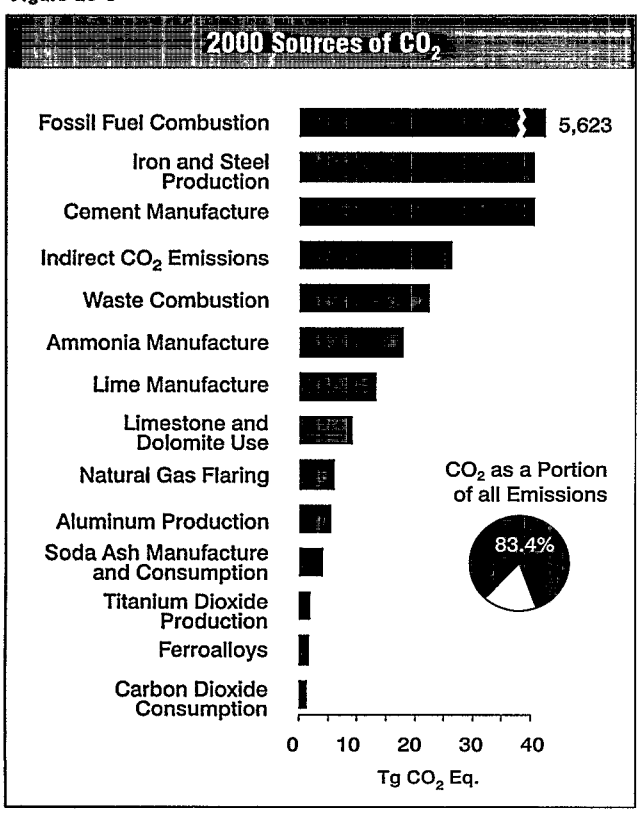
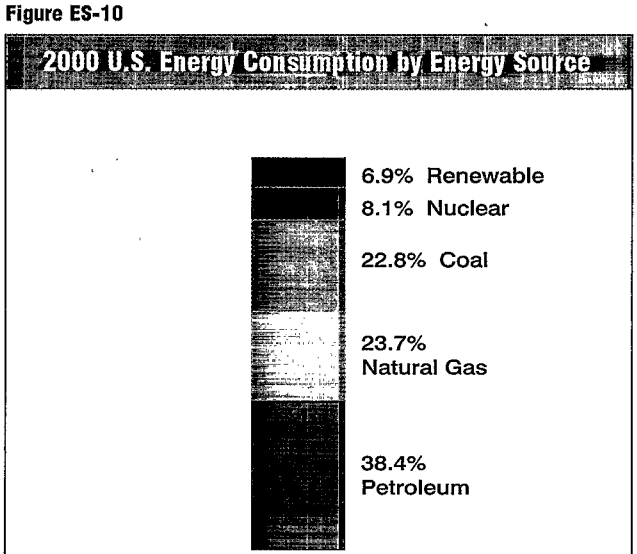



Figure ES-10



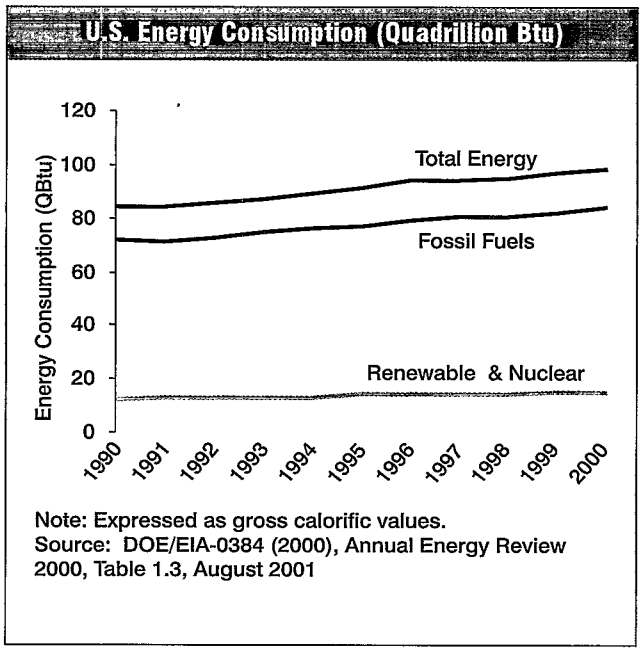

Source: DOE/EIA-0384(2000), Annual Energy Review 2000, Table 1.3, August 2001.

**Table ES-8: U.S. Sources of $CO_2$ Emissions and Sinks (Tg $CO_2$ Eq.)**

| Source or Sink | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Fossil Fuel Combustion | 4,779.8 | 5,085.0 | 5,266.6 | 5,339.6 | 5,356.2 | 5,448.6 | 5,623.3 |
| Electricity Generation | 1,858.9 | 1,989.3 | 2,061.2 | 2,137.9 | 2,226.4 | 2,246.2 | 2,352.5 |
| Transportation | 1,471.8 | 1,579.4 | 1,618.7 | 1,628.8 | 1,655.0 | 1,728.2 | 1,789.5 |
| Industrial | 871.6 | 894.9 | 936.5 | 935.2 | 881.1 | 858.1 | 829.2 |
| Residential | 332.1 | 362.3 | 390.4 | 374.9 | 341.8 | 360.5 | 374.8 |
| Commercial | 217.3 | 223.9 | 232.8 | 233.7 | 217.5 | 219.8 | 239.3 |
| U.S. Territories | 28.1 | 35.3 | 27.0 | 29.1 | 34.4 | 35.8 | 38.0 |
| Iron and Steel Production | 85.4 | 74.4 | 68.3 | 76.1 | 67.4 | 64.4 | 65.7 |
| Cement Manufacture | 33.3 | 36.8 | 37.1 | 38.3 | 39.2 | 40.0 | 41.1 |
| Indirect $CO_2$ From $CH_4$ Oxidation | 30.9 | 29.5 | 28.9 | 28.4 | 28.2 | 27.0 | 26.3 |
| Waste Combustion | 14.1 | 18.6 | 19.6 | 21.3 | 20.3 | 21.8 | 22.5 |
| Ammonia Manufacture | 18.5 | 18.9 | 19.5 | 19.5 | 20.1 | 18.9 | 18.0 |
| Lime Manufacture | 11.2 | 12.8 | 13.5 | 13.7 | 13.9 | 13.5 | 13.3 |
| Limestone and Dolomite Use | 5.2 | 7.0 | 7.4 | 8.4 | 8.2 | 9.1 | 9.2 |
| Natural Gas Flaring | 5.5 | 8.7 | 8.2 | 7.6 | 6.3 | 6.7 | 6.1 |
| Aluminum Production | 6.3 | 5.3 | 5.6 | 5.6 | 5.8 | 5.9 | 5.4 |
| Soda Ash Manufacture and Consumption | 4.1 | 4.3 | 4.2 | 4.4 | 4.3 | 4.2 | 4.2 |
| Titanium Dioxide Production | 1.3 | 1.7 | 1.7 | 1.8 | 1.8 | 1.9 | 2.0 |
| Ferroalloys | 2.0 | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 | 1.7 |
| Carbon Dioxide Consumption | 0.8 | 1.0 | 1.1 | 1.3 | 1.4 | 1.6 | 1.4 |
| Land-Use Change and Forestry (Sink)[a] | (1,097.7) | (1,110.0) | (1,108.1) | (887.5) | (885.9) | (896.4) | (902.5) |
| International Bunker Fuels[b] | 113.9 | 101.0 | 102.3 | 109.9 | 112.9 | 105.3 | 100.2 |
| **Total** | **4,998.5** | **5,305.9** | **5,483.7** | **5,568.0** | **5,575.1** | **5,665.5** | **5,840.0** |
| **Net Emissions (Sources and Sinks)** | **3,900.8** | **4,195.9** | **4,375.6** | **4,680.5** | **4,689.2** | **4,769.1** | **4,937.5** |

[a] Sinks are only included in net emissions total, and are based partially on projected activity data. Parentheses indicate negative values (or sequestration).
[b] Emissions from International Bunker Fuels are not included in totals.
Note: Totals may not sum due to independent rounding.

**Figure ES-11**




Note: Expressed as gross calorific values.
Source: DOE/EIA-0384 (2000), Annual Energy Review 2000, Table 1.3, August 2001

### Fossil Fuel Combustion (5,623.3 Tg $CO_2$ Eq.)

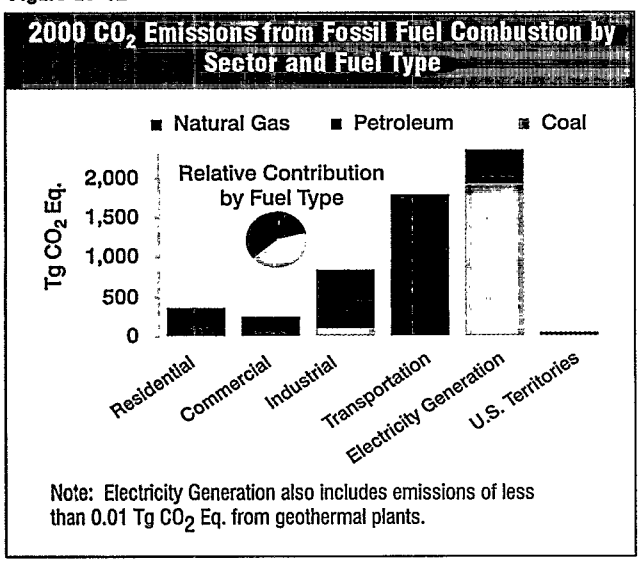
As fossil fuels are combusted, the carbon stored in them is almost entirely emitted as $CO_2$. The amount of carbon in fuels per unit of energy content varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of energy, while petroleum has about 25 percent less carbon than coal, and natural gas about 45 percent less. From 1990 through 2000, petroleum supplied the largest share of U.S. energy demands, accounting for an average of 39 percent of total energy consumption. Natural gas and coal followed in order of importance, accounting for an average of 24 and 23 percent of total energy consumption, respectively. Most petroleum was consumed in the transportation end-use sector, while the vast majority of coal was used by electric power generators, and natural gas was consumed largely in the industrial and residential end-use sectors.

Emissions of $CO_2$ from fossil fuel combustion increased at an average annual rate of 1.6 percent from 1990 to 2000. The fundamental factors behind this trend include (1) a robust domestic economy, (2) relatively low energy prices

as compared to 1990, (3) significant growth in emissions from transportation activities and electricity generation, and (4) heavier reliance on nuclear energy. Between 1990 and 2000, $CO_2$ emissions from fossil fuel combustion steadily increased from 4,779.8 Tg $CO_2$ Eq. to 5,623.3 Tg $CO_2$ Eq.—an 18 percent total increase over the eleven year period.

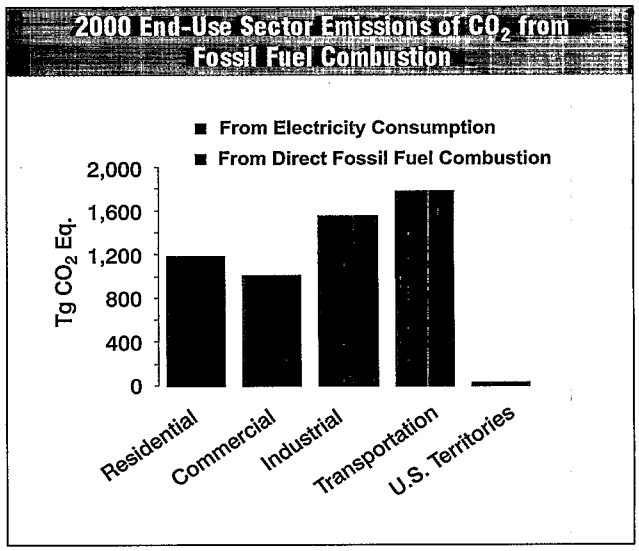
As introduced above, the four end-use sectors contributing to $CO_2$ emissions from fossil fuel combustion include industrial, transportation, residential, and commercial. Electricity generation also emits $CO_2$, although these emissions are produced as they consume fossil fuel to provide electricity to one of the four end-use sectors. For the discussion below, electricity generation emissions have been distributed to each end-use sector based upon the sector's share of aggregate electricity consumption. This method of distributing emissions assumes that each end-use sector consumes electricity that is generated with the national average mix of fuels according to their carbon intensity. In reality, sources of electricity vary widely in carbon intensity. By assuming the same carbon intensity for each end-use sector's electricity consumption, for example, emissions attributed to the residential end-use sector may be underestimated, while emissions attributed to the industrial end-use sector may be overestimated. Emissions from electricity generation are also addressed separately after the end-use sectors have been discussed.

**Figure ES-12**




Note: Electricity Generation also includes emissions of less than 0.01 Tg $CO_2$ Eq. from geothermal plants.

**Figure ES-13**




Note that emissions from U.S. territories are calculated separately due to a lack of specific consumption data for the individual end-use sectors. Table ES-9, Figure ES-12, and Figure ES-13 summarize $CO_2$ emissions from fossil fuel combustion by end-use sector.

*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 2000. About half of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The other half of the emissions resulted from consuming electricity for motors, electric furnaces, ovens, lighting, and other applications.

*Transportation End-Use Sector.* Transportation activities—excluding international bunker fuels—accounted for 32 percent of $CO_2$ emissions from fossil fuel combustion in 2000.[14] Virtually all of the energy consumed in this end-use sector came from petroleum products. Just over half of the emissions resulted from gasoline consumption in motor vehicles. The remaining emissions came from other transportation activities, including the combustion of diesel fuel in heavy-duty vehicles and jet fuel in aircraft.

[14] 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 2000.

**Table ES-9: $CO_2$ Emissions from Fossil Fuel Combustion by End-Use Sector (Tg $CO_2$ Eq.)**

| End-Use Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Industrial** | **1,519.6** | **1,563.4** | **1,623.5** | **1,640.8** | **1,598.1** | **1,575.7** | **1,568.5** |
| Combustion | 871.6 | 894.9 | 936.5 | 935.2 | 881.1 | 858.1 | 829.2 |
| Electricity | 648.0 | 668.5 | 687.0 | 705.6 | 717.0 | 717.7 | 739.3 |
| **Transportation** | **1,474.5** | **1,582.0** | **1,621.3** | **1,631.5** | **1,657.7** | **1,731.0** | **1,792.3** |
| Combustion | 1,471.8 | 1,579.4 | 1,618.7 | 1,628.8 | 1,655.0 | 1,728.2 | 1,789.5 |
| Electricity | 2.7 | 2.6 | 2.7 | 2.7 | 2.7 | 2.7 | 2.8 |
| **Residential** | **965.3** | **1,050.6** | **1,109.9** | **1,106.1** | **1,112.6** | **1,136.9** | **1,199.8** |
| Combustion | 332.1 | 362.3 | 390.4 | 374.9 | 341.8 | 360.5 | 374.8 |
| Electricity | 633.2 | 688.2 | 719.5 | 731.2 | 770.8 | 776.5 | 825.0 |
| **Commercial** | **792.3** | **853.8** | **884.8** | **932.0** | **953.4** | **969.2** | **1,024.7** |
| Combustion | 217.3 | 223.9 | 232.8 | 233.7 | 217.5 | 219.8 | 239.3 |
| Electricity | 575.0 | 629.9 | 652.0 | 698.4 | 735.9 | 749.4 | 785.4 |
| **U.S. Territories** | **28.1** | **35.3** | **27.0** | **29.1** | **34.4** | **35.8** | **38.0** |
| **Total** | **4,779.8** | **5,085.0** | **5,266.6** | **5,339.6** | **5,356.2** | **5,448.6** | **5,623.3** |
| **Electricity Generation** | **1,858.9** | **1,989.3** | **2,061.2** | **2,137.9** | **2,226.4** | **2,246.2** | **2,352.5** |

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.

*Residential and Commercial End-Use Sectors.* The residential and commercial end-use sectors accounted for 21 and 18 percent, respectively, of $CO_2$ emissions from fossil fuel consumption in 2000. Both sectors relied heavily on electricity for meeting energy needs, with 69 and 77 percent, respectively, of their emissions attributable to electricity consumption for lighting, heating, cooling, and operating appliances. The remaining emissions were largely due to the consumption of natural gas and petroleum, primarily for meeting heating and cooking needs.

*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 generation is responsible for consuming 34 percent of U.S. energy from fossil fuels and emitted 42 percent of the $CO_2$ from fossil fuel combustion in 2000. 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 in the United States in 2000. Consequently, changes in electricity demand have a significant impact on coal consumption and associated $CO_2$ emissions.

### Indirect $CO_2$ from $CH_4$ Oxidation (26.3 Tg $CO_2$ Eq.)

Indirect $CO_2$ emissions are formed in the atmosphere from the oxidation of methane ($CH_4$). Although this indirect $CO_2$ is a greenhouse gas, its generation is not accounted for within the global warming potential (GWP) of $CH_4$. Thus for the sake of completion, it is necessary to account for these indirect emissions whenever anthropogenic sources of $CH_4$ are calculated. Non-biogenic and non-combustion emissions of $CH_4$ are considered in this calculation.

### Waste Combustion (22.5 Tg $CO_2$ Eq.)

Waste combustion involves the burning of garbage and non-hazardous solids, referred to as municipal solid waste (MSW), as well as the burning of hazardous waste. Waste combustion, in the United States, is usually performed to recover energy from the waste materials. Carbon dioxide emissions arise from the organic (i.e., carbon) materials found in these wastes. Within MSW, many products contain carbon of biogenic origin, and the $CO_2$ emissions from their combustion are accounted for under the Land-Use Change and Forestry chapter. However, several components of MSW—plastics, synthetic rubber, synthetic fibers, and carbon black—are of fossil fuel origin, and are included as sources of $CO_2$ emissions.

### Natural Gas Flaring (6.1 Tg $CO_2$ Eq.)

Carbon dioxide is produced when natural gas from oil wells is flared (i.e., combusted) to relieve rising pressure or to dispose of small quantities of gas that are not commercially marketable. In 2000, flaring activities emitted less than 0.1 percent of U.S. $CO_2$ emissions.

### Biomass Combustion (184.4 Tg $CO_2$ Eq.)

Biomass in the form of fuel wood and wood waste was used primarily by the industrial end-use sector, while the transportation end-use sector was the predominant user of biomass-based fuels, such as ethanol from corn and woody crops.

Although these fuels do emit $CO_2$, in the long run the $CO_2$ emitted from biomass consumption does not increase atmospheric $CO_2$ concentrations if the biogenic carbon emitted is offset by the growth of new biomass. For example, fuel wood burned one year but re-grown the next only recycles carbon, rather than creating a net increase in total atmospheric carbon. Net carbon fluxes from changes in biogenic carbon reservoirs in wooded or croplands are accounted for under Land-Use Change and Forestry.

The industrial sector accounted for 74 percent of gross $CO_2$ emissions from biomass combustion, and the residential sector accounted for 19 percent. Ethanol consumption by the transportation sector accounted for only 5 percent.

## Industrial Processes

Emissions are produced as a by-product of many non-energy-related activities. For example, industrial processes can chemically transform raw materials. This transformation often releases greenhouse gases such as $CO_2$. The major production processes that emit $CO_2$ include iron and steel production, cement manufacture, lime manufacture, limestone and dolomite use, soda ash manufacture and consumption, $CO_2$ consumption, titanium dioxide production, ferroalloy production, and ammonia manufacturing. Carbon dioxide emissions from these sources were approximately 161.9 Tg $CO_2$ Eq. in 2000, accounting for about 3 percent of total $CO_2$ emissions.

### Iron and Steel Production (65.7 Tg $CO_2$ Eq.)

The production of iron and steel generates process-related emissions of $CO_2$. Iron is produced by first reducing iron oxide (i.e., iron ore) with metallurgical coke in a blast furnace to produce pig iron. Carbon dioxide is produced as the metallurgical coke used in the blast furnace process is oxidized. Steel—containing less than 2 percent carbon by weight—is produced from pig iron in a variety of specialized steel making furnaces. The majority of $CO_2$ emissions from the iron and steel processes come from the use of coke in the production of pig iron, with smaller amounts evolving from the removal of carbon from pig iron used to produce steel.

### Cement Manufacture (41.1 Tg $CO_2$ Eq.)

Carbon dioxide is produced primarily during the production of clinker, an intermediate product from which finished Portland and masonry cement are made. When calcium carbonate ($CaCO_3$) is heated in a cement kiln to form lime and $CO_2$, the lime combines with other materials to produce clinker, and the $CO_2$ is released into the atmosphere.

### Ammonia Manufacturing (18.0 Tg $CO_2$ Eq.)

Carbon dioxide emissions occur during the production of ammonia. In the United States, roughly 98 percent of synthetic ammonia is produced by catalytic steam reforming of natural gas, and the remainder is produced using naphtha (i.e., a petroleum fraction) or the electrolysis of brine at chlorine plants (EPA 1997). The former two fossil fuel-based reactions produce carbon monoxide and hydrogen gas. This carbon monoxide is transformed into $CO_2$ in the presence of a catalyst—usually a metallic oxide—and generally released into the atmosphere.

### Lime Manufacture (13.3 Tg $CO_2$ Eq.)

Lime is used in steel making, construction, pulp and paper manufacturing, and water and sewage treatment. It is manufactured by heating limestone (mostly calcium carbonate, $CaCO_3$) in a kiln, creating quicklime (calcium oxide, CaO) and $CO_2$, which is normally emitted to the atmosphere.

### Limestone and Dolomite Use (9.2 Tg $CO_2$ Eq.)

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

### Aluminum Production (5.4 Tg $CO_2$ Eq.)

Carbon dioxide is emitted during the aluminum smelting process when alumina (aluminum oxide, $Al_2O_3$) is reduced to aluminum. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite. The reduction cells contain a carbon lining that serves as the cathode. Carbon is also contained in the anode, which can be a carbon mass of paste, coke briquettes, or prebaked carbon blocks from petroleum coke. During reduction, some of this carbon is oxidized and released to the atmosphere as $CO_2$.

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

Commercial soda ash (sodium carbonate, $Na_2CO_3$) is used in many consumer products, such as glass, soap and detergents, paper, textiles, and food. During the manufacturing of soda ash, some natural sources of sodium carbonate are heated and transformed into a crude soda ash, in which $CO_2$ is generated as a by-product. In addition, $CO_2$ is often released when the soda ash is consumed.

### Titanium Dioxide Production (2.0 Tg $CO_2$ Eq.)

Titanium dioxide ($TiO_2$) is a metal oxide manufactured from titanium ore, and is principally used as a pigment. Titanium dioxide is used as an ingredient in white paint and 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. Carbon dioxide is emitted from the chloride process, which uses petroleum coke and chlorine as raw materials.

### Ferroalloy Production (1.7 Tg $CO_2$ Eq.)

Carbon dioxide is emitted from the production of several ferroalloys through the use of metallurgical coke as a raw material. Ferroalloys are composites of iron and other elements often including silicon, manganese, and chromium. When incorporated in alloy steels, ferroalloys are used to alter the material properties of the steel.

### Carbon Dioxide Consumption (1.4 Tg $CO_2$ Eq.)

Carbon dioxide ($CO_2$) is used directly in many segments of the economy, including food processing, beverage manufacturing, chemical processing, and a host of industrial and other miscellaneous applications. Carbon dioxide may be produced as a by-product from the production of certain chemicals (e.g., ammonia) from select natural gas wells, or by separating it from crude oil and natural gas. For the most part, the $CO_2$ used in these applications is eventually released to the atmosphere.

## Land-Use Change and Forestry

When humans alter the terrestrial biosphere through land use, changes in land-use, and forest management practices, they alter the natural carbon flux between biomass, soils, and the atmosphere. Forest management practices, the management of agricultural soils, management of trees in urban areas, and landfilling of yard trimmings have resulted in a net uptake (sequestration) of carbon in the United States that is equivalent to about 13 percent of total U.S. gross emissions. Forests (including vegetation, soils, and harvested wood) accounted for approximately 85 percent of the total sequestration, agricultural soils (including mineral and organic soils and the application of lime) accounted for over 7 percent, urban trees accounted for more than 6 percent, and landfilled yard trimmings accounted for less than 1 percent of the total sequestration. The net forest sequestration is largely a result of improved forest management practices, the regeneration of previously cleared forest areas, and timber harvesting. In agricultural soils, mineral soils account for a net carbon sink that is more than three times larger than the sum of emissions from organic soils and liming. Net sequestration in agricultural mineral soils is largely due to improved cropland and grazing land management practices, especially the adoption of conservation tillage practices and leaving residues on the field after harvest, and to taking erodable lands out of production and planting them with grass or trees through the Conservation Reserve Program. The landfilled yard trimmings net sequestration is due to the long-term accumulation of yard trimming carbon in landfills.

# Methane Emissions

Atmospheric methane ($CH_4$) is an integral component of the greenhouse effect. Methane's overall contribution to global warming is significant because it has been estimated to be more than 20 times as effective at trapping heat in the atmosphere as $CO_2$. Over the last two hundred and fifty years, methane's concentration in the atmosphere has increased by 150 percent (IPCC 2001). Experts believe

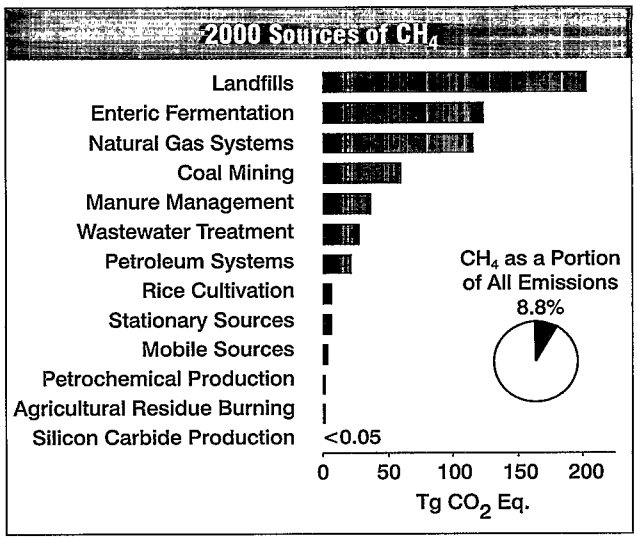
that over half of these atmospheric increases were due to emissions from anthropogenic sources, such as landfills, natural gas and petroleum systems, agricultural activities, coal mining, stationary and mobile combustion, wastewater treatment, and certain industrial processes (see Figure ES-14 and Table ES-10).

### Landfills (203.5 Tg $CO_2$ Eq.)

Landfills are the largest source of anthropogenic $CH_4$ emissions in the United States. In an environment where the oxygen content is low or nonexistent, organic materials, such as yard waste, household waste, food waste, and paper, can be decomposed by bacteria, resulting in the generation of $CH_4$ and biogenic $CO_2$. Methane emissions from landfills are affected by site-specific factors such as waste composition, moisture, and landfill size.

Methane emissions from U.S. landfills have decreased by almost 5 percent since 1990. The generally declining emission estimates are a result of two offsetting trends: (1) the amount of municipal solid waste in landfills contributing to $CH_4$ emissions has increased, thereby increasing the potential for emissions; and (2) the amount of landfill gas collected and combusted by landfill operators has also increased, thereby reducing emissions. Additionally, a regulation promulgated in March 1996 requires the largest U.S. landfills to begin collecting and combusting their landfill gas to reduce emissions of NMVOCs.

Figure ES-14




### Natural Gas and Petroleum Systems (138.2 Tg $CO_2$ Eq.)

Methane is the major component of natural gas. During the production, processing, transmission, and distribution of natural gas, fugitive emissions of methane often occur. Because natural gas is often found in conjunction with petroleum deposits, leakage from petroleum systems is also a source of emissions. Emissions vary greatly from facility to facility and are largely a function of operation and maintenance procedures and equipment conditions. In 2000, $CH_4$ emissions from U.S. natural gas systems were accounted for approximately 19 percent of U.S. $CH_4$ emissions.

**Table ES-10: U.S. Sources of Methane Emissions (Tg $CO_2$ Eq.)**

| Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Landfills | 213.4 | 216.6 | 211.5 | 206.4 | 201.0 | 203.1 | 203.5 |
| Enteric Fermentation | 127.9 | 133.2 | 129.6 | 126.8 | 124.9 | 124.5 | 123.9 |
| Natural Gas Systems | 121.2 | 125.7 | 126.6 | 122.7 | 122.2 | 118.6 | 116.4 |
| Coal Mining | 87.1 | 73.5 | 68.4 | 68.1 | 67.9 | 63.7 | 61.0 |
| Manure Management | 29.2 | 34.8 | 34.2 | 35.8 | 38.0 | 37.6 | 37.5 |
| Wastewater Treatment | 24.3 | 26.8 | 27.0 | 27.5 | 27.8 | 28.3 | 28.7 |
| Petroleum Systems | 26.4 | 24.2 | 24.0 | 24.0 | 23.4 | 22.3 | 21.9 |
| Stationary Sources | 7.9 | 8.2 | 8.4 | 7.5 | 7.0 | 7.3 | 7.5 |
| Rice Cultivation | 7.1 | 7.6 | 7.0 | 7.5 | 7.9 | 8.3 | 7.5 |
| Mobile Sources | 4.9 | 4.8 | 4.7 | 4.6 | 4.5 | 4.4 | 4.4 |
| Petrochemical Production | 1.2 | 1.5 | 1.6 | 1.6 | 1.6 | 1.7 | 1.7 |
| Agricultural Residue Burning | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 |
| Silicon Carbide Production | + | + | + | + | + | + | + |
| International Bunker Fuels* | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Total*** | **651.3** | **657.6** | **643.7** | **633.3** | **627.1** | **620.5** | **614.5** |

+ Does not exceed 0.05 Tg $CO_2$ Eq.
* Emissions from International Bunker Fuels are not included in totals.
Note: Totals may not sum due to independent rounding.

Petroleum is found in the same geological structures as natural gas, and the two are often retrieved together. Methane is also saturated in crude oil, and volatilizes as the oil is exposed to the atmosphere at various points along the system. Methane emissions from the components of petroleum systems—including crude oil production, crude oil refining, transportation, and distribution—generally occur as a result of system leaks, disruptions, and routine maintenance. In 2000, emissions from petroleum systems were just under 4 percent of U.S. methane emissions.

### Enteric Fermentation (123.9 Tg $CO_2$ Eq.)

During animal digestion, methane is produced through the process of enteric fermentation, in which microbes residing in animal digestive systems break down the feed consumed by the animal. Ruminants, which include cattle, buffalo, sheep, and goats, have the highest $CH_4$ emissions among all animal types because they have a rumen, or large fore-stomach, in which $CH_4$-producing fermentation occurs. Non-ruminant domestic animals, such as pigs and horses, have much lower $CH_4$ emissions. In 2000, enteric fermentation was the source of about 20 percent of U.S. $CH_4$ emissions, and more than half of the $CH_4$ emissions from agriculture. From 1990 to 2000, emissions from this source decreased by 3 percent. Emissions from enteric fermentation have been generally decreasing since 1995, primarily due to declining dairy cow and beef cattle populations.

### Coal Mining (61.0 Tg $CO_2$ Eq.)

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

Methane from surface mines is emitted directly to the atmosphere as the rock strata overlying the coal seam are removed. Because $CH_4$ in underground mines is explosive at concentrations of 5 to 15 percent in air, most active underground mines are required to vent this methane, typically to the atmosphere. At some mines, $CH_4$-recovery systems may supplement these ventilation systems. Recovery of $CH_4$ in the United States has increased in recent years. During 2000, coal mining activities emitted 10 percent of U.S. $CH_4$ emissions. From 1990 to 2000, emissions from this source decreased by 30 percent due to increased use of the $CH_4$ collected by mine degasification systems and a general shift toward surface mining.

### Manure Management (37.5 Tg $CO_2$ Eq.)

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

Emissions from manure management were about 6 percent of U.S. $CH_4$ emissions in 2000 and 22 percent of the methane emissions from agriculture. From 1990 to 2000, emissions from this source increased by 28 percent. The bulk of this increase was from swine and dairy cow manure, and is attributed to the shift in the composition of the swine and dairy industries towards larger facilities. Larger swine and dairy farms tend to use liquid management systems.

### Wastewater Treatment (28.7 Tg $CO_2$ Eq.)

Wastewater from domestic sources (i.e., municipal sewage) and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms and chemical contaminants. Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, with the latter condition producing $CH_4$. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. Untreated wastewater may also produce $CH_4$ if contained under anaerobic conditions.

### Stationary and Mobile Combustion (11.9 Tg $CO_2$ Eq.)

Stationary and mobile combustion were responsible for methane emissions of 7.5 and 4.4 Tg $CO_2$ Eq., respectively. The majority of emissions from stationary combustion resulted from the burning of wood in the residential end-use sector. The combustion of gasoline in highway vehicles was responsible for the majority of the $CH_4$ emitted from mobile combustion.

### Rice Cultivation (7.5 Tg $CO_2$ Eq.)

Most of the world's rice, and all of the rice in the United States, is grown on flooded fields. When fields are flooded, anaerobic conditions develop and the organic matter in the soil decomposes, releasing methane to the atmosphere, primarily through the rice plants. In 2000, rice cultivation was the source of 1 percent of U.S. methane emissions, and about 4 percent of U.S. $CH_4$ emissions from agriculture. Emission estimates from this source have increased about 5 percent since 1990 due to an increase in the area harvested.

### Petrochemical and Silicon Carbide Production (1.7 Tg $CO_2$ Eq.)

Methane emissions resulted from two industrial sources, petrochemical and silicon carbide production. Small amounts of $CH_4$ were released during the production of five petrochemicals: carbon black, ethylene, ethylene dichloride, styrene, and methanol. These production processes resulted in emissions of 1.7 Tg $CO_2$ Eq. in 2000. Methane is also emitted from the production of silicon carbide, a material used as an industrial abrasive. In 2000, silicon carbide production resulted in emissions of less than 0.1 Tg $CO_2$ Eq.

### Agricultural Residue Burning (0.8 Tg $CO_2$ Eq.)

Burning crop residue releases a number of greenhouse gases, including $CH_4$. Because field burning is not a common debris clearing method used in the United States, it was responsible for only 0.1 percent of U.S. $CH_4$ emissions in 1999.

## Nitrous Oxide Emissions

Nitrous oxide ($N_2O$) is a greenhouse gas that is produced both naturally—from a wide variety of biological sources in soil and water—and anthropogenically by a variety of agricultural, energy-related, industrial, and waste management activities. While total $N_2O$ emissions are much smaller than $CO_2$ emissions, $N_2O$ is approximately 300 times more powerful than $CO_2$ at trapping heat in the atmosphere. Since 1750, atmospheric concentrations of $N_2O$ have risen by approximately 16 percent (IPCC 2001). The main anthropogenic activities producing $N_2O$ in the United States were agricultural soil management, fuel combustion in motor vehicles, and nitric acid production (see Figure ES-15 and Table ES-11).

### Agricultural Soil Management (297.6 Tg $CO_2$ Eq.)

Nitrous oxide is produced naturally in soils through microbial processes of nitrification and denitrification. A number of anthropogenic activities add to the amount of nitrogen available to be emitted as $N_2O$ by microbial

**Figure ES-15**

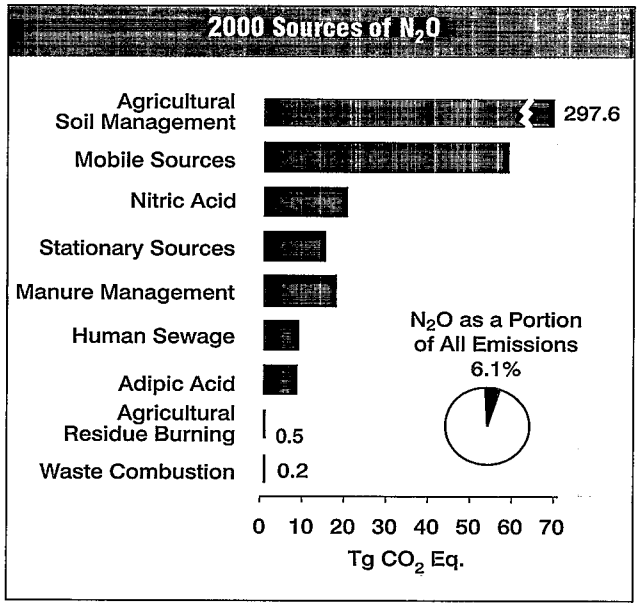


**Table ES-11: U.S. Sources of Nitrous Oxide Emissions (Tg $CO_2$ Eq.)**

| Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Agricultural Soil Management | 267.1 | 283.4 | 292.6 | 297.5 | 298.4 | 296.3 | 297.6 |
| Mobile Sources | 50.9 | 60.4 | 60.1 | 59.7 | 59.1 | 58.7 | 58.3 |
| Nitric Acid | 17.8 | 19.9 | 20.7 | 21.2 | 20.9 | 20.1 | 19.8 |
| Manure Management | 16.0 | 16.4 | 16.8 | 17.1 | 17.1 | 17.1 | 17.5 |
| Stationary Sources | 12.8 | 13.5 | 14.1 | 14.2 | 14.3 | 14.6 | 14.9 |
| Human Sewage | 7.0 | 7.7 | 7.8 | 7.9 | 8.1 | 8.4 | 8.5 |
| Adipic Acid | 14.9 | 17.9 | 17.8 | 11.5 | 7.7 | 7.7 | 8.1 |
| Agricultural Residue Burning | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.4 | 0.5 |
| Waste Combustion | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 |
| International Bunker Fuels* | 1.0 | 0.9 | 0.9 | 1.0 | 1.0 | 0.9 | 0.9 |
| **Total*** | **387.3** | **419.8** | **430.5** | **429.8** | **426.3** | **423.5** | **425.3** |

* Emissions from International Bunker Fuels are not included in totals.
Note: Totals may not sum due to independent rounding.

processes. These activities may add nitrogen to soils either directly or indirectly. Direct additions occur through the application of synthetic and organic fertilizers; production of nitrogen-fixing crops; the application of livestock manure, crop residues, and sewage sludge; cultivation of high-organic-content soils; and direct excretion by animals onto soil. Indirect additions result from volatilization and subsequent atmospheric deposition, and from leaching and surface run-off of some of the nitrogen applied to soils as fertilizer, livestock manure, and sewage sludge.

In 2000, agricultural soil management accounted for 70 percent of U.S. $N_2O$ emissions. From 1990 to 2000, emissions from this source increased by 11 percent as fertilizer consumption, manure production, and crop production rose.

### Stationary and Mobile Combustion (73.2 Tg $CO_2$ Eq.)

Nitrous oxide is a product of the reaction that occurs between nitrogen and oxygen during fuel combustion. Both mobile and stationary combustion emit $N_2O$, and the quantity emitted varies according to the type of fuel, technology, and pollution control device used, as well as maintenance and operating practices. For example, catalytic converters installed to reduce motor vehicle pollution can result in the formation of $N_2O$.

In 2000, $N_2O$ emissions from mobile combustion were 14 percent of U.S. $N_2O$ emissions, while stationary combustion accounted for 4 percent. From 1990 to 2000, combined $N_2O$ emissions from stationary and mobile combustion increased by 15 percent, primarily due to increased rates of $N_2O$ generation in highway vehicles.

### Adipic Acid Production (8.1 Tg $CO_2$ Eq.)

Most adipic acid produced in the United States is used to manufacture nylon 6,6. Adipic acid is also used to produce some low-temperature lubricants and to add a "tangy" flavor to foods. Nitrous oxide is emitted as a by-product of the chemical synthesis of adipic acid.

In 2000, U.S. adipic acid plants emitted 2 percent of U.S. $N_2O$ emissions. Even though adipic acid production has increased, by 1998, all three major adipic acid plants in the United States had voluntarily implemented $N_2O$ abatement technology. As a result, emissions have decreased by 46 percent since 1990.

### Nitric Acid Production (19.8 Tg $CO_2$ Eq.)

Nitric acid production is another industrial source of $N_2O$ emissions. Used primarily to make synthetic commercial fertilizer, this raw material is also a major component in the production of adipic acid and explosives.

Virtually all of the nitric acid manufactured in the United States is produced by the oxidation of ammonia, during which $N_2O$ is formed and emitted to the atmosphere. In 2000, $N_2O$ emissions from nitric acid production accounted for 5 percent of U.S. $N_2O$ emissions. From 1990 to 2000, emissions from this source category increased by 11 percent as nitric acid production grew.

### Manure Management (17.5 Tg $CO_2$ Eq.)

Nitrous oxide is produced as part of microbial nitrification and denitrification processes in managed and unmanaged manure, the latter of which is addressed under agricultural soil management. Total $N_2O$ emissions from managed manure systems in 2000 accounted for 4 percent of U.S. $N_2O$ emissions. From 1990 to 2000, emissions from this source category increased by 9 percent, as poultry and swine populations have increased.

### Agricultural Residue Burning (0.5 Tg $CO_2$ Eq.)

Large quantities of agricultural crop residues are produced by farming activities, some of which is disposed by burning in the field. Field burning of crop residues is a source of $N_2O$, which is released during combustion. Field burning is not a common method of agricultural residue disposal in the United States; therefore, emissions from this source are minor.

### Human Sewage (8.5 Tg $CO_2$ Eq.)

Domestic human sewage is usually mixed with other household wastewater and transported by a collection system to either a direct discharge, an on-site or decentralized wastewater system, or a centralized wastewater system. After processing, treated effluent may be discharged to a receiving water environment (e.g., river, lake, estuary, etc.), applied to soils, or disposed of below the surface. Nitrous oxide ($N_2O$) may be generated during both nitrification and denitrification of the nitrogen that is present in the sewage, usually in the form of urea and proteins. Emissions of $N_2O$ from treated human sewage discharged into aquatic environments were estimated to be 8.5 Tg $CO_2$ Eq. in 2000.

### Waste Combustion (0.2 Tg $CO_2$ Eq.)

Combustion is used to manage about 7 to 17 percent of the municipal solid wastes (MSW) generated in the United States. Almost all combustion of MSW in the United States occurs at waste-to-energy facilities where energy is recovered. Most of the organic materials in MSW are of biogenic origin (e.g., paper, yard trimmings). However, some components—plastics, synthetic rubber, and synthetic fibers—are of fossil origin, which accounted for emissions of 0.2 Tg $CO_2$ Eq. in 2000.

## HFC, PFC, and $SF_6$ Emissions

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are categories of synthetic chemicals that are being used as alternatives to the ozone depleting substances (ODSs), which are being phased out under the *Montreal Protocol* and Clean Air Act Amendments of 1990. Because HFCs and PFCs do not deplete the stratospheric ozone layer, they are not controlled by the *Montreal Protocol.*

These compounds, however, along with sulfur hexafluoride ($SF_6$), 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 aluminum production, HCFC-22 production, semiconductor manufacturing, electrical transmission and distribution systems, and magnesium production and processing. Figure ES-16 and Table ES-12 present emission estimates for HFCs, PFCs, and $SF_6$, which totaled 121.3 Tg $CO_2$ Eq. in 2000.

**Figure ES-16**

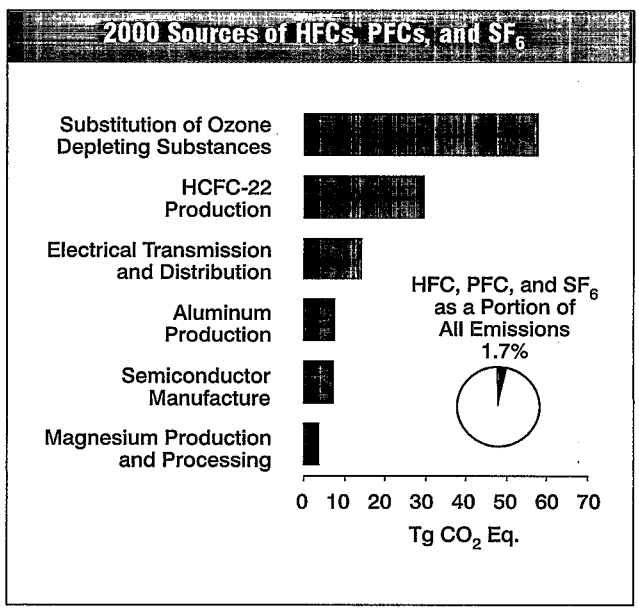


**Table ES-12: Emissions of HFCs, PFCs, and $SF_6$ (Tg $CO_2$ Eq.)**

| Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Substitution of Ozone Depleting Substances | 0.9 | 21.8 | 30.6 | 38.0 | 44.9 | 51.3 | 57.8 |
| HCFC-22 Production | 35.0 | 27.0 | 31.1 | 30.0 | 40.2 | 30.4 | 29.8 |
| Electrical Transmission and Distribution | 31.2 | 26.5 | 26.8 | 24.5 | 20.1 | 15.5 | 14.4 |
| Aluminum Production | 18.1 | 11.8 | 12.5 | 11.0 | 9.0 | 8.9 | 7.9 |
| Semiconductor Manufacture | 2.9 | 5.9 | 5.4 | 6.5 | 7.3 | 7.7 | 7.4 |
| Magnesium Production and Processing | 5.5 | 5.5 | 5.5 | 6.9 | 6.2 | 6.1 | 4.0 |
| **Total** | **93.6** | **98.5** | **111.9** | **116.9** | **127.7** | **120.0** | **121.3** |

Note: Totals may not sum due to independent rounding.

### Substitution of Ozone Depleting Substances (57.8 Tg $CO_2$ Eq.)

The use and subsequent emissions of HFCs and PFCs as substitutes for ozone depleting substances (ODSs) have increased from small amounts in 1990 to account for 48 percent of aggregate HFC, PFC, and $SF_6$ emissions. This increase was in large part the result of efforts to phase-out chlorofluorocarbons (CFCs) and other ODSs in the United States, especially the introduction of HFC-134a as a CFC substitute in refrigeration and air-conditioning applications. In the short term, this trend is expected to continue, and will likely accelerate in the next decade as hydrochlorofluorcarbons (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.

### Aluminum Production (7.9 Tg $CO_2$ Eq.)

During the production of primary aluminum, two PFCs—$CF_4$ and $C_2F_6$—are emitted as intermittent by-products of the smelting process. These PFCs are primarily formed when fluorine from the croylite bath combines with carbon from the electrolyte anode. Emissions from aluminum production have decreased by 56 percent between 1990 and 2000 due to emission reduction efforts by the industry and falling domestic aluminum production.

### HCFC-22 Production (29.8 Tg $CO_2$ Eq.)

HFC-23 is a by-product emitted during the production of HCFC-22. Emissions from this source have decreased by 15 percent since 1990. The intensity of HFC-23 emissions (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) has declined significantly since 1990, although production has been increasing.

### Semiconductor Manufacturing (7.4 Tg $CO_2$ Eq.)

The semiconductor industry uses combinations of HFCs, PFCs, $SF_6$, and other gases for plasma etching and to clean chemical vapor deposition tools. Emissions from this source category have increased with the growth in the semiconductor industry and the rising intricacy of chip designs. However, the growth rate in emissions has slowed since 1997, and emissions actually declined between 1999 and 2000. This later reduction is due to the implementation of PFC emission reduction methods, such as process optimization.

### Electrical Transmission and Distribution Systems (14.4 Tg $CO_2$ Eq.)

The primary use of $SF_6$ is as a dielectric in electrical transmission and distribution systems. Fugitive emissions of $SF_6$ occur from leaks in and servicing of substations and circuit breakers, especially from older equipment. Estimated emissions from this source decreased by 54 percent since 1990, primarily due to higher $SF_6$ prices and industrial efforts to reduce emissions.

### Magnesium Production (4.0 Tg $CO_2$ Eq.)

$SF_6$ is also used as a protective covergas for the casting of molten magnesium. Emissions from primary magnesium production and magnesium casting have decreased by 27 percent since 1990. Emissions have decreased since 1999, due to a decrease in the quantity of magnesium die cast and the closure of a U.S. primary magnesium production facility.

## Box ES-3: Emissions of Ozone Depleting Substances

Manmade halogenated compounds were first emitted into the atmosphere in significant quantities during the 20th century. This family of man-made compounds includes CFCs, halons, methyl chloroform, carbon tetrachloride, methyl bromide, and hydrochlorofluorocarbons (HCFCs). These substances have been used in a variety of industrial applications, including refrigeration, air conditioning, foam blowing, solvent cleaning, sterilization, fire extinguishing, agricultural fumigation and sterilization, coatings, paints, and aerosols.

Because these compounds have been shown to deplete stratospheric ozone, they are typically referred to as ozone depleting substances (ODSs). However, they are also potent greenhouse gases.

Recognizing the harmful effects of these compounds on the ozone layer, in 1987 many governments signed the *Montreal Protocol on Substances that Deplete the Ozone Layer* to limit the production and importation of a number of CFCs and other halogenated compounds. The United States furthered its commitment to phase out ODSs by signing and ratifying the Copenhagen Amendments to the *Montreal Protocol* in 1992. Under these amendments, the United States committed to ending the production and importation of halons by 1994, and CFCs by 1996.

The IPCC Guidelines and the UNFCCC do not include reporting instructions for estimating emissions of ODSs because their use is being phased out under the *Montreal Protocol*. The United States believes that a greenhouse gas emissions inventory is incomplete without these emissions; therefore, estimates for several Class I and Class II ODSs are provided in Table ES-13. Compounds are grouped by class according to their ozone depleting potential. Class I compounds are the primary ODSs; Class II compounds include partially halogenated chlorine compounds (i.e., HCFCs), some of which were developed as interim replacements for CFCs. Because these HCFC compounds are only partially halogenated, their hydrogen-carbon bonds are more vulnerable to oxidation in the troposphere and, therefore, pose only one-tenth to one-hundredth the threat to stratospheric ozone compared to CFCs.

It should be noted that the effects of these compounds on radiative forcing are not provided. Although many ODSs have relatively high direct GWPs, their indirect effects from the destruction of ozone—also a greenhouse gas—are believed to have negative radiative forcing effects, and therefore could significantly reduce the overall magnitude of their radiative forcing effects. Given the uncertainties surrounding the net effect of these gases, emissions are reported on an unweighted basis.

### Table ES-13: Emissions of Ozone Depleting Substances (Gg)

| Compound | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Class I** | | | | | | | |
| CFC-11 | 53.5 | 36.2 | 26.6 | 25.1 | 24.9 | 24.0 | 22.8 |
| CFC-12 | 112.6 | 51.8 | 35.5 | 23.1 | 21.0 | 14.0 | 17.2 |
| CFC-113 | 52.7 | 17.1 | + | + | + | + | + |
| CFC-114 | 4.7 | 1.6 | 0.3 | 0.1 | 0.1 | + | + |
| CFC-115 | 4.2 | 3.0 | 3.2 | 2.9 | 2.7 | 2.6 | 2.3 |
| Carbon Tetrachloride | 32.3 | 4.7 | + | + | + | + | + |
| Methyl Chloroform | 316.6 | 92.8 | + | + | + | + | + |
| Halon-1211 | 1.0 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Halon-1301 | 1.8 | 1.4 | 1.4 | 1.3 | 1.3 | 1.3 | 1.3 |
| **Class II** | | | | | | | |
| HCFC-22 | 34.0 | 39.3 | 41.0 | 42.4 | 43.8 | 74.1 | 79.1 |
| HCFC-123 | + | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 |
| HCFC-124 | + | 5.6 | 5.9 | 6.2 | 6.4 | 6.5 | 6.5 |
| HCFC-141b | 1.3 | 9.9 | 9.9 | 8.8 | 9.7 | 10.9 | 10.9 |
| HCFC-142b | 0.8 | 3.6 | 4.0 | 4.3 | 4.7 | 5.0 | 5.4 |
| HCFC-225ca/cb | + | + | + | + | + | + | + |

Source: EPA, Office of Atmospheric Programs
+ Does not exceed 0.5 Gg

## Ambient Air Pollutant Emissions

In the United States, carbon monoxide (CO), nitrogen oxides ($NO_x$), nonmethane volatile organic compounds (NMVOCs), and sulfur dioxide ($SO_2$) are referred to as "ambient air pollutants," as termed in the Clean Air Act. These pollutants 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. 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 nitrous oxide ($N_2O$). NMVOCs—which includes 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.

Ambient air pollutants are regulated under the Clean Air Act in an effort to protect human health and the environment. These gases also indirectly affect the global climate by either acting as short-lived greenhouse gases or reacting with other chemical compounds in the atmosphere to form compounds that are greenhouse gases. Unlike the other ambient air pollutants, sulfur-containing compounds emitted into the atmosphere affect the Earth's radiative budget negatively; therefore, it is 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 ambient air pollutant formation into greenhouse gases is carbon monoxide's interaction with the hydroxyl radical—the major atmospheric sink for methane emissions—to form $CO_2$. Therefore, increased atmospheric concentrations of CO limit the number of hydroxyl molecules (OH) available to destroy methane.

Since 1970, the United States has published estimates of annual emissions of ambient air pollutants (EPA 2001).[15] Table ES-14 shows that fuel combustion accounts for the majority of emissions of these gases. Industrial processes—such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents—are also significant sources of CO, $NO_x$, and NMVOCs.

**Box ES-4: 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 63 percent in 2000. Coal combustion contributes nearly all of those emissions (approximately 94 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.

[15] $NO_x$ and CO emission estimates from agricultural residue burning were estimated separately, and therefore not taken from EPA (2001).

## Table ES-14: Emissions of $NO_x$, CO, NMVOCs, and $SO_2$ (Gg)

| Gas/Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$NO_x$** | **21,873** | **24,126** | **24,999** | **25,508** | **25,470** | **25,224** | **25,038** |
| Stationary Fossil Fuel Combustion | 9,884 | 9,822 | 9,522 | 9,577 | 9,400 | 9,022 | 8,740 |
| Mobile Fossil Fuel Combustion | 10,900 | 13,329 | 14,338 | 14,771 | 14,976 | 15,087 | 14,941 |
| Oil and Gas Activities | 139 | 100 | 126 | 130 | 130 | 130 | 132 |
| Industrial Processes | 921 | 842 | 976 | 991 | 924 | 946 | 1,184 |
| Solvent Use | 1 | 3 | 3 | 3 | 3 | 3 | 3 |
| Agricultural Burning | 28 | 29 | 32 | 34 | 35 | 34 | 35 |
| Waste | + | 1 | 3 | 3 | 3 | 3 | 3 |
| **CO** | **85,016** | **79,726** | **87,109** | **87,567** | **83,379** | **86,354** | **94,033** |
| Stationary Fossil Fuel Combustion | 4,999 | 5,383 | 3,936 | 3,926 | 3,905 | 3,928 | 4,140 |
| Mobile Fossil Fuel Combustion | 69,523 | 68,072 | 74,927 | 73,764 | 72,797 | 70,565 | 69,296 |
| Oil and Gas Activities | 302 | 316 | 321 | 333 | 332 | 332 | 335 |
| Industrial Processes | 9,502 | 5,291 | 7,171 | 8,776 | 5,557 | 10,763 | 19,469 |
| Solvent Use | 4 | 5 | 1 | 1 | 1 | 1 | 1 |
| Agricultural Burning | 685 | 656 | 747 | 761 | 781 | 760 | 786 |
| Waste | 1 | 2 | 5 | 5 | 5 | 5 | 5 |
| **NMVOCs** | **18,630** | **18,434** | **17,411** | **17,766** | **16,797** | **16,970** | **17,907** |
| Stationary Fossil Fuel Combustion | 912 | 973 | 1,020 | 1,019 | 1,018 | 1,025 | 1,089 |
| Mobile Fossil Fuel Combustion | 8,154 | 7,725 | 8,485 | 8,257 | 8,158 | 7,962 | 7,638 |
| Oil and Gas Activities | 555 | 582 | 433 | 442 | 440 | 385 | 393 |
| Industrial Processes | 3,110 | 2,805 | 2,344 | 2,783 | 2,341 | 3,043 | 4,232 |
| Solvent Use | 5,225 | 5,618 | 4,973 | 5,108 | 4,679 | 4,390 | 4,388 |
| Agricultural Burning | NA | NA | NA | NA | NA | NA | NA |
| Waste | 673 | 731 | 156 | 157 | 161 | 164 | 168 |
| **$SO_2$** | **21,481** | **17,408** | **17,629** | **18,076** | **18,185** | **17,541** | **16,498** |
| Stationary Fossil Fuel Combustion | 18,407 | 14,724 | 14,726 | 15,104 | 15,192 | 14,540 | 13,496 |
| Mobile Fossil Fuel Combustion | 1,339 | 1,189 | 1,612 | 1,636 | 1,655 | 1,668 | 1,626 |
| Oil and Gas Activities | 390 | 334 | 304 | 312 | 310 | 309 | 314 |
| Industrial Processes | 1,306 | 1,117 | 958 | 993 | 996 | 992 | 1,031 |
| Solvent Use | + | 1 | 1 | 1 | 1 | 1 | + |
| Agricultural Burning | NA | NA | NA | NA | NA | NA | NA |
| Waste | 39 | 43 | 29 | 30 | 31 | 31 | 32 |

Source: (EPA 2001) except for estimates from agricultural burning.
+ Does not exceed 0.5 Gg
NA (Not Available)
Note: Totals may not sum due to independent rounding.

# Changes in This Year's Inventory Report

Each year the U.S. Greenhouse Gas Inventory Program not only recalculates and revises the emission and sink estimates for all years that are presented in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* but also attempts to improve the analyses themselves through the use of better methods or data as well as the overall usefulness of the report. A summary of this year's changes is presented in the following sections and includes changes in methodology in addition to updates to historical data. The magnitude of each change is also described. Table Changes-1 summarizes the quantitative effect of these changes on U.S. greenhouse gas emissions and Table Changes-2 summarizes the quantitative effect on U.S. sinks, both relative to the previously published U.S. Inventory (i.e., 1990-1999 report). These tables present the magnitude of these changes in units of teragrams of carbon dioxide ($CO_2$) equivalents (Tg $CO_2$ Eq.).

A number of significant methodological and data revisions have been made to this year's Inventory. Fuel consumption for electricity generation by non-utilities was removed from the industrial end-use sector and instead combined with electric utility consumption - thus creating a comprehensive "electricity generation" sector. A series of improvements were made to the estimate of $CO_2$ emissions and carbon storage from the non-energy use (NEU) of fossil fuels, including an enhanced analysis of storage and emissions for a set of fuels used as raw material inputs in petrochemicals production, as well as reallocating emissions from non-energy fuel uses in industrial processes to the Industrial Processes chapter (e.g., Iron and Steel Production), and, finally, accounting for the oxidation of non-combustion, non-biogenic fossil sources of methane. Methane emission estimates for industrial wastewater now include food processing, whereas they previously included only the pulp and paper industry. The Land-Use Change and Forestry chapter now includes estimates on changes in carbon stocks in urban trees. Significant revisions have also been made to estimates of $SF_6$ emissions from Magnesium Production and Processing and from Electric Power Transmission and Distribution Systems, based on newly reported data from industry. These revisions are among numerous others explained in detail below.

Changes in historical data are generally the result of changes in statistical data supplied by other agencies. Data sources are provided for further reference.

For methodological changes, differences between the previous Inventory report and this report are explained. In general, when methodological changes have been implemented, the entire time series (i.e., 1990 through 1999) has been recalculated to reflect the change.

## Table Changes-1: Revisions to U.S. Greenhouse Gas Emissions (Tg $CO_2$ Eq.)

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 |
|---|---|---|---|---|---|---|
| **$CO_2$** | **85.6** | **86.1** | **80.5** | **89.3** | **85.4** | **107.3** |
| Fossil Fuel Combustion | (55.8) | (36.2) | (36.3) | (35.4) | (30.6) | (4.5) |
| Natural Gas Flaring | 0.4 | (4.9) | (4.8) | (4.5) | (4.6) | (5.0) |
| Cement Manufacture | NC | NC | NC | NC | NC | 0.1 |
| Lime Manufacture | + | + | + | NC | NC | + |
| Limestone and Dolomite Use | 0.1 | + | 0.1 | 0.1 | 0.1 | 0.8 |
| Soda Ash Manufacture and Consumption | + | + | + | (0.1) | NC | NC |
| Carbon Dioxide Consumption | NC | NC | NC | NC | NC | + |
| Waste Combustion | (3.5) | (4.5) | (4.4) | (4.3) | (4.9) | (4.1) |
| Titanium Dioxide Production[a] | 1.3 | 1.7 | 1.7 | 1.8 | 1.8 | 1.9 |
| Aluminum Production[a] | 6.3 | 5.3 | 5.6 | 5.6 | 5.8 | 5.9 |
| Iron and Steel Production[a] | 85.4 | 74.4 | 68.3 | 76.1 | 67.4 | 64.4 |
| Ferroalloys[a] | 2.0 | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation[a] | 30.9 | 29.5 | 28.9 | 28.4 | 28.2 | 27.0 |
| Ammonia Manufacture[a] | 18.5 | 18.9 | 19.5 | 19.5 | 20.1 | 18.9 |
| International Bunker Fuels | (0.1) | + | 0.1 | 0.1 | 0.1 | (2.0) |
| **$CH_4$** | **6.8** | **7.1** | **5.8** | **1.3** | **2.9** | **0.9** |
| Stationary Sources | (0.6) | (0.6) | (0.6) | (0.6) | (0.6) | (0.8) |
| Mobile Sources | (0.1) | (0.1) | (0.1) | (0.2) | (0.1) | (0.1) |
| Coal Mining | (0.7) | (1.0) | (1.0) | (0.6) | 1.4 | 1.9 |
| Natural Gas Systems | + | 1.5 | 0.8 | 0.1 | 0.1 | (3.2) |
| Petroleum Systems | (0.8) | (0.3) | + | + | 0.1 | 0.4 |
| Petrochemical Production | NC | + | + | + | + | + |
| Silicon Carbide Production | NC | NC | NC | NC | NC | + |
| Enteric Fermentation | (1.6) | (3.1) | (2.6) | (2.8) | (2.6) | (2.7) |
| Manure Management | 2.8 | 3.8 | 3.5 | 3.2 | 2.8 | 3.2 |
| Rice Cultivation | (1.6) | (1.9) | (1.8) | (2.1) | (2.2) | (2.4) |
| Agricultural Residue Burning | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 |
| Landfills | (3.9) | (6.3) | (7.6) | (11.4) | (12.6) | (11.5) |
| Wastewater Treatment | 13.1 | 15.0 | 15.1 | 15.5 | 15.7 | 16.1 |
| International Bunker Fuels | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **$N_2O$** | **(9.6)** | **(12.2)** | **(11.1)** | **(14.3)** | **(7.4)** | **(9.0)** |
| Stationary Sources | (0.8) | (0.8) | (0.8) | (0.8) | (0.7) | (1.1) |
| Mobile Sources | (3.4) | (6.4) | (5.2) | (5.5) | (5.1) | (4.7) |
| Adipic Acid | (3.4) | (2.4) | (3.0) | (5.6) | 0.5 | (1.3) |
| Nitric Acid | NC | NC | NC | NC | NC | (0.1) |
| Manure Management | + | + | + | + | + | + |
| Agricultural Soil Management | (1.9) | (1.9) | (2.0) | (2.3) | (1.9) | (2.0) |
| Agricultural Residue Burning | + | + | + | + | + | + |
| Human Sewage | (0.1) | (0.5) | + | + | + | 0.2 |
| Waste Combustion | NC | NC | NC | NC | NC | + |
| International Bunker Fuels | + | + | + | + | + | + |
| **HFCs, PFCs, and $SF_6$** | **9.7** | **(0.5)** | **(3.2)** | **(6.4)** | **(10.9)** | **(15.8)** |
| Substitution of Ozone Depleting Substances | NC | (2.2) | (3.4) | (4.1) | (4.8) | (5.4) |
| Aluminum Production | (1.2) | 0.6 | 0.9 | 0.1 | (1.1) | (1.1) |
| HCFC-22 Production | 0.2 | (0.1) | (0.1) | (0.1) | 0.2 | + |
| Semiconductor Manufacture | + | 0.4 | (1.6) | (0.5) | 0.5 | 0.9 |
| Electrical Transmission and Distribution | 10.7 | 0.8 | 1.1 | (1.2) | (5.6) | (10.2) |
| Magnesium Production and Processing | NC | + | (0.1) | (0.6) | (0.1) | + |
| **Net Change in Total Emissions[b]** | **92.5** | **80.5** | **71.9** | **70.0** | **69.4** | **83.4** |
| **Percent Change** | **1.5%** | **1.3%** | **1.1%** | **1.0%** | **1.0%** | **1.2%** |

+ Absolute value does not exceed 0.05 Tg $CO_2$ Eq.
[a] New source category relative to previous inventory.
[b] Excludes emissions from land-use change and forestry.
NC (No Change)
Note: Totals may not sum due to independent rounding.

**Table Changes-2: Revisions to Net $CO_2$ Sequestration from Land-Use Change and Forestry (Tg $CO_2$ Eq.)**

| Component | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 |
|---|---|---|---|---|---|---|
| Forests | 19.1 | (40.7) | (36.3) | 144.5 | 145.6 | 143.0 |
| Urban Trees[a] | (58.7) | (58.7) | (58.7) | (58.7) | (58.7) | (58.7) |
| Agricultural Soils[a] | 3.1 | 8.6 | 8.6 | 8.6 | 10.1 | 9.2 |
| Landfilled Yard Trimmings | (1.3) | (0.2) | (0.1) | (0.1) | 0.4 | 0.4 |
| **Net Change in Total Flux** | (37.8) | (90.9) | (86.5) | 94.4 | 97.4 | 94.0 |
| **Percent Change** | 3.6% | 8.9% | 8.5% | -9.6% | -9.9% | -9.5% |

NC (No Change)
Note: Numbers in parentheses indicate an *increase* in estimated net sequestration, or a decrease in net flux of $CO_2$ to the atmosphere. In the "percent change" row, negative numbers indicate that the sequestration estimate has decreased, and positive numbers indicate that the sequestration estimate has increased. Totals may not sum due to independent rounding.
[a] New source category relative to previous inventory.

# Methodological Changes

## Emissions and Storage from Non-Energy Uses of Fossil Fuels

The following section addresses changes associated with estimation of $CO_2$ emissions from non-energy uses (NEU) of fossil fuels. These changes affect a number of source categories in both the Energy and Industrial Processes chapters, including:

- $CO_2$ from Fossil Fuel Combustion
- Waste Combustion
- Titanium Dioxide Production
- Aluminum Production
- Iron and Steel Production
- Ferroalloy Production
- Ammonia Manufacture

Among the most significant methodological changes made in last year's inventory were a series of improvements in the estimation of $CO_2$ emissions and carbon storage from NEU of fossil fuels. This year, as in years past, these NEU emissions are addressed in the Energy chapter, as an adjustment to total potential energy emissions. This year's inventory introduces several new improvements, and better integrates the characterization of non-energy fuel use with the estimation of emissions from industrial processes.

Most of the changes relate to an improved analysis of storage and emissions for a set of fuels used as raw material inputs in petrochemicals production: petrochemical feedstocks, liquefied petroleum gas, pentanes plus, and natural gas (for "other uses"). For these fuels—collectively referred to as "feedstocks"—an empirically determined storage factor was developed. The storage factor is equal to the ratio of (a) carbon stored in the final products to (b) total carbon content of the feedstocks used as inputs to non-energy uses. Last year's inventory used a storage factor for these fuels of 91 percent; revisions made this year changed the estimate by first accounting for net exports (i.e., approximately 9 percent of non-energy fuel consumption), and then applying a revised storage factor of 63 percent.

In addition, this year's inventory makes several changes in its approach for handling non-energy fuel uses in industrial processes. In past years, most of the emissions from these processes were captured as part of the NEU storage and emissions calculations, and addressed in the Energy chapter of the inventory.[1] This year, the emissions are included in the Industrial Processes chapter in keeping with IPCC Guidelines (IPCC/UNEP/OECD/IEA 1997).

These changes are summarized below, first addressing the feedstocks storage factor calculation, and then the changes in the integration of non-energy uses into the Industrial Processes chapter. The complete methods are described in the Energy and Industrial Processes chapters, and in Annex B.

[1] For example, petroleum coke used to produce carbon anodes for aluminum production was previously considered as non-energy fossil fuel use, and carbon emissions from aluminum production were accounted for in the Energy chapter.

### Feedstocks Storage Factor

The approach for characterizing emissions from non-energy uses of feedstocks relies on a mass balance approach, in which total carbon is allocated between long-term storage in products and losses through emissive processes. The overall balance is expressed as a storage factor. This year's storage factor for feedstocks incorporates several new analyses:

- *Imports and Exports of Chemical Intermediates and Products.* To some degree, the energy flows tracked by the Energy Information Administration do not capture fossil-derived materials once they leave refineries labeled as "feedstocks," and are thus no longer valued for their energy content. Although direct imports and exports of primary chemicals are included in EIA's statistics, imports and exports of some chemical intermediates and products produced by the chemical industry (e.g., xylenes, vinyl chloride, and polypropylene resins) are not covered. This year's analysis accounts for these flows—which results in an adjustment for net exports, thus lowering potential emissions—based on data collected by the National Petroleum Refiners' Association.
- *Energy Recovery from NEU Byproducts.* The chemical reactions in which fuel feedstocks are used are not 100 percent efficient, and unreacted feedstocks or byproducts of production may be combusted for energy recovery in industrial boilers. This year's inventory includes an estimate of $CO_2$ released by industrial boilers as a result of combustion of these byproducts. The estimate is based on newly available data from EIA's Manufacturers Energy Consumption Survey (MECS) for 1998. The survey includes data on the consumption for energy recovery of "other" fuels in the petroleum and coal products, chemicals, primary metals, nonmetallic minerals, and other manufacturing sectors. Of the improvements to the methodology made this year, this component has the greatest effect, increasing the amount of carbon emitted (versus stored).
- *Solvent Evaporation.* Some feedstocks are used to produce solvents. Most solvents are organic (thus containing carbon), and when emitted to the atmosphere, eventually oxidize into $CO_2$. Carbon emissions are the product of (a) total solvent tonnage released and (b) the average carbon content of the solvents. This year's inventory incorporates a more accurate estimate of the latter factor, based on newly available data categorizing solvent emissions by chemical species (last year's estimate was based on an assumed average carbon content).
- *Non-Combustion CO.* Similarly, some processes using feedstocks for non-energy uses emit CO, which eventually oxidizes to $CO_2$ in the atmosphere. This year's inventory includes emissions from non-combustion sources in the mass balance on carbon (combustion sources are accounted for as part of the fossil fuel combustion analysis).
- *Waste Combustion.* Last year's inventory addressed combustion of fossil-derived waste materials in the Waste chapter. This year waste combustion is incorporated in the Energy chapter because the vast majority of waste combustion is performed with energy recovery. Hazardous waste combustion is considered one of the processes through which feedstock carbon is emitted, and is among the components of the mass balance calculation of the storage factor.[2] Municipal waste combustion is addressed separately in the Energy chapter.
- *Assumed Fate of "Unaccounted for" Carbon.* As with last year, it was not possible to account for all reported feedstock carbon by tallying all carbon in products and emissions. Last year's inventory assumed that the "unaccounted for" carbon had the same proportions, in terms of storage and emissions, as the "accounted" for carbon. This year, most of the unaccounted for carbon was "found" through further investigation—primarily in the analysis of exports and energy recovery. To be conservative, and to reflect the fact that most of

[2] In last year's inventory, hazardous waste combustion was subdivided into energy recovery and incineration (i.e., combustion without energy recovery). This year's calculation included a large flow of carbon in the form of "Energy Recovery of NEU Byproducts"; a subset of this would involve combustion of hazardous waste. Thus, the storage factor for this year specifically incorporates only incineration of hazardous waste. See Annex B for details.

the newly "found" carbon was emitted—rather than stored—this year's inventory assumes that all remaining carbon that is unaccounted for is emitted.

### Integration of Non-Energy Uses and Industrial Processes

In some cases, it is difficult to make a distinction between $CO_2$ emissions from fossil fuels used in non-energy applications and $CO_2$ emissions from industrial processes. This year, five sources previously characterized as non-energy uses—and addressed in the Energy chapter—were recharacterized as Industrial Process emissions in keeping with the IPCC Guidelines (IPCC/UNEP/OECD/IEA 1997):

- *Natural Gas used in Ammonia Production.* Ammonia is produced from natural gas, which is used as both a raw material feedstock and as a fuel for process heat in the ammonia production process. In previous inventory calculations, carbon emissions from the portion used as a raw material feedstock were accounted for under the non-energy use portion of the Energy chapter. In the current inventory, these emissions are calculated based on multiplying a newly developed emission factor by reported annual ammonia production. This year, natural gas used for ammonia production was classified as an industrial process, resulting in an average transfer of emissions of 19.2 Tg $CO_2$ Eq. from the Energy chapter to the Industrial Processes chapter from 1990 to 1999.
- *Industrial Coking Coal used in Iron and Steel Production.* Iron and steel production is an industrial process in which coal coke is used as a raw material (i.e., reducing agent) in the blast furnace process. In this year's Inventory, production and use of coal coke for iron and steel production was classified as an industrial process use rather than a fuel use. Iron and steel production accounts for the major portion of consumption of coal coke in the United States. This year the total non-energy use of industrial coking coal, as reported by EIA, was adjusted downward to account for the consumption by the industry, as reported by the U.S. Geological Survey. The remaining industrial non-energy uses of coal coke—accounting for less than 5 percent of total consumption—have not been recharacterized as industrial process uses, and are still reported in the Energy chapter as non-energy use of industrial coking coal. This change resulted in an average transfer of emissions of 73.1 Tg $CO_2$ from the Energy chapter to the Industrial Processes chapter from 1990 to 1999.
- *Petroleum Coke used in Ferroalloy Production.* In previous years, ferroalloy production data were adjusted such that production of miscellaneous alloys (i.e., 32-65 percent silicon) were not included in the emission calculation. This year's calculation has been revised to include production of these miscellaneous alloys. The ferroalloy process uses metallurgical coke as a raw material. In previous years, consumption of coke in the ferrosilicon production process was not calculated explicitly. Emissions from coke consumption for ferroalloy production were accounted for in the calculations for industrial coking coal under fossil fuel combustion in the Energy chapter. This year, coke used for ferroalloy production was classified as an industrial process, resulting in an average transfer of emissions of 2.0 Tg $CO_2$ Eq. from the Energy chapter to the Industrial Processes chapter from 1990 to 1999.

  In past years, metallurgical coke used in the production of ferrosilicon was assumed to be coal coke. However, it is now assumed that 100 percent of U.S. ferroalloy production is produced using petroleum coke using an electric arc furnace process, although it is possible that some ferroalloys may be produced with coking coal, wood, other biomass, or graphite carbon inputs. Carbon dioxide emissions from ferroalloy production for this inventory were calculated based on IPCC emission factors and annual ferroalloy production data. Consumption of petroleum coke for ferroalloy production was calculated from the $CO_2$ emissions based on the carbon content of petroleum coke. The calculated petroleum coke consumption for ferroalloy production was then subtracted from total non-energy consumption of petroleum coke reported by EIA.
- *Petroleum Coke used in Aluminum Production.* The aluminum production process uses carbon anodes that are manufactured from coal tar pitch and petroleum coke. In past years, consumption of petroleum coke and coal tar pitch for carbon anodes for aluminum production was considered as non-energy fossil fuel use, and carbon emissions from aluminum production

were accounted for in the Energy chapter. This year, emissions from petroleum coke and coal tar pitch used for aluminum production were reported under the Industrial Processes chapter. This resulted in an average transfer of emissions of 5.8 Tg $CO_2$ from the Energy chapter to the Industrial Processes chapter.

Carbon dioxide emissions from aluminum production were calculated based on IPCC emission factors and annual aluminum production data. Consumption of petroleum coke and coal tar pitch for aluminum production was calculated from the $CO_2$ emissions based on the petroleum coke and coal tar pitch content of the carbon anodes used in the process. The petroleum coke consumption was then subtracted from the total non-energy consumption of petroleum coke reported by EIA. The calculated coal tar pitch consumption was also factored into the mass balance calculation for Iron and Steel Production.

Additional changes to the estimates of $CO_2$ and PFC emissions for 1990 through 1999 are explained below in the section entitled Aluminum Production.

- *Petroleum Coke used in Titanium Dioxide Production.* The titanium dioxide production process (i.e., chloride process), which uses petroleum coke as a raw material, was not previously included in the Inventory. Previously, petroleum coke consumed in the titanium dioxide process was embedded in the reported non-energy use of petroleum coke in the Energy chapter, and the associated $CO_2$ emissions were included in the Inventory only indirectly through application of a storage factor to the non-energy use of petroleum coke. For the current Inventory, carbon emissions from titanium dioxide production are calculated based on an emission factor and titanium dioxide production data. The petroleum coke consumed for titanium dioxide production was then subtracted from the total non-energy consumption of petroleum coke reported by EIA. This year, petroleum coke used for titanium dioxide production was classified as an industrial process, resulting in an average transfer of emissions of 1.6 Tg $CO_2$ from the Energy chapter to the Industrial Processes chapter from 1990 to 1999.

## Mobile Combustion (excluding $CO_2$)

The $N_2O$ emission factors for light-duty gasoline trucks (LDGT), heavy-duty gasoline vehicles (HDGV), and motorcycles (MC) found in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) have been revised. In the previous Inventory, $N_2O$ emission factors for these vehicle types were estimated by using data on grams of $CO_2$/km (as a proxy for fuel consumption) taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) for each vehicle type as a scaling factor, and applying this factor to the passenger car $N_2O$ emission factors to derive the LDGT, HDGV, and MC factors. This $CO_2$/km data, however, was found to contain inconsistencies and potential errors. To correct for these errors and use more country-specific information, U.S. miles per gallon (MPG) data were applied as proxy data for this Inventory. Fuel economy data were derived from a number of sources, including DOE's *Transportation Energy Data Book* (DOE 1993 through 2001), FHWA's *Highway Statistics* (FHWA 1996 through 2001), EPA and DOE's *Fuel Economy 2001* Datafile (EPA, DOE 2001), and the *Vehicle Inventory and Use Survey* (Census 1997).

Previously, a static 8.7 percent of U.S. vehicle miles traveled (VMT) was assumed to be attributable to California for each year. (Due to stricter motor vehicle control technologies standards in California, the VMT in California is treated separately from national VMT to estimate emissions.) This assumption has been replaced using the percent of U.S. VMT represented by California for each year, as obtained from the Federal Highway Administration (FHWA 1996 through 2001).

Historically U.S. VMT data were obtained from EPA's Office of Air Quality Planning and Standards (OAQPS), as they redistribute FHWA VMT data into the vehicle categories for which emission factors exist. This redistribution was recalculated using fuel economy and consumption data from FHWA's Highway Statistics.[3] Fuel economy and consumption data were disaggregated by fuel type using a number of sources, including DOE's Transportation Energy Data Book (DOE 1993 through 2001), FHWA's Highway Statistics (FHWA 1996 through 2001), EPA and DOE's Fuel Economy 2001 Datafile (EPA,

[3] The existing VMT data from OAQPS was believed to contain some inconsistencies.

DOE 2001), and the Vehicle Inventory and Use Survey (Census 1997). These data were used to distribute national VMT estimates across vehicle categories. All of the revisions discussed above resulted in an annual average decrease of 0.1 Tg of $CO_2$ Eq. (2.2 percent) in $CH_4$ emissions and an annual average decrease of 5.2 Tg of $CO_2$ Eq. (8.2 percent) in $N_2O$ emissions for 1990 through 1999.

## Coal Mining

The methodology used to estimate emissions avoided at underground coal mines has changed from the previous Inventory. For most mines with recovery systems, coal mine operators and state agencies provided individual well production data for all coalbed methane wells. Previously, the amount of methane recovered was estimated based on reported gas sales and a pre-drainage timing factor. The new methodology produces a more realistic estimate of emissions avoided for mines that utilize pre-drainage wells for two reasons. First, the new methodology takes into account the location of a well to determine if the well should be included in the emissions avoided estimate. Many of the pre-drainage wells within a degas field adjacent to a coal mine were never inside the footprint of the mine workings. Second, the entire cumulative production of a pre-drainage well is credited toward emissions avoided for only the year in which it is mined through, and not spread out over several years. Recent research showed that the life of a well within the same degas field can vary greatly. Although the data used for annual gas sales was accurate, the methodology resulted in an overestimation due to the inclusion of production from pre-drainage wells that did not contribute to emissions avoided at the coal mine. This methodological revision resulted in average decrease of 0.1 Tg of $CO_2$ Eq. (less than 0.1 percent) in annual $CH_4$ emissions from coal mining for 1990 through 1999.

## Petroleum Systems

In the Petroleum systems section of the Energy chapter, this year's inventory corrects the activity factors for thirteen methane emissions activities. The thirteen activities include separators (heavy and light crude oil), heater/treaters and compressors, pneumatic devices (high and low bleeds), vessel blowdowns, compressor blowdowns, compressor starts, chemical injection pumps, headers (heavy and light crude oil), and gas engines. Two changes were made in how activity data were estimated. First, the base year for activity data estimation was changed. In the previous report, the activity data were based on Radian (1996a-e), which represented activity data for the year 1995. However, Radian activity data for these thirteen activities were found to be based on 1993 data rather than 1995 data. Therefore, this year's inventory applies Radian's activity data to the correct year, which is 1993, not 1995. Secondly, the drivers used to estimate activity data outside the base year were refined. In the previous inventory report, non-base year activity data were related only to changes in crude production. This year's inventory follows the Radian approach, which estimated the annual activity data by calculating arithmetic mean of component estimates based on oil well counts and oil production for the years 1990 through 1992 and 1994 through 2000. The magnitude of the combined changes was small. For example, the activity data for pneumatic devices used in this year's Inventory is 3.4 percent lower for the years 1990 to 1995 compared to the 1999 Inventory, but the same data have been increased by an average of 2.9 percent over the period 1996 to 1999 for this year's Inventory. These methodological revisions, together with the data changes described below, resulted in average decrease of 0.2 Tg of $CO_2$ Eq. (0.8 percent) in annual $CH_4$ emissions from petroleum systems for 1990 through 1999.

## Natural Gas Flaring and Ambient Air Pollutant Emissions in Oil and Gas Activities

Estimates of natural gas flaring have been modified. The amount of natural gas flared was previously calculated by subtracting the vented gas emissions from the total amount of natural gas reported as vented and flared (EIA 2001a). However, for the current Inventory, it was assumed that all reported vented and flared gas was flared. This assumption is consistent with that used by EIA in preparing their emission estimates, under the assumption that many states require flaring of natural gas (EIA 2000b). Additionally, one facility in Wyoming had been incorrectly reporting $CO_2$ vented as $CH_4$. EIA has corrected these data in the *Natural Gas Annual* (EIA 2001a) for the years 1998 and 1999 only; data for previous years were corrected for this Inventory by assuming a proportionate share of $CO_2$ in the flare gas for those years as

for 1998 and 1999. These changes resulted in average decrease of 3.2 Tg of $CO_2$ Eq. (28.7 percent) in annual $CO_2$ emissions for 1990 through 1999.

The *National Air Pollutant Emission Trends Report 2000* revised the data for nitrogen oxides ($NO_x$), carbon monoxide (CO) and non-methane volatile organic compound (NMVOC) emissions. These changes resulted in an average increase of 1,073 Gg (4.6 percent) in annual $NO_x$ emissions, an average decrease of 196 Gg (0.2 percent) in annual CO emissions, and an average decrease of 4 Gg (0.1 percent) in annual NMVOC emissions for 1990 through 1999.

## Indirect $CO_2$ from $CH_4$ Oxidation

Indirect $CO_2$ emissions from $CH_4$ oxidation originating from non-combustion fossil sources—coal mining, natural gas systems, petroleum systems, petrochemical production, and silicon carbide production—have been added to this year's report to account for the global warming properties of methane that occur in the atmosphere after the gas oxidizes. These indirect emissions of $CO_2$ are not accounted for in the GWP of $CH_4$. Emissions from this source category added an average of 29.3 Tg of $CO_2$ Eq. to total Energy chapter emissions.

## Limestone and Dolomite Use

The method for estimating carbon dioxide emissions from limestone and dolomite use has been revised to include the thermic reduction of dolomite ($CaMg(CO_3)_2$) to magnesium metal vapor. This change, combined with the data changes described below, resulted in an increase in $CO_2$ emissions for 1999 of 1.0 Tg of $CO_2$ Eq. (9.9 percent). For the years 1990 through 1998, these updates resulted in an average increase in $CO_2$ emissions of 0.1 Tg $CO_2$ Eq. (1.8 percent).

## Aluminum Production

The estimates of PFC emissions for 1990 through 1999 have been revised due to the receipt of additional smelter-specific information on aluminum production and anode effect frequency and duration. In addition, the estimates reflect updated information on the average frequency and duration of anode effects throughout the industry as reported in the 2000 International Aluminum Institute survey on anode effects. The revision of Aluminum Production led to an average decrease of 0.4 Tg of $CO_2$ Eq. (2.8 percent) in annual $CF_4$ and $C_2F_6$ emissions for 1990 through 1999.

The estimates of $CO_2$ emissions for 1990 through 1999 have been revised to use emission factors from the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997). These factors are 1.5 tons $CO_2$/ton Aluminum for Prebake and 1.8 tons $CO_2$/ton Aluminum for Soderberg. (Production in the United States is estimated to be split approximately 80/20 for Prebake/Soderberg.) Previously, a single emission factor of 1.47 tons $CO_2$/ton Aluminum was used. Other revisions to estimates of $CO_2$ emissions for 1990 through 1999 are explained above in the section entitled Emissions and Storage from Non-Energy Uses of Fossil Fuels. These revisions led to an average increase of 5.8 Tg of $CO_2$ Eq. in annual $CO_2$ emissions for 1990 through 1999.

## Semiconductor Manufacturing

The estimates for 1990 through 1999 have been revised, reflecting a change in method. Both the previous method and the new method are based on the total annual emissions reported by the participants in the PFC Emission Reduction Partnership for the Semiconductor Industry. However, while the previous method used plant-specific emission factors, the new method uses layer-weighted capacities of plants and a per-layer emission factor to estimate total U.S. emissions. By considering both the average number of layers per chip and the silicon capacities of each plant, the new method more closely reflects the activity associated with PFC emissions. The methodological changes resulted in an average decrease of 0.1 Tg of $CO_2$ Eq. (1.5 percent) in annual HFCs, PFCs, and $SF_6$ emissions for 1990 through 1999.

## Electric Power Transmission and Distribution Systems

Estimates of $SF_6$ emissions from electrical equipment have been revised based on two new pieces of information: (1) the reported 1999 and 2000 $SF_6$ emissions from EPA's utility partners in the $SF_6$ Emissions Reduction Partnership for Electric Power Systems, and (2) updated aggregate world sales of $SF_6$ to utilities between 1990 and 1999 as reported by the RAND Corporation for seven major world producers

of $SF_6$. These new data, which rely on industry statistics for $SF_6$ emission and consumption, have reduced the uncertainty in the reported emission estimates.

The revised emissions trajectory differs from the previously estimated trend both in magnitude and in direction. The earlier trend showed estimated emissions rising from 20.5 Tg $CO_2$ Eq. in 1990 to 25.7 Tg $CO_2$ Eq. in 1995, plateauing thereafter. The revised estimates show a trend in the opposite direction, with estimated emissions fluctuating around 32 Tg $CO_2$ Eq. between 1990 and 1994, and then steadily falling to 14.4 Tg $CO_2$ Eq. in 2000.

The previous estimates were based on estimated U.S. $SF_6$ production capacity in 1994, along with the assumption that 90 percent of this capacity was utilized, 75 percent of produced $SF_6$ was sold for electrical equipment, and 50 percent of this gas replaced emitted gas as of 1994. Although these estimates were consistent with industry norms and with current research regarding usage of $SF_6$ world wide, they were highly uncertain, particularly the estimate that 50 percent of the gas sold into the electric equipment sector replaced emitted gas. In addition, they did not account for imports, exports, or year-to-year changes in actual sales for electrical equipment. Information on these factors was not available. Instead, the estimates were simply grown at rates intended to match the growth rate of the electrical power industry. (The exception to this was during the years 1997 through 1999, when emissions estimates were held steady in recognition of the fact that emissions had probably fallen during the mid 1990s in response to the sharp rise in the price of $SF_6$. At that time, there was not sufficient information available to develop alternative estimates.) These revisions lead to an average increase of 3.1 Tg of $CO_2$ Eq. (15.0 percent) in annual $SF_6$ emissions from electric power systems for 1990 through 1999.

## Magnesium Production and Processing

The emissions estimates for 1993 through 1999 were revised slightly to reflect changes to the estimated emission factors for different segments of the magnesium industry. The revisions result in an average decrease of 0.1 Tg $CO_2$ Eq. (1.6 percent) in annual $SF_6$ emissions for the years 1993 through 1999.

## Manure Management

This Inventory includes an improvement to the calculations of MCFs for liquid/slurry and deep pit systems for the entire time series. Previously, these MCFs were calculated using the van't Hoff-Arrhenius equation and an annual average temperature. The calculation now uses a monthly average temperature to better represent seasonal variations that affect the production of methane.

The calculation of MCFs for all liquid systems (liquid/slurry, anaerobic lagoon, and deep pit) are based on the van't Hoff-Arrhenius equation and a monthly ambient temperature used to represent the temperature of the system throughout the year. Some areas of the United States experience extremely cold temperatures and the use of this equation results in insignificant biological activity or methane generation below 5°C. However, there is evidence to suggest that a minimum level of biological activity continues to occur in the manure management system even in cold ambient temperatures, and that the minimum temperatures experienced at depth in these systems is higher than the surrounding ambient temperature. Anaerobic lagoons are therefore modeled with a minimum temperature of 5°C and other covered or partially covered liquid/slurry and deep pit systems are assumed to have a minimum temperature of 7.5°C.

These changes, combined with the data changes described below, resulted in an average increase of 3.3 Tg of $CO_2$ Eq. (10.9 percent) in annual $CH_4$ emissions, and an average decrease of less than 0.1 Tg of $CO_2$ Eq. (0.2 percent) in annual $N_2O$ emissions, from 1990 through 1999.

## Rice Cultivation

The method for calculating methane emissions from rice cultivation has been revised to follow the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Emissions are now estimated from annual areas harvested and U.S.-specific, area-based, seasonally integrated emission factors; previously, these emissions were based on annual areas harvested, flooding season lengths, and daily average emission factors. This revision, in combination with the revision to the historical data described below, resulted in an average decrease of 1.9 Tg $CO_2$ Eq. (20.0 percent) in estimated annual $CH_4$ emissions from rice cultivation over the entire time series.

## Agricultural Soil Management

The methodology used to estimate emissions from agricultural soil management includes two changes. First, the calculation of $N_2O$ emissions from cultivated histosols has been revised to take into account the climate of the cropland area. The areas are now split into temperate and sub-tropical categories with different $N_2O$ emission factors. Second, the calculation of indirect emissions from leaching and runoff of manure nitrogen has been corrected so that the portion of manure that is not applied or deposited on soils (i.e., the poultry manure used as a feed supplement—less than 1 percent of total manure nitrogen) is excluded. These two methodological changes, in combination with the revisions to historical data described below, resulted in an average annual decrease of 2.0 Tg of $CO_2$ Eq. (0.7 percent) in total $N_2O$ emissions from agricultural soil management for 1990 through 1999.

## Agricultural Residue Burning

The emission ratio for methane from agricultural residue burning was revised from 0.004 to 0.005 to reflect the correct IPCC default value from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

The calculation of rice straw burning was revised for the entire time series. Instead of applying area-weighted percent burned figures to national production numbers, state estimates of percent residue burned were applied to state production numbers. These calculations were then summed over all the states to yield the national estimates of rice residue burned. These two methodological changes, in combination with the revisions to historical data described below, resulted in average increases in agricultural residue burning emissions of 0.2 Tg $CO_2$ Eq. (27.9 percent) for methane, less than 0.1 Tg $CO_2$ Eq. (1.9 percent) for nitrous oxide, 15.8 Gg (2.3 percent) for CO, and 0.6 Gg (1.9 percent) for $NO_x$ for 1990 through 1999.

## Land-Use Change and Forestry

The Land-Use Change and Forestry chapter comprises four sections: 1) Forests; 2) Urban Trees; 3) Agricultural Soils; and 4) Landfilled Yard Trimmings. The section on urban trees is new to this year's Inventory. The methodologies used in the first and third sections have changed relative to the previous Inventory. The changes to each section are described below.

- *Forests.* In this year's Inventory, down dead wood from both logging and mortality were counted explicitly. In addition, new volume-to-carbon conversion factors and new forest floor carbon equations were used. Soil carbon densities (carbon per hectare) were assumed constant over time, so that soil carbon changed only if forest type changed or if forest land area changed.
- *Agricultural Soils.* The method for calculating mineral soil carbon changes for cropping systems containing rice and rice in rotation was modified this year. In last year's Inventory, mineral soil carbon stock changes were slightly overestimated due to a programming error that resulted in a double-counting of soil carbon increases for systems containing rice. The corrected program, combined with revisions to the historical data described below, resulted in an average decrease of 10 percent in total net sequestration from mineral and organic soils for 1990 through 1999.
- *Urban Trees.* A new section on changes in carbon stocks in urban trees has been added. The primary input data were obtained from Nowak and Crane (2001).

These changes, combined with the revisions to historical data described below, resulted in an average increase of 75.4 Tg $CO_2$ Eq. (7 percent) in annual carbon sequestration from land-use change and forestry for 1990 through 1996, and an average decrease of 95.3 Tg $CO_2$ Eq. (10 percent) in annual carbon sequestration from land-use change and forestry for 1997 through 1999.

## Landfills

The methodology used to estimate $CH_4$ emissions avoided through flaring was modified in the following ways. First, emissions avoided for all flares were based on reported flow range or fit to standard flow ranges established by one of the vendors. In many cases, vendors reported only a flow rate without establishing whether the reported flow rate represented the minimum, average, or maximum flow rate. In previous year's the flow rate was used. To improve consistency across vendors, for this year's inventory individual flare flow rates were mapped into standard flow ranges provided by one of the vendors. The midpoint of this range was then used to calculate emissions avoided. Second, multiple flares for landfills were tracked, while previously only one flare per landfill was included. Finally,

emission reductions at utility flares were included as long as they were not affiliated with a landfill-gas-to-energy project. In past inventories, all utility flares were excluded as it was unclear whether they corresponded to a landfill-gas-to-energy project. This year's flaring estimate reflects emission reductions taking place at 585 flares nationwide, as compared to 487 flares in the previous inventory. These methodological changes, together with the data changes described below, resulted in an average decrease in annual methane emissions from landfills of 7.2 Tg $CO_2$ Eq. (3.3 percent). This decrease is mainly the result of the incorporation of additional data on the national population of flares.

### Wastewater Treatment

In the Wastewater Treatment section of the Waste chapter, the fraction of domestic wastewater that degrades anaerobically was changed to reflect the use of septic tanks in addition to treatment plants. Recent research has shown that twenty five percent of domestic wastewater is disposed into septic tanks. The new factor is 16.25 percent, an increase from the 15 percent used in the previous Inventory.

The industrial wastewater estimate was changed to reflect new information on pulp & paper wastewater. Estimates from vegetables, fruits, and juice processing and the meat and poultry industry were also included for the first time. The pulp and paper estimates were revised to account for secondary treatment lagoons, which, in this industry, are more prone to anaerobic conditions.

These changes to wastewater treatment emissions, coupled with the data changes described below, resulted in an average increase of 14.6 Tg of $CO_2$ Eq. (124.6 percent) in annual $CH_4$ emissions for 1990 through 1999, primarily due to the expansion of the categories of industrial wastewater covered by the estimate.

### Human Sewage

In the Human Sewage section of the Waste chapter, a change was made to the 1990 through 1999 sewage sludge applications. In previous years, the sewage sludge applied to soils was subtracted from the amount discharged into aquatic environments. In this year's Inventory, the amount landfilled is also subtracted from the amount discharged into aquatic environments. This revision, in combination with the revision to the historical data described below, resulted in an average decrease of 0.1 Tg $CO_2$ Eq. (0.8 percent) in estimated annual $N_2O$ emissions from human sewage over the entire time series.

## Changes in Historical Data

- In the $CO_2$ Emissions from Fossil Fuel Combustion section of the Energy chapter, energy consumption data have been updated by the Energy Information Administration (EIA 2001a) for selected years (see above for detail on methodological changes). To highlight one significant revision, EIA removed fuel consumption for electricity generation by non-utilities from the industry end-use sector, and combined it with electric utility consumption—thus creating a comprehensive electric power industry sector. This sector is referred to in this report as "electricity generation." In another instance, Puerto Rico began consuming natural gas in 2000, which has been reflected in the $CO_2$ estimates from U.S. Territories for 2000. Puerto Rico began importing liquefied natural gas (LNG) in August 2000 to fuel its new natural gas-fired electricity generation plant. This consumption estimate provided by the EIA is based on available data on LNG shipments to Puerto Rico from Trinidad. Additionally, the carbon storage factor for miscellaneous products under other petroleum for U.S. territories, originally assumed as ten percent has been modified to 100 percent. This revision is based on the assumption that the carbon consumption for miscellaneous products is used for asphalt and road oil. These changes, along with the methodological changes in "Emissions and Storage from Non-Energy Uses of Fossil Fuels" (which affect this sector), resulted in an average decrease of 36.0 Tg $CO_2$ Eq. (0.7 percent) in annual $CO_2$ emissions from fossil fuel combustion for 1990 through 1999.
- In the Stationary Combustion (excluding $CO_2$) section of the Energy chapter, changes to emission estimates were entirely due to revised data from EIA (2001a). These revisions are explained in more detail in the section above on $CO_2$ Emissions from Fossil Fuel Combustion [and] Carbon Stored in Products from Non-Energy Uses of Fossil Fuels. On average, annual stationary combustion

methane emissions estimates decreased by 0.6 Tg of $CO_2$ Eq. (7.4 percent), and annual stationary combustion $N_2O$ emissions increased by 0.8 Tg of $CO_2$ Eq. (5.8 percent) for 1990 through 1999.

- In the Natural Gas Systems section of the Energy chapter, methane emission estimates have been revised to incorporate new activity driver data for distribution mains and services for 1993 through 2000 (OPS 2001). These data changes resulted in an average increase of 0.4 Tg of $CO_2$ Eq. (0.3 percent) in annual methane emissions from natural gas systems from 1990 through 1999. Furthermore, the emissions reduction estimates for 1999, as reported by EPA's Natural Gas STAR partners, were updated to incorporate more recent data. This change has resulted in a decrease in annual methane emissions of 3.2 Tg of $CO_2$ Eq. (2.6 percent) in 1999.
- In the Petroleum Systems section of the Energy chapter, this year's inventory reflects one historical data change. A different data source for the number of producing wells has been used. In the previous report, the data source for producing wells was the American Petroleum Institute's (API), *Petroleum Data Book 1999*. Although published annually, the API's data lags two years behind the publication year. In this year's Inventory, data for producing wells were taken from the Energy Information Administration's (EIA), *Annual Energy Review* 2001, which has data for 2000, unlike the API publication. This change, combined with the methodological changes described above, results in an average emissions decrease of 0.2 Tg of $CO_2$ Eq. (0.8 percent) across the entire period.
- In the International Bunker Fuels section of the Energy chapter, the $CH_4$ emission factor for marine fuels was revised from 0.03 to 0.315 g $CH_4$/kg fuel. In addition, DESC (2001) revised their estimates of marine and aviation jet fuel consumption for international bunkers for 2000. The military international bunker fuel data provided by DESC for 2000 are from a data set developed by the Navy Fuels and Logistics office, which is more consistent with the 1995 to 1999 DESC maritime data. An additional marine fuel, intermediate fuel oil (IFO 180 and IFO 380), is included in the estimates for this inventory providing consumption data for 1996 through 2000. IFO is a blend of distillate and residual fuels and is used by some Military Sealift Command vessels. These revisions result in average emission decreases of 0.2 Tg $CO_2$ Eq. and less than 0.1 Tg $CO_2$ Eq. of $CO_2$ and $N_2O$, respectively, and an average increase of 0.1 Tg $CO_2$ Eq. of $CH_4$.
- In the Cement Manufacture section of the Industrial Processes chapter, the clinker production data was altered to reflect the information in the *Cement Annual Report 2001* (USGS 2001a). The revisions increased the annual $CO_2$ emissions by 0.1 Tg of $CO_2$ Eq. (0.2 percent) for 1999.
- In the Lime Manufacture section of the Industrial Processes chapter, the activity data was altered to incorporate revised production numbers (USGS 2001b) for dolomitic quicklime and high-calcium hydrated lime. The revisions increased the total lime production and sugar refining data for 1999 leading to an emissions increase of 0.04 Tg of $CO_2$ Eq. (0.3 percent) for that year. These revisions also decreased total emissions from lime manufacture by less than 0.001 Tg of $CO_2$ Eq. (0.01 percent) for 1990 through 1996.
- In the Limestone and Dolomite Use section of the Industrial Processes chapter, the activity data used to calculate $CO_2$ emissions have been changed to incorporate revised numbers for the total flux stone consumption numbers for both limestone and dolomite (USGS 2001c). This change, combined with the methodological change described above, resulted in an increase in $CO_2$ emissions for 1999 of 1.0 Tg of $CO_2$ Eq. (9.9 percent). For the years 1990 through 1998, these updates resulted in an average increase in $CO_2$ emissions of 0.1 Tg $CO_2$ Eq. (1.8 percent).
- In the Soda Ash Manufacture and Consumption section of the Industrial Processes chapter, the activity data used to calculate $CO_2$ emissions have been revised to incorporate published 2001 data (USGS 2001d). Trona Production was changed for 1990 and 1991 while soda ash consumption changed 1990 through 1997 according to the *Soda Ash Annual Report 2001*. These updates resulted in a decrease in annual $CO_2$ emissions by less than 0.1 Tg of $CO_2$ Eq. (0.4 percent) for 1990 through 1997.

- In the Carbon Dioxide Consumption section of the Industrial Processes chapter, the activity data used to calculate $CO_2$ emissions has been revised reflect an updated 1999 figure published by the Freedonia Group. This resulted in a change of less than 0.01 Tg $CO_2$ Eq. in $CO_2$ emissions from this source for 1999.
- In the Petrochemical Production section of the Industrial Processes chapter, the activity data used to calculate $CH_4$ emissions were revised to reflect modified data from the American Chemistry Council 2001. The production data was altered for dichloroethylene, styrene, methanol for the years 1995 through 1999. Carbon black and ethylene data was revised for 1999 only. The revisions increased $CH_4$ emissions on average less than 0.1 Tg of $CO_2$ Eq. (0.5 percent) for the years 1995 through 1999.
- In the Adipic Acid Production section of the Industrial Processes chapter, information on emission estimates for 1990 to 2000 was directly obtained from two of the four adipic acid plants. These data were updated for the whole time series for these plants. These revisions resulted in an average decrease of 3.5 Tg of $CO_2$ Eq. (18.9 percent) in annual $N_2O$ emissions from 1990 through 1999.
- In the Nitric Acid Production section of the Industrial Processes chapter, 1999 production data were revised using updated estimates from *Chemical and Engineering News* (C&EN 2001). The revision resulted in a decrease of 0.1 Tg $CO_2$ Eq. (0.6 percent) in $N_2O$ emissions from nitric acid production in 1999.
- In the Substitution of Ozone Depleting Substances section of the Industrial Processes chapter, a review of the current chemical substitution trends, together with input from industry representatives, resulted in updated assumptions for the Vintaging Model, particularly in the precision cleaning solvents, stationary refrigeration, and fire extinguishing sectors. These revisions resulted in an average decrease of 3.6 Tg $CO_2$ Eq. (10.6 percent) in HFC, PFC, and $SF_6$ emissions from substitution of ozone depleting substances for 1994 through 1999.
- For emissions of HFC-23 from HCFC-22 Production within the Industrial Processes chapter, the emission estimates for 1990 to 1998 were changed to correct a small error in the conversion from Gg of HFC-23 to Tg of $CO_2$ equivalent. None of the changes were greater than ± 0.2 Tg $CO_2$. The revision lead to an average increase of less than 0.1 Tg of $CO_2$ Eq. (less than 0.1 percent) in annual HFC-23 emissions from the production of HCFC-22.
- In the Enteric Fermentation section of the Agriculture chapter, the emission estimates have been recalculated using updated animal population data. Specifically, horse population data for 1990 through 1999 were updated by the Food and Agriculture Organization (FAO 2001). Additionally, population data for swine, goats, and sheep were adjusted to match the most updated data from USDA. Some cattle population data were also revised to reflect updated USDA estimates. Lastly, stocker and feedlot numbers were modified to include animals at feedlots with less than 1000 head. These data modifications caused an average decrease of 2.5 Tg of $CO_2$ Eq. (1.9 percent) in annual $CH_4$ emissions from enteric fermentation for 1990 through 1999.
- In the Manure Management section of the Agriculture chapter, four changes have been incorporated into the emission estimates. Each of these major changes is discussed in more detail below.
  - USDA updated the quarterly estimates for swine population for the years 1998 and 1999; therefore, population data for these years changed slightly. The volatile solids and nitrogen excretion estimates for these years have changed accordingly.
  - The Food and Agriculture Organization of the United Nations (FAO) has an online database that is used for horse population estimates. These data, from 1990 through 2000, have been updated. Therefore, all $N_2O$ and $CH_4$ emission estimates for horses have changed relative to the previous Inventory. The effect of the population changes on the predicted $CH_4$ emissions is less than the effect on the predicted $N_2O$ emissions due to the nonlinear effect of the change on the $CH_4$ calculations.
  - The beef cattle population data used to calculate $N_2O$ emissions for the previous inventory were slightly different than the data used to calculate $CH_4$ emissions. The $N_2O$ population data excluded

a small portion of the population, which were animal counts from states with a very small number of animals, compared to the U.S. total population. The $CH_4$ populations included these counts. In order to be consistent between the $N_2O$ and $CH_4$ emission calculations, the $N_2O$ populations were changed to include population from these states.

— The supporting documentation for the previous inventory indicated that the relationship of volatile solids excretion and milk production in dairy cows was estimated using a polynomial fit curve. These estimates were actually calculated using a logarithmic curve.

The $CH_4$ emission estimates for horses decreased an average of 4 percent across the time series. The $N_2O$ emission time series for horses decreased emissions by an average of 12 percent across the time series. These changes, combined with the methodological changes described above, changes in total resulted in an average increase of 3.3 Tg of $CO_2$ Eq. (10.9 percent) in annual $CH_4$ emissions, and an average decrease of less than 0.1 Tg of $CO_2$ Eq. (0.2 percent) in annual $N_2O$ emissions, from 1990 through 1999.

- In the Rice Cultivation section of the Agriculture chapter, one change has been made to the historical data. Revised harvested rice areas for the primary crops in Arkansas and California have been incorporated for the years 1998 and 1999, based on the latest statistics from USDA (2001d). These changes resulted in a less than 2 percent decrease in rice area harvested for each of the affected years. This revision, together with the methodological revision described above, resulted in an average decrease of 1.9 Tg $CO_2$ Eq. (20.0 percent) in estimated annual $CH_4$ emissions from rice cultivation over the entire time series.
- The estimates of $N_2O$ emissions from agricultural soil management include several data changes, as described below:
  - — Fertilizer consumption data for 1990 through 1999 were revised using the most recent estimates for each year provided by TVA and AAPFCO (TVA 1990, 1991, 1992, 1993, 1994, and AAPFCO 1995, 1996, 1997, 1998, 1999, 2000b). Also, for the commercial organic fertilizers, fertilizer type-specific nitrogen contents were used to estimate total nitrogen applied. These nitrogen contents were obtained from TVA (1991, 1992, 1993, 1994) and AAPFCO (1995; 1996; 1997; 1998; 1999; 2000a,b).
  - — New manure data were incorporated based on updated swine and horse population estimates, and a regrouping of the beef cattle and cattle-not-on-feed animal groups (USDA 2001a; FAO 2001; USDA 2001b,c).
  - — The estimates of sewage sludge production and land application were refined through new data sources. Additional annual figures and projections from EPA (1999) were incorporated, reducing the amount of interpolation necessary. The nitrogen content of the sludge was also revised from 4 percent to 3.3 percent based upon information in Metcalf and Eddy, Inc. (1991).
  - — Crop production figures for 1990 through 1999 were revised using the most recent estimates for each year provided by USDA (1994, 1998c, 2001a). This change resulted in a less than 1 percent revision in crop production for a few crops. In the crop residue calculations, the rice component was revised to include Florida data, which had been omitted previously. Histosol area estimates were revised, as they were extracted from NRI incorrectly last year, and disaggregated into broad climatic regions.

  These revisions, in combination with the methodological revisions described above, resulted in an average annual 2.0 Tg $CO_2$ Eq. (0.7 percent) decrease in total $N_2O$ emissions from agricultural soil management for 1990 through 1999.
- The emission estimates for agricultural residue burning include several changes. Crop production figures for the time series from 1990 through 1999 were revised using the most recent estimates from USDA (1994, 1998c, 2001). This change resulted in less than a 1 percent revision in crop production for a few crops.[4]

[4] The production statistics presented in Table 5-19 of the Agriculture chapter were also revised to include Florida rice production, which had been omitted previously. However, this had no effect on the emission estimates because rice residue burning does not occur in Florida.

Agricultural extension agents in each rice-growing state, and the California Air Resources Board, were contacted to verify, and update as needed, the historical estimates of rice acreage burned in each state. Estimates for California, Mississippi and Missouri were revised. For California, a new estimate of 1999 rice area burned in Sacramento Valley was obtained from California Air Resources Board (2001), resulting in a 13 percent increase in California's burned acreage for that year. New estimates of the percentage of rice area burned in Mississippi were obtained from Street (2001), as the previous estimates are now thought to be too low. The 1990 to 1998 estimates were revised from 5 to 10 percent, and the 1999 estimate from 10 to 40 percent. The previous 1990 to 1998 estimates for Missouri were also revised from 3.5 to 5 percent (Guethle 2001). These revisions, in combination with the methodological revisions described above, resulted in average increases in agricultural residue burning emissions of less than 0.2 Tg $CO_2$ Eq. (27.9 percent) for $CH_4$, less than 0.1 Tg $CO_2$ Eq. (1.9 percent) for $N_2O$, 15.8 Gg (2.3 percent) for CO, and 0.6 Gg (1.9 percent) for $NO_x$ for 1990 through 1999.

- In the Land-Use Change and Forestry chapter, the following changes were made:
  - — In the Forest Carbon section, results from the USDA Forest Service Forest Sector Modeling System were used to develop a projected stock estimate for 2001. In last year's Inventory, results from the modeling system were used to develop both carbon flux and stock estimates for 1990 through 1999. This year, the USDA Forest Service, Forest Inventory & Analysis data were used directly as the base data (i.e., areas, volumes, growth, land-use changes, and other forest characteristics) for 1987 and 1997. For areas with limited survey data on volume (i.e., Reserved Forest Land and Other Forest Land), average volumes were estimated using the Timberland data for the appropriate forest type and region.
  - — In the Agricultural Soils section, the soil carbon stock data were obtained from the updated (final release) *1997 National Resources Inventory* (NRI) data. Last year's estimates were based on the initial (unofficial) 1997 NRI data. Use of the final 1997 NRI data, in combination with the agricultural soils methodological revisions described above, resulted in an average decrease of 10 percent in total net sequestration from mineral and organic soils for the 1990 to 1999 period.
  - — In the Agricultural Soils section, the 1999 carbon dioxide emission estimates for liming were revised based on the U.S. Geological Survey's latest estimates of limestone and dolomite use in 1999 (Tepordei 2000). This decreased the 1999 emission estimate for that source by about 9 percent.
  - — In the Landfilled Yard Trimmings section, the landfilled yard trimmings data were revised to correct incorrect data entry from last year's inventory. These revisions resulted in an average annual 10 percent decrease in yard trimmings carbon storage for 1990 through 1999.

  These changes, combined with the methodological revisions described above, resulted in an average increase of 75.4 Tg $CO_2$ Eq. (7.4 percent) in annual carbon sequestration from land-use change and forestry for 1990 through 1996, and an average decrease of 95.3 Tg $CO_2$ Eq. (9.7 percent) in annual carbon sequestration from land-use change and forestry for 1997 through 1999.
- In the Landfills section of the Waste chapter, this year's inventory reflects an updated 1999 waste generation and percent-landfilled estimate published by BioCycle (2000). This revision caused the 1999 $CH_4$ generation estimate to decrease from 214.6 to 203.1 Tg $CO_2$ Eq. In addition, EPA used an updated database on landfill-gas-to-energy projects. The methane mitigated from these projects changed from 1990 through 1999. The most recent data indicated a smaller quantity of $CH_4$ mitigated in 1999 than last year's landfill gas-to-energy database. For 1999, this year's landfill gas-to-energy data showed 1.1 Tg $CO_2$ Eq. less mitigated $CH_4$ than last year's data. The difference is primarily attributed to revised estimates of municipal waste capacity for electricity projects and landfill gas flow for direct use projects. Finally, new data from an additional vendor of landfill gas flares was obtained. These revisions, coupled with the methodological changes described

above, resulted in resulted in an average decrease of 7.2 Tg $CO_2$ Eq. (3.3 percent) in annual $CH_4$ emissions from landfills for 1990 through 1999.

- In the Wastewater Treatment section of the Waste chapter, small changes were made to the 1990 through 1999 population data based on new estimates provided by the U.S. Census. Along with the more substantive methodological changes mentioned above, these revisions resulted in average increase of 14.6 Tg of $CO_2$ Eq. (125 percent) in annual $CH_4$ emissions.
- In the Human Sewage section of the Waste chapter, small changes were made to the 1990 to 1999 per capita protein consumption data based on new estimates provided by the FAO. These revisions, together with the new census population data mentioned previously and the methodological changes described above, resulted in an annual average decrease of 0.1 Tg $CO_2$ Eq. (0.8 percent) in $N_2O$ emissions from 1990 through 1999.

# 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 2000. A summary of these estimates is provided in Table 1-8 and Table 1-9 by gas and source category. 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.[1,2] This report also discusses the methods and data used to calculate these emission estimates.

In June of 1992, the United States signed, and later ratified in October, the United Nations Framework Convention on Climate Change (UNFCCC). The objective of the UNFCCC is "to achieve...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." [3,4]

Parties to the Convention, by signing, make commitments "to 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..."[5] The United States views this report as an opportunity to fulfill this commitment under the UNFCCC.

In 1988, preceding the creation of the UNFCCC, the Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). The charter of the IPCC is to assess available scientific information on climate change, assess the environmental and socio-economic impacts of climate change, and formulate response strategies (IPCC 1996). 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 *Revised 1996 IPCC Guidelines* were accepted by the IPCC at its Twelfth Session (Mexico City, 11-13 September 1996). The information provided in this inventory is presented in accordance with these guidelines. Additionally, in order to fully comply with the *Revised 1996 IPCC Guidelines*, the United States has provided estimates of carbon dioxide emissions from fossil fuel combustion using the IPCC Reference Approach in Annex U. In addition, this inventory is in accordance with the recently published IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, which further expanded upon the methodologies in the *Revised 1996 IPCC Guidelines.*

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

[2] See the section below entitled *What is Climate Change?* for an explanation of radiative forcing.

[3] 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).

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

[5] Article 4 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change (also identified in Article 12). See <http://www.unfccc.de>. (UNEP/WMO 2000)

Overall, the purpose of an inventory of anthropogenic greenhouse gas emissions is (1) to provide a basis for the ongoing development of methodologies for estimating sources and sinks of greenhouse gases; (2) to provide a common and consistent mechanism through which Parties to the UNFCCC can estimate emissions and compare the relative contribution of individual sources, gases, and nations to climate change; and (3) as a prerequisite for accounting for reductions and evaluating possible mitigation strategies.

## What is Climate Change?

Climate change refers to long-term fluctuations in temperature, precipitation, wind, and other elements of the Earth's climate system.[6] Natural processes such as solar-irradiance variations, variations in the Earth's orbital parameters,[7] and volcanic activity can produce variations in climate. The climate system can also be influenced by changes in the concentration of various gases in the atmosphere, which affect the Earth's absorption of radiation.

The Earth naturally absorbs and reflects incoming solar radiation and emits longer wavelength terrestrial (thermal) radiation back into space. On average, the absorbed solar radiation is balanced by the outgoing terrestrial radiation emitted to space. A portion of this terrestrial radiation, though, is itself absorbed by gases in the atmosphere. The energy from this absorbed terrestrial radiation warms the Earth's surface and atmosphere, creating what is known as the "natural greenhouse effect." Without the natural heat-trapping properties of these atmospheric gases, the average surface temperature of the Earth would be about 33°C lower (IPCC 2001).

Under the UNFCCC, the definition of climate change is "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods."[8] Given that definition, in its Second Assessment Report of the science of climate change, the IPCC concluded that:

*Human activities are changing the atmospheric concentrations and distributions of greenhouse gases and aerosols. These changes can produce a radiative forcing by changing either the reflection or absorption of solar radiation, or the emission and absorption of terrestrial radiation* (IPCC 1996).

Building on that conclusion, the more recent IPCC Third Assessment Report asserts that "[c]oncentrations of atmospheric greenhouse gases and their radiative forcing have continued to increase as a result of human activities." (IPCC 2001)

The IPCC went on to report that the global average surface temperature of the Earth has increased by between 0.6± 0.2° C over the 20th century (IPCC 2001). This value is about 0.15° C larger than that estimated by the Second Assessment Report, which reported for the period up to 1994, "owing to the relatively high temperatures of the additional years (1995 to 2000) and improved methods of processing the data" (IPCC 2001).

While the Second Assessment Report concluded, "the balance of evidence suggests that there is a discernible human influence on global climate," the Third Assessment Report states the influence of human activities on climate in even starker terms. It concludes that, "[I]n light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations" (IPCC 2001).

## 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, and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC 1996). Changes in the atmospheric concentrations of these greenhouse gases can alter the

[6] The Earth's climate system comprises the atmosphere, oceans, biosphere, cryosphere, and geosphere.

[7] For example, eccentricity, precession, and inclination.

[8] Article 1 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change. (UNEP/WMO 2000)

balance of energy transfers between the atmosphere, space, land, and the oceans. A gauge of these changes is called radiative forcing, which is a simple measure of changes in the energy available to the Earth-atmosphere system (IPCC 1996). 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, 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). Because CFCs, HCFCs, and halons are stratospheric ozone depleting substances, they are covered under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. The UNFCCC defers to this earlier international treaty; consequently these gases are not included in national greenhouse gas inventories.[9] 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 referred to as ambient air pollutants include carbon monoxide (CO), nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$), and tropospheric (ground level) ozone ($O_3$). Tropospheric ozone is formed by two precursor pollutants, volatile organic compounds (VOCs) and nitrogen oxides ($NO_x$) in the presence of ultraviolet light (sunlight). Aerosols extremely small particles or liquid droplets often composed of sulfur compounds, carbonaceous combustion products, crustal materials and other human induced pollutants can affect the absorptive characteristics of the atmosphere. However, the level of scientific understanding of aerosols is still very low (IPCC 2001).

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

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

*Water Vapor ($H_2O$).* 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 directly affect the average global concentration of water vapor; however, the radiative forcing produced by the increased concentrations of other greenhouse gases may indirectly affect the hydrologic cycle. A warmer atmosphere has an increased water holding capacity; yet, increased concentrations of water vapor affects the formation of clouds, which can both absorb and reflect

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

**Table 1-1: Global atmospheric concentration (ppm unless otherwise specified), rate of concentration change (ppb/year) and atmospheric lifetime (years) of selected greenhouse gases**

| Atmospheric Variable | $CO_2$ | $CH_4$ | $N_2O$ | $SF_6$[a] | $CF_4$[a] |
|---|---|---|---|---|---|
| Pre-Industrial atmospheric concentration | 278 | 0.700 | 0.270 | 0 | 40 |
| Atmospheric concentration (1998) | 365 | 1.745 | 0.314 | 4.2 | 80 |
| Rate of concentration change[b] | 1.5[c] | 0.007[c] | 0.0008 | 0.24 | 1.0 |
| Atmospheric Lifetime | 50-200[d] | 12[e] | 114[e] | 3,200 | >50,000 |

Source: IPCC (2001)
[a] Concentrations in parts per trillion (ppt) and rate of concentration change in ppt/year.
[b] Rate is calculated over the period 1990 to 1999.
[c] Rate has fluctuated between 0.9 and 2.8 ppm per year for $CO_2$ and between 0 and 0.013 ppm per year for $CH_4$ over the period 1990 to 1999.
[d] No single lifetime can be defined for $CO_2$ because of the different rates of uptake by different removal processes.
[e] This lifetime has been defined as an "adjustment time" that takes into account the indirect effect of the gas on its own residence time.

solar and terrestrial radiation. Aircraft contrails, which consist of water vapor and other aircraft emittants, are similar to clouds in their radiative forcing effects (IPCC 1999).

*Carbon Dioxide ($CO_2$).* In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as $CO_2$. Atmospheric carbon dioxide is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppmv) in pre-industrial[10] times to 367 ppmv in 1999, a 31 percent increase (IPCC 2001).[11] The IPCC notes that "[t]his concentration has not been exceeded during the past 420,000 years, and likely not during the past 20 million years. The rate of increase over the past century is unprecedented, at least during the past 20,000 years." The IPCC definitively states that "the present atmospheric $CO_2$ increase is caused by anthropogenic emissions of $CO_2$" (IPCC 2001). Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of carbon dioxide.

In its second assessment, the IPCC also stated that "[t]he increased amount of carbon dioxide [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 ($CH_4$).* Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit $CH_4$, as does the decomposition of municipal solid wastes. Methane 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 methane have increased by about 150 percent since pre-industrial times, although the rate of increase has been declining. The IPCC has estimated that slightly more than half of the current $CH_4$ flux to the atmosphere is anthropogenic, from human activities such as agriculture, fossil fuel use and waste disposal (IPCC 2001).

Methane is removed from the atmosphere by reacting with the hydroxyl radical (OH) and is ultimately converted to $CO_2$. Minor removal processes also include reaction with Cl in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of methane reduce the concentration of OH, a feedback which may increase methane's atmospheric lifetime (IPCC 2001).

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

[11] 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).

*Nitrous Oxide ($N_2O$).* Anthropogenic sources of $N_2O$ emissions include agricultural soils, especially the use of synthetic and manure fertilizers; 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 nitrous oxide ($N_2O$) has increased by 16 percent since 1750, from a pre industrial value of about 270 ppb to 314 ppb in 1998, a concentration that has not been exceeded during the last thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere.

*Ozone ($O_3$).* Ozone is present in both the upper stratosphere,[12] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[13] 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 chlorofluorocarbons (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 nitrogen oxides ($NO_x$) in the presence of sunlight. Ozone, carbon monoxide (CO), sulfur dioxide ($SO_2$), nitrogen dioxide ($NO_2$) and particulate matter are included in the category referred to as "criteria pollutants" in the United States under the Clean Air Act[14] and its subsequent amendments. The tropospheric concentrations of ozone and these other pollutants are short-lived and, therefore, spatially variable.

*Halocarbons, Perfluorocarbons, and Sulfur Hexafluoride ($SF_6$).* Halocarbons are, for the most part, man-made chemicals that have both direct and indirect radiative forcing effects. Halocarbons that contain chlorine chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl chloroform, and carbon tetrachloride and bromine halons, methyl bromide, and hydrobromofluorocarbons (HBFCs) result in stratospheric ozone depletion and are therefore controlled under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. Although CFCs and HCFCs include potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which is itself 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[15] countries beginning in 1996, and then followed by a complete phase-out by the year 2030. The ozone depleting gases covered under the *Montreal Protocol* and its Amendments are not covered by the UNFCCC; however, they are reported in this inventory under Annex R.

Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride ($SF_6$) are not ozone depleting substances, and therefore are not covered under the *Montreal Protocol*. They are, however, powerful greenhouse gases. HFCs primarily used as replacements for ozone depleting substances but also emitted as a by-product of the HCFC-22 manufacturing process currently have a small aggregate radiative forcing impact; however, it is anticipated that their

[12] 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.

[13] 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.

[14] [42 U.S.C § 7408, CAA § 108]

[15] 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.

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

*Nitrogen Oxides ($NO_x$).* The primary climate change effects of nitrogen oxides (i.e., NO and $NO_2$) are indirect 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.[16] Additionally, $NO_x$ emissions from aircraft are also likely to decrease methane 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 nitrous oxide ($N_2O$). Concentrations of $NO_x$ are both relatively short-lived in the atmosphere and spatially variable.

*Nonmethane Volatile Organic Compounds (NMVOCs).* Nonmethane volatile organic compounds include compounds 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. They affect radiative forcing in both direct and indirect ways: directly by scattering and absorbing solar and thermal infrared radiation; and indirectly by increasing droplet counts that modify the formation, precipitation efficiency, and radiative properties of clouds. Aerosols are removed from the atmosphere relatively rapidly by precipitation. Because aerosols generally have short atmospheric lifetimes, and have concentrations and compositions that vary regionally, spatially, and temporally, their contributions to radiative forcing are difficult to quantify (IPCC 2001).

The indirect radiative forcing from aerosols are 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, sulphates, and volcanic aerosols, and anthropogenically manufactured aerosols such as industrial dust and carbonaceous[17] aerosols (e.g., black carbon, organic carbon) from transportation, coal combustion, cement manufacturing, waste incineration, and biomass burning.

The net effect of aerosols is believed to produce a negative radiative forcing effect (i.e., net cooling effect on the climate), although because they are short-lived in the atmosphere lasting days to weeks their concentrations

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

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

respond rapidly to changes in emissions.[18] 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 may have a positive radiative forcing (Jacobson 2001). The primary anthropogenic emission sources of elemental carbon include diesel exhaust, coal combustion, and biomass burning.

**Table 1-2: Global Warming Potentials and Atmospheric Lifetimes (Years)**

| Gas | Atmospheric Lifetime | GWP[a] |
|---|---|---|
| Carbon dioxide ($CO_2$) | 50-200 | 1 |
| Methane ($CH_4$)[b] | 12 3 | 21 |
| Nitrous oxide ($N_2O$) | 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 methane 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.

## Global Warming Potentials

A Global Warming Potential (GWP) is intended as 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 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. Indirect radiative forcing occurs when chemical transformations involving the original gas produces 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 $CO_2$ equivalents (Tg $CO_2$ Eq.).[19] The relationship between gigagrams (Gg) of a gas and Tg $CO_2$ Eq. can be expressed as follows:

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

where,

Tg $CO_2$ Eq. = Teragrams of Carbon Dioxide Equivalents

Gg = Gigagrams (equivalent to a thousand metric tons)

GWP = Global Warming Potential

Tg = Teragrams

GWP values allow policy makers to compare 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.

*In addition to communicating emissions in units of mass, Parties may choose also to use global warming potentials (GWPs) to reflect their inventories and projections in carbon dioxide-equivalent terms, using information provided by the Intergovernmental Panel on Climate Change (IPCC) in its Second Assessment Report. Any use*

[18] 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).

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

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

The IPCC recently published its Third Assessment Report (TAR), providing the most current and 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.

Although the GWPs have been updated by the IPCC, estimates of emissions presented in this Inventory will continue to use the GWPs from the Second Assessment Report. The guidelines under which this Inventory is developed, the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and the UNFCCC reporting guidelines for national inventories[20] were developed prior to the publication of the TAR. Therefore, to comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. For informational purposes, emission estimates that use the updated GWPs are presented in below and in even more detail in Annex Q. Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends, as shown in Table 1-4.

Table 1-5 below shows a comparison of total emissions estimates by sector using both the IPCC SAR and TAR GWP values. For most sectors, the change in emissions was minimal. The effect on emissions from waste was by far the greatest (9.1 percent), due the predominance of $CH_4$ emissions in this sector. Emissions from all other sectors were comprised of mainly $CO_2$ or a mix of gases, which moderated the effect of the changes.

### Table 1-3: Comparison of 100 Year GWPs

| Gas | SAR | TAR | Change | |
|---|---|---|---|---|
| Carbon dioxide ($CO_2$) | 1 | 1 | NC | NC |
| Methane ($CH_4$)* | 21 | 23 | 2 | 10% |
| Nitrous oxide ($N_2O$) | 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)
* The methane 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.

[20] See FCCC/CP/1999/7 at www.unfccc.de.

**Table 1-4: Effects on U.S. Greenhouse Gas Emission Trends Using IPCC SAR and TAR GWP Values (Tg $CO_2$ Eq.) Change from 1990 to 2000 Revisions to Annual Estimates**

| | Change from 1990 to 2000 | | Revisions to Annual Estimates | |
|---|---|---|---|---|
| **Gas** | **SAR** | **TAR** | **1990** | **2000** |
| $CO_2$ | 841.5 | 841.5 | 0 | 0 |
| $CH_4$ | (36.8) | (40.3) | 62.0 | 58.5 |
| $N_2O$ | 38.0 | 36.3 | (17.5) | (19.2) |
| HFCs, PFCs, and $SF_6$ | 27.7 | 34.0 | (2.6) | 3.8 |
| **Total** | **870.5** | **871.6** | **42.0** | **43.1** |
| **Percent Change** | **14.2%** | **14.1%** | **0.7%** | **0.6%** |

**Table 1-5: Comparison of Emissions by Sector using IPCC SAR and TAR GWP Values (Tg $CO_2$ Eq.)**

| Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Energy** | | | | | | | |
| SAR GWP (Used In Inventory) | 5,141.9 | 5,452.4 | 5,629.9 | 5,697.9 | 5,709.5 | 5,793.9 | 5,962.6 |
| TAR GWP | 5,162.6 | 5,471.6 | 5,648.6 | 5,716.2 | 5,727.6 | 5,811.2 | 5,979.4 |
| Difference (%) | 0.4% | 0.4% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% |
| **Industrial Processes** | | | | | | | |
| SAR GWP (Used In Inventory) | 295.7 | 301.9 | 312.3 | 322.4 | 322.1 | 310.8 | 312.8 |
| TAR GWP | 291.8 | 299.6 | 310.8 | 321.7 | 323.1 | 312.6 | 315.5 |
| Difference (%) | -1.3% | -0.8% | -0.5% | -0.2% | 0.3% | 0.6% | 0.8% |
| **Agriculture** | | | | | | | |
| SAR GWP (Used In Inventory) | 448.4 | 476.4 | 481.3 | 485.9 | 487.6 | 485.0 | 485.1 |
| TAR GWP | 451.3 | 479.6 | 483.6 | 487.9 | 489.7 | 487.1 | 487.1 |
| Difference (%) | 0.6% | 0.7% | 0.5% | 0.4% | 0.4% | 0.4% | 0.4% |
| **Land-Use Change and Forestry** | | | | | | | |
| SAR GWP (Used In Inventory) | (1,097.7) | (1,110.0) | (1,108.1) | (887.5) | (885.9) | (896.4) | (902.5) |
| TAR GWP | (1,097.7) | (1,110.0) | (1,108.1) | (887.5) | (885.9) | (896.4) | (902.5) |
| Difference (%) | NC | NC | NC | NC | NC | NC | NC |
| **Waste** | | | | | | | |
| SAR GWP (Used In Inventory) | 244.7 | 251.1 | 246.3 | 241.9 | 236.9 | 239.8 | 240.6 |
| TAR GWP | 267.0 | 273.9 | 268.7 | 263.8 | 258.3 | 261.5 | 262.4 |
| Difference (%) | 9.1% | 9.1% | 9.1% | 9.1% | 9.0% | 9.0% | 9.0% |
| **Net Emissions (Sources and Sinks)** | | | | | | | |
| **SAR GWP (Used In Inventory)** | **5,033.0** | **5,371.8** | **5,561.7** | **5,860.5** | **5,870.3** | **5,933.1** | **6,098.7** |
| **TAR GWP** | **5,074.9** | **5,414.7** | **5,603.6** | **5,902.1** | **5,912.9** | **5,975.9** | **6,141.8** |
| **Difference (%)** | **0.8%** | **0.8%** | **0.7%** | **0.7%** | **0.7%** | **0.7%** | **0.7%** |

NC (No change)
Note: Totals may not sum due to independent rounding.

*of GWPs should be based on the effects of the greenhouse gases over a 100-year time horizon. In addition, Parties may also use other time horizons.*[21]

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

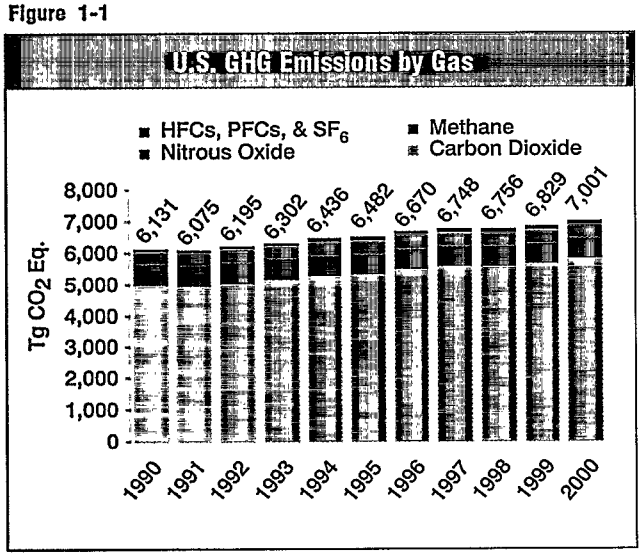
[21] Framework Convention on Climate Change; FCCC/CP/1996/15/Add.1; 29 October 1996; Report of the Conference of the Parties at its second session; held at Geneva from 8 to 19 July 1996; Addendum; Part Two: Action taken by the Conference of the Parties at its second session; Decision 9/CP.2; Communications from Parties included in Annex I to the Convention: guidelines, schedule and process for consideration; Annex: Revised Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention; p. 18. FCCC (1996)

global radiative forcing impacts. No GWP values are attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere.

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

In 2000, total U.S. greenhouse gas emissions rose to 7,001.2 teragrams of carbon dioxide equivalents (Tg $CO_2$ Eq.)[22] (14.2 percent above 1990 emissions). The single year increase in emissions from 1999 to 2000 was 2.5 percent (171.7 Tg $CO_2$ Eq.), which was greater than the average annual rate of increase for 1990 through 2000 (1.3 percent). The higher than average increase in emissions in 2000 was, in part, attributable to the following factors: 1) robust economic growth in 2000, leading to increased demand for electricity and transportation fuels, 2) cooler winter conditions compared to the previous two years, and 3) decreased output from hydroelectric dams. (See following section for an analysis of emission trends by general economic sectors). Figure 1-1 through Figure 1-3 illustrate the overall trends in total U.S. emissions by gas, annual changes, and absolute changes since 1990.

Figure 1-1




As the largest source of U.S. greenhouse gas emissions, $CO_2$ from fossil fuel combustion accounted for a nearly constant 79 percent of global warming potential (GWP) weighted emissions in the 1990s.[23] Emissions from this source category grew by 18 percent (843.4 Tg $CO_2$ Eq.) from 1990 to 2000 and were responsible for most of the increase in national emissions during this period. The annual increase in $CO_2$ emissions from fossil fuel combustion was 3.2 percent in 2000, double the source's average annual rate of 1.6 percent from 1990 through 2000. 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 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, 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 would be expected to have 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 changes that affect the scale of consumption (e.g., population, number of cars, and size of houses), the efficiency with which energy is used in equipment (e.g., cars, power plants, steel mills, and light bulbs) and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

Energy-related $CO_2$ emissions are also a function of the type fuel or energy consumed and its carbon intensity. Producing heat or electricity using natural gas instead of coal, for example, can reduce the $CO_2$ emissions associated

[22] Estimates are presented in units of teragrams of carbon dioxide equivalents (Tg $CO_2$ Eq.), which weight each gas by its Global Warming Potential, or GWP, value. (See section on Global Warming Potentials, Chapter 1.)

[23] If a full accounting of emissions from fossil fuel combustion is made by including emissions from the combustion of international bunker fuels and $CH_4$ and $N_2O$ emissions associated with fuel combustion, then this percentage increases to a nearly constant 80 percent during the 1990s.

Figure 1-2

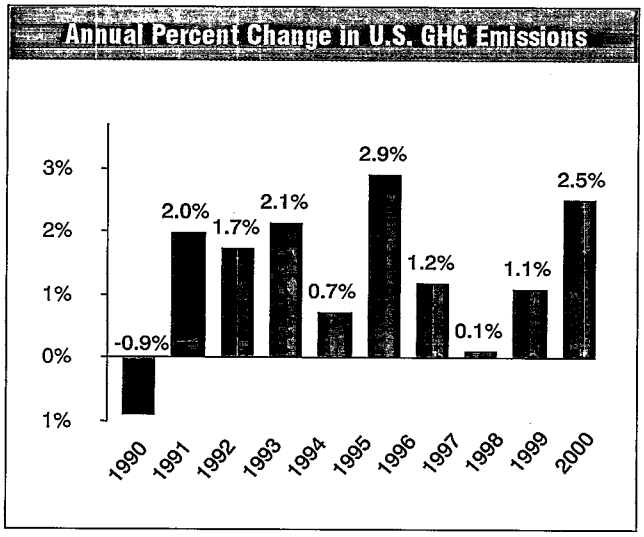
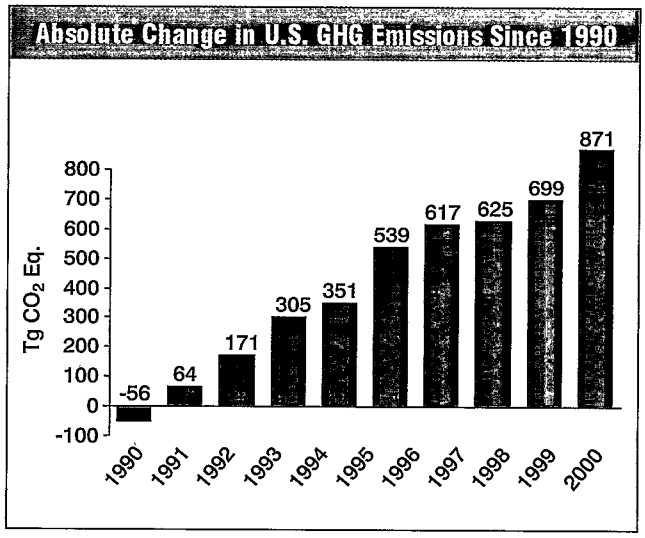



Figure 1-3




with energy consumption because of the lower carbon content of natural gas per unit of useful energy produced. Table 1-6 shows annual changes in emissions during the last few years of the 1990s for selected fuel types and sectors.

Carbon dioxide emissions from fossil fuel combustion grew rapidly in 1996, due primarily to two factors: 1) fuel switching by electric utilities from natural gas to more carbon intensive coal as colder winter conditions and the associated rise in demand for natural gas from residential and commercial customers for heating caused gas prices to rise sharply; and 2) higher consumption of petroleum fuels for transportation. Milder weather conditions in summer and winter moderated the growth in emissions in 1997; however, the shut-down of several nuclear power plants lead electric utilities to increase their consumption of coal and other fuels to offset the lost nuclear capacity.

In 1998, weather conditions were again a dominant factor in slowing the growth in emissions. Warm winter temperatures resulted in a significant drop in residential and commercial natural gas consumption. This drop in emissions from natural gas used for heating was primarily offset by two factors: 1) electric utility emissions, which increased in part due to a hot summer and its associated air conditioning demand; and 2) increased motor gasoline consumption for transportation.

In 1999, the increase in emissions from fossil fuel combustion was driven largely by growth in petroleum consumption for transportation. In addition, residential and commercial heating fuel demand partially recovered as winter temperatures dropped relative to 1998, although temperatures were still warmer than normal. These

**Table 1-6: Annual Change in $CO_2$ Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (Tg $CO_2$ Eq. and Percent)**

| Sector | Fuel Type | 1995 to 1996 | | 1996 to 1997 | | 1997 to 1998 | | 1998 to 1999 | | 1999 to 2000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Electricity Generation | Coal | 91.2 | 5.5% | 49.9 | 2.9% | 28.0 | 1.6% | 11.1 | 0.6% | 87.3 | 4.8% |
| Electricity Generation | Natural Gas | (24.3) | -8.8% | 17.9 | 7.1% | 32.4 | 12.0% | 7.5 | 2.5% | 31.5 | 10.2% |
| Electricity Generation | Petroleum | 5.0 | 7.8% | 8.9 | 12.9% | 28.1 | 35.8% | 1.2 | 1.2% | (12.5) | -11.6% |
| Transportation[a] | Petroleum | 38.7 | 2.5% | 7.6 | 0.5% | 32.7 | 2.1% | 68.0 | 4.2% | 59.6 | 3.5% |
| Residential | Natural Gas | 21.4 | 8.1% | (14.0) | -4.9% | (24.0) | -8.9% | 10.0 | 4.0% | 11.8 | 4.6% |
| Commercial | Natural Gas | 7.0 | 4.3% | 3.1 | 1.8% | (11.1) | -6.4% | 1.7 | 1.0% | 15.6 | 9.4% |
| Industrial | Coal | (5.7) | -4.4% | 1.4 | 1.1% | (5.6) | -4.4% | (4.4) | -3.6% | (14.1) | -12.1% |
| Industrial | Natural Gas | 16.3 | 4.1% | (5.2) | -1.3% | (31.6) | -7.7% | (5.0) | -1.3% | (1.6) | -0.4% |
| **All Sectors[b]** | **All Fuels[b]** | **181.6** | **3.6%** | **72.9** | **1.4%** | **16.6** | **0.3%** | **92.4** | **1.7%** | **174.7** | **3.2%** |

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

increases were offset, in part, by a decline in emissions from electric power producers due primarily to: 1) an increase in net generation of electricity by nuclear plants to record levels, which reduced demand from fossil fuel plants; and 2) moderated summer temperatures compared to the previous year-thereby reducing electricity demand for air conditioning.

Emissions from fuel combustion increased considerably in 2000, due to several factors. The primary reason for the increase was the robust U.S. economy, which produced a high demand for fuels—especially for petroleum in the transportation sector—despite increases in the price of both natural gas and petroleum. Colder winter conditions relative to the previous year triggered a rise in residential and commercial demand for heating. Structural and other economic changes taking place within U.S. industry especially manufacturing lead to lower coal consumption. Additionally, electricity generation became more carbon intensive as coal and natural gas consumption offset reduced hydropower output. In sum, emissions from fossil fuel combustion exhibited the second highest annual increase since 1990.

Other significant trends in emissions from additional source categories over the eleven year period from 1990 through 2000 included the following:

- Aggregate HFC and PFC emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) increased by 56.8 Tg $CO_2$ Eq. This increase was significantly offset, however, by reductions in PFC emissions from aluminum production (10.2 Tg $CO_2$ Eq. or 56 percent), reductions in emissions of HFC-23 from the production of HCFC-22 (5.2 Tg $CO_2$ Eq. or 15 percent), and reductions of $SF_6$ from electric power transmission and distribution systems (16.8 Tg $CO_2$ Eq. or 54 percent). Reductions in PFC emissions from aluminum production were the result of both industry emission reduction efforts and lower domestic aluminum production. HFC-23 emissions from the production of HCFC-22 decreased due to a reduction in the intensity of emissions from that source, despite increased HCFC-22 production. Reduced emissions of $SF_6$ from electric power transmission and distribution systems are primarily the result of higher purchase prices for $SF_6$ and efforts by industry to reduce emissions.
- Methane emissions from coal mining dropped by 26.2 Tg $CO_2$ Eq. (30 percent) as a result of the mining of less gassy coal from underground mines and the increased use of methane from degasification systems.
- Nitrous oxide emissions from agricultural soil management increased by 30.5 Tg $CO_2$ Eq. (11 percent) as fertilizer consumption and cultivation of nitrogen fixing crops rose.
- By 1998, all of the three major adipic acid producing plants had voluntarily implemented $N_2O$ abatement technology, and as a result, emissions fell by 6.8 Tg $CO_2$ Eq. (46 percent). The majority of this decline occurred from 1997 to 1998, despite increased production.
- Carbon dioxide emissions from feedstock uses of coal coke for iron and steel production decreased by 19.7 Tg $CO_2$ Eq. (23 percent), as imports of steel have increased.
- Methane emissions from U.S. landfills decreased 5 percent, as the amount of landfill gas collected and combusted by landfill operators has increased.
- Emissions of $N_2O$ from mobile combustion rose by 7.4 Tg $CO_2$ Eq. (14 percent), primarily due to an increased average $N_2O$ generation rate for the U.S. highway vehicle fleet.

Overall, from 1990 to 2000, total emissions of $CO_2$ and $N_2O$ increased by 841.5 (17 percent) and 38.0 Tg $CO_2$ Eq. (10 percent), respectively, while $CH_4$ emissions decreased by 36.8 Tg $CO_2$ Eq. (6 percent). During the same period, aggregate weighted emissions of HFCs, PFCs, and $SF_6$ rose by 27.7 Tg $CO_2$ Eq. (30 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, agricultural soils, and in landfilled carbon, which were estimated to be 13 percent of total emissions in 2000.

As an alternative, emissions can be aggregated across gases by the IPCC defined sectors, referred to here as chapters. Over the ten year period of 1990 to 2000, total emissions in the Energy, Industrial Processes, and Agriculture chapters climbed by 817.8 (16 percent), 17.1

## Box 1-2: Recent Trends in Various U.S. Greenhouse Gas Emissions-Related Data

There are several ways to assess a nation's greenhouse gas emitting intensity. The basis for measures of intensity can be 1) per unit of aggregate energy consumption, because energy-related activities are the largest sources of emissions; 2) per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; 3) per unit of electricity consumption, because the electric power industry—utilities and nonutilities combined—were the largest sources of U.S. greenhouse gas emissions in 2000; 4) per unit of total gross domestic product as a measure of national economic activity; or 5) on a per capita basis. Depending upon the measure used, the United States could appear to have reduced or increased its national greenhouse gas intensity during the 1990s.

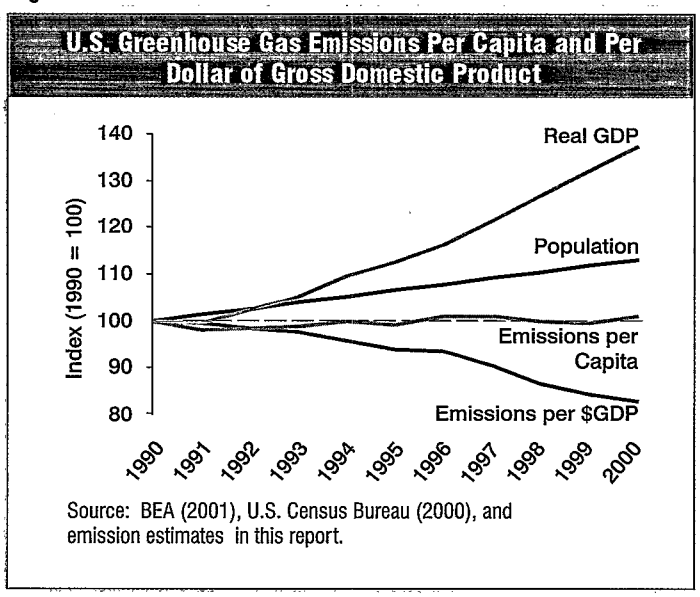
Table 1-7 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. Greenhouse gas emissions in the U.S. have grown at an average annual rate of 1.3 percent since 1990. This rate is slightly slower than that for total energy or fossil fuel consumption thereby indicating an improved or lower greenhouse gas emitting intensity and much slower than that for either electricity consumption or overall gross domestic product. At the same time, total U.S. greenhouse gas emissions have grown at about the same rate as national population during the last decade (see Figure 1-4). Overall, atmospheric $CO_2$ concentrations a function of many complex anthropogenic and natural processes are increasing at 0.4 percent per year.

### Table 1-7: Recent Trends in Various U.S. Data (Index 1990 = 100)

| Variable | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | Growth Rate[f] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GHG Emissions[a] | 99 | 101 | 103 | 105 | 106 | 109 | 110 | 110 | 111 | 114 | 1.3% |
| Energy Consumption[b] | 100 | 101 | 104 | 106 | 108 | 111 | 112 | 112 | 115 | 117 | 1.6% |
| Fossil Fuel Consumption[b] | 99 | 101 | 103 | 106 | 107 | 110 | 112 | 112 | 114 | 116 | 1.5% |
| Electricity Consumption[b] | 102 | 102 | 105 | 108 | 111 | 114 | 116 | 120 | 122 | 125 | 2.3% |
| GDP[c] | 100 | 103 | 105 | 110 | 112 | 116 | 122 | 127 | 132 | 138 | 3.2% |
| Population[d] | 101 | 103 | 104 | 105 | 107 | 108 | 109 | 110 | 112 | 113 | 1.2% |
| Atmospheric $CO_2$ Concentration[e] | 100 | 101 | 101 | 101 | 102 | 102 | 103 | 104 | 104 | 104 | 0.4% |

[a] GWP weighted values
[b] Energy content weighted values (EIA 2001)
[c] Gross Domestic Product in chained 1996 dollars (BEA 2000)
[d] (U.S. Census Bureau 2000)
[e] Mauna Loa Observatory, Hawaii (Keeling and Whorf 2000)
[f] Average annual growth rate

**Figure 1-4**




Source: BEA (2001), U.S. Census Bureau (2000), and emission estimates in this report.

**Table 1-8: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Tg $CO_2$ Eq.)**

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | **4,998.5** | **5,305.9** | **5,483.7** | **5,568.0** | **5,575.1** | **5,665.5** | **5,840.0** |
| Fossil Fuel Combustion | 4,779.8 | 5,085.0 | 5,266.6 | 5,339.6 | 5,356.2 | 5,448.6 | 5,623.3 |
| Iron and Steel Production | 85.4 | 74.4 | 68.3 | 76.1 | 67.4 | 64.4 | 65.7 |
| Cement Manufacture | 33.3 | 36.8 | 37.1 | 38.3 | 39.2 | 40.0 | 41.1 |
| Indirect $CO_2$ from $CH_4$ Oxidation | 30.9 | 29.5 | 28.9 | 28.4 | 28.2 | 27.0 | 26.3 |
| Waste Combustion | 14.1 | 18.6 | 19.6 | 21.3 | 20.3 | 21.8 | 22.5 |
| Ammonia Manufacture | 18.5 | 18.9 | 19.5 | 19.5 | 20.1 | 18.9 | 18.0 |
| Lime Manufacture | 11.2 | 12.8 | 13.5 | 13.7 | 13.9 | 13.5 | 13.3 |
| Limestone and Dolomite Use | 5.2 | 7.0 | 7.4 | 8.4 | 8.2 | 9.1 | 9.2 |
| Natural Gas Flaring | 5.5 | 8.7 | 8.2 | 7.6 | 6.3 | 6.7 | 6.1 |
| Aluminum Production | 6.3 | 5.3 | 5.6 | 5.6 | 5.8 | 5.9 | 5.4 |
| Soda Ash Manufacture and Consumption | 4.1 | 4.3 | 4.2 | 4.4 | 4.3 | 4.2 | 4.2 |
| Titanium Dioxide Production | 1.3 | 1.7 | 1.7 | 1.8 | 1.8 | 1.9 | 2.0 |
| Ferroalloys | 2.0 | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 | 1.7 |
| Carbon Dioxide Consumption | 0.8 | 1.0 | 1.1 | 1.3 | 1.4 | 1.6 | 1.4 |
| Land-Use Change & Forestry (Sink)[a] | (1,097.7) | (1,110.0) | (1,108.1) | (887.5) | (885.9) | (896.4) | (902.5) |
| International Bunker Fuels[b] | 113.9 | 101.0 | 102.3 | 109.9 | 112.9 | 105.3 | 100.2 |
| **$CH_4$** | **651.3** | **657.6** | **643.7** | **633.3** | **627.1** | **620.5** | **614.5** |
| Landfills | 213.4 | 216.6 | 211.5 | 206.4 | 201.0 | 203.1 | 203.5 |
| Enteric Fermentation | 127.9 | 133.2 | 129.6 | 126.8 | 124.9 | 124.5 | 123.9 |
| Natural Gas Systems | 121.2 | 125.7 | 126.6 | 122.7 | 122.2 | 118.6 | 116.4 |
| Coal Mining | 87.1 | 73.5 | 68.4 | 68.1 | 67.9 | 63.7 | 61.0 |
| Manure Management | 29.2 | 34.8 | 34.2 | 35.8 | 38.0 | 37.6 | 37.5 |
| Wastewater Treatment | 24.3 | 26.8 | 27.0 | 27.5 | 27.8 | 28.3 | 28.7 |
| Petroleum Systems | 26.4 | 24.2 | 24.0 | 24.0 | 23.4 | 22.3 | 21.9 |
| Stationary Sources | 7.9 | 8.2 | 8.4 | 7.5 | 7.0 | 7.3 | 7.5 |
| Rice Cultivation | 7.1 | 7.6 | 7.0 | 7.5 | 7.9 | 8.3 | 7.5 |
| Mobile Sources | 4.9 | 4.8 | 4.7 | 4.6 | 4.5 | 4.4 | 4.4 |
| Petrochemical Production | 1.2 | 1.5 | 1.6 | 1.6 | 1.6 | 1.7 | 1.7 |
| Agricultural Residue Burning | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 |
| Silicon Carbide Production | + | + | + | + | + | + | + |
| International Bunker Fuels[b] | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **$N_2O$** | **387.3** | **419.8** | **430.5** | **429.8** | **426.3** | **423.5** | **425.3** |
| Agricultural Soil Management | 267.1 | 283.4 | 292.6 | 297.5 | 298.4 | 296.3 | 297.6 |
| Mobile Sources | 50.9 | 60.4 | 60.1 | 59.7 | 59.1 | 58.7 | 58.3 |
| Nitric Acid | 17.8 | 19.9 | 20.7 | 21.2 | 20.9 | 20.1 | 19.8 |
| Manure Management | 16.0 | 16.4 | 16.8 | 17.1 | 17.1 | 17.1 | 17.5 |
| Stationary Sources | 12.8 | 13.5 | 14.1 | 14.2 | 14.3 | 14.6 | 14.9 |
| Human Sewage | 7.0 | 7.7 | 7.8 | 7.9 | 8.1 | 8.4 | 8.5 |
| Adipic Acid | 14.9 | 17.9 | 17.8 | 11.5 | 7.7 | 7.7 | 8.1 |
| Agricultural Residue Burning | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.4 | 0.5 |
| Waste Combustion | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 |
| International Bunker Fuels[b] | 1.0 | 0.9 | 0.9 | 1.0 | 1.0 | 0.9 | 0.9 |
| **HFCs, PFCs, and $SF_6$** | **93.6** | **98.5** | **111.9** | **116.9** | **127.7** | **120.0** | **121.3** |
| Substitution of Ozone Depleting Substances | 0.9 | 21.8 | 30.6 | 38.0 | 44.9 | 51.3 | 57.8 |
| HCFC-22 Production | 35.0 | 27.0 | 31.1 | 30.0 | 40.2 | 30.4 | 29.8 |
| Electrical Transmission and Distribution | 31.2 | 26.5 | 26.8 | 24.5 | 20.1 | 15.5 | 14.4 |
| Aluminum Production | 18.1 | 11.8 | 12.5 | 11.0 | 9.0 | 8.9 | 7.9 |
| Semiconductor Manufacture | 2.9 | 5.9 | 5.4 | 6.5 | 7.3 | 7.7 | 7.4 |
| Magnesium Production and Processing | 5.5 | 5.5 | 5.5 | 6.9 | 6.2 | 6.1 | 4.0 |
| **Total** | **6,130.7** | **6,481.8** | **6,669.8** | **6,748.1** | **6,756.2** | **6,829.5** | **7,001.2** |
| **Net Emissions (Sources and Sinks)** | **5,033.0** | **5,371.8** | **5,561.7** | **5,860.5** | **5,870.3** | **5,933.1** | **6,098.7** |

+ Does not exceed 0.05 Tg $CO_2$ Eq.

[a] Sinks are only included in net emissions total, and are based partially on projected activity data. Parentheses indicate negative values (or sequestration).

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

Note: Totals may not sum due to independent rounding.

**Table 1-9: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Gg)**

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | **4,998,515** | **5,305,895** | **5,483,670** | **5,567,981** | **5,575,083** | **5,665,472** | **5,840,039** |
| Fossil Fuel Combustion | 4,779,847 | 5,085,044 | 5,266,619 | 5,339,562 | 5,356,161 | 5,448,589 | 5,623,268 |
| Iron and Steel Production | 85,414 | 74,357 | 68,324 | 76,127 | 67,429 | 64,376 | 65,709 |
| Cement Manufacture | 33,278 | 36,847 | 37,079 | 38,323 | 39,218 | 39,991 | 41,067 |
| Indirect $CO_2$ from $CH_4$ Oxidation | 30,899 | 29,458 | 28,891 | 28,354 | 28,183 | 27,004 | 26,302 |
| Waste Combustion | 14,091 | 18,608 | 19,569 | 21,344 | 20,251 | 21,843 | 22,470 |
| Ammonia Manufacture | 18,510 | 18,946 | 19,512 | 19,477 | 20,113 | 18,874 | 18,017 |
| Lime Manufacture | 11,238 | 12,804 | 13,495 | 13,685 | 13,914 | 13,466 | 13,316 |
| Limestone and Dolomite Use | 5,181 | 7,028 | 7,379 | 8,401 | 8,187 | 9,115 | 9,196 |
| Natural Gas Flaring | 5,514 | 8,729 | 8,233 | 7,565 | 6,250 | 6,679 | 6,059 |
| Aluminum Production | 6,315 | 5,265 | 5,580 | 5,621 | 5,792 | 5,895 | 5,410 |
| Soda Ash Manufacture & Consumption | 4,142 | 4,305 | 4,239 | 4,355 | 4,325 | 4,217 | 4,181 |
| Titanium Dioxide Production | 1,308 | 1,670 | 1,657 | 1,836 | 1,819 | 1,853 | 1,963 |
| Ferroalloys | 1,980 | 1,866 | 1,954 | 2,038 | 2,027 | 1,996 | 1,719 |
| Carbon Dioxide Consumption | 800 | 968 | 1,140 | 1,294 | 1,413 | 1,572 | 1,361 |
| Land-Use Change and Forestry (Sink)[a] | (1,097,747) | (1,110,016) | (1,108066) | (887,531) | (885,883) | (896,392) | (902,495) |
| International Bunker Fuels[b] | 113,863 | 101,037 | 102,272 | 109,885 | 112,913 | 105,341 | 100,228 |
| **$CH_4$** | **31,014** | **31,134** | **30,654** | **30,159** | **29,863** | **29,548** | **29,262** |
| Landfills | 10,162 | 10,315 | 10,072 | 9,827 | 9,571 | 9,671 | 9,690 |
| Enteric Fermentation | 6,089 | 6,342 | 6,171 | 6,037 | 5,948 | 5,929 | 5,898 |
| Natural Gas Systems | 5,772 | 5,984 | 6,030 | 5,845 | 5,820 | 5,646 | 5,541 |
| Coal Mining | 4,149 | 3,502 | 3,255 | 3,244 | 3,235 | 3,033 | 2,903 |
| Manure Management | 1,390 | 1,657 | 1,628 | 1,707 | 1,811 | 1,788 | 1,784 |
| Wastewater Treatment | 1,155 | 1,275 | 1,287 | 1,311 | 1,326 | 1,350 | 1,367 |
| Petroleum Systems | 1,258 | 1,154 | 1,145 | 1,144 | 1,114 | 1,061 | 1,041 |
| Stationary Sources | 376 | 392 | 400 | 356 | 334 | 350 | 357 |
| Rice Cultivation | 339 | 363 | 332 | 356 | 376 | 395 | 357 |
| Mobile Sources | 233 | 228 | 222 | 217 | 212 | 209 | 208 |
| Petrochemical Production | 56 | 72 | 75 | 77 | 78 | 79 | 79 |
| Agricultural Residue Burning | 33 | 31 | 36 | 36 | 37 | 36 | 37 |
| Silicon Carbide Production | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| International Bunker Fuels[b] | 8 | 6 | 6 | 7 | 7 | 6 | 6 |
| **$N_2O$** | **1,249** | **1,354** | **1,389** | **1,387** | **1,375** | **1,366** | **1,372** |
| Agricultural Soil Management | 862 | 914 | 944 | 960 | 963 | 956 | 960 |
| Mobile Sources | 164 | 195 | 194 | 192 | 191 | 189 | 188 |
| Nitric Acid | 58 | 64 | 67 | 68 | 67 | 65 | 64 |
| Manure Management | 52 | 53 | 54 | 55 | 55 | 55 | 57 |
| Stationary Source | 41 | 43 | 45 | 46 | 46 | 47 | 48 |
| Human Sewage | 23 | 25 | 25 | 26 | 26 | 27 | 27 |
| Adipic Acid | 48 | 58 | 57 | 37 | 25 | 25 | 26 |
| Agricultural Residue Burning | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Waste Combustion | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| International Bunker Fuels[b] | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **HFCs, PFCs, and $SF_6$** | **M** | **M** | **M** | **M** | **M** | **M** | **M** |
| Substitution of Ozone Depleting Substances | M | M | M | M | M | M | M |
| HCFC-22 Production[c] | 3 | 2 | 3 | 3 | 3 | 3 | 3 |
| Electrical Transmission and Distribution[d] | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Aluminum Production | M | M | M | M | M | M | M |
| Semiconductor Manufacture | M | M | M | M | M | M | M |
| Magnesium Production and Processing[d] | + | + | + | + | + | + | + |
| **$NO_x$** | **21,955** | **24,214** | **25,075** | **25,584** | **25,546** | **25,300** | **25,116** |
| **CO** | **85,994** | **80,798** | **90,319** | **90,778** | **86,593** | **89,568** | **97,300** |
| **NMVOCs** | **18,851** | **18,671** | **17,763** | **18,118** | **17,150** | **17,323** | **18,267** |

+ Does not exceed 0.5 Gg.
M Mixture of multiple gases
[a] Sinks are not included in $CO_2$ emissions total, and are based partially on projected activity data.
[b] Emissions from International Bunker Fuels are not included in totals.
[c] HFC-23 emitted
[d] $SF_6$ emitted
Note: Totals may not sum due to independent rounding.

**Table 1-10: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (Tg $CO_2$ Eq.)**

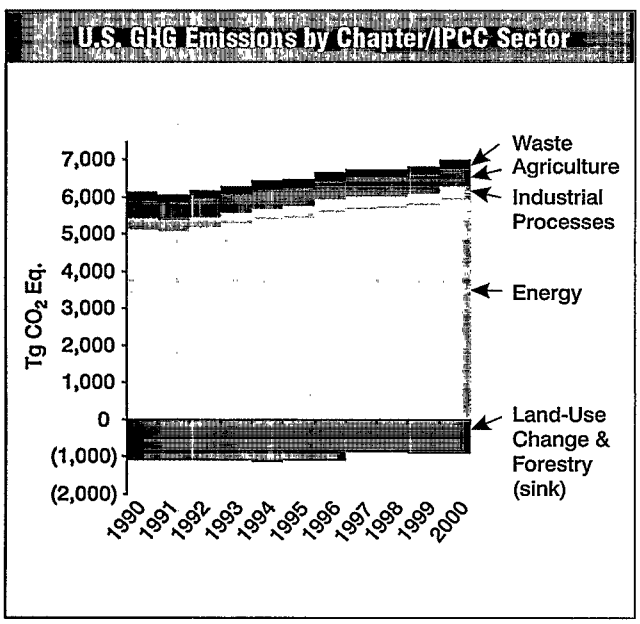
| Chapter/IPCC Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Energy | 5,141.9 | 5,452.4 | 5,629.9 | 5,697.9 | 5,709.5 | 5,793.9 | 5,962.6 |
| Industrial Processes | 295.7 | 301.9 | 312.3 | 322.4 | 322.1 | 310.8 | 312.8 |
| Agriculture | 448.4 | 476.4 | 481.3 | 485.9 | 487.6 | 485.0 | 485.1 |
| Land-Use Change and Forestry (Sink)* | (1,097.7) | (1,110.0) | (1,108.1) | (887.5) | (885.9) | (896.4) | (902.5) |
| Waste | 244.7 | 251.1 | 246.3 | 241.9 | 236.9 | 239.8 | 240.6 |
| **Total** | **6,130.7** | **6,481.8** | **6,669.8** | **6,748.1** | **6,756.2** | **6,829.5** | **7,001.2** |
| **Net Emissions (Sources and Sinks)** | **5,033.0** | **5,371.8** | **5,561.7** | **5,860.5** | **5,870.3** | **5,933.1** | **6,098.7** |

* Sinks are only included in net emissions total, and are based partially on projected activity data.
Note: Totals may not sum due to independent rounding.
Note: Parentheses indicate negative values (or sequestration).

(6 percent), and 35.7 Tg $CO_2$ Eq. (8 percent), respectively, while the Waste chapter decreased 4.1 Tg $CO_2$ Eq. (2 percent). Estimates of net carbon sequestration in the Land-Use Change and Forestry chapter declined by 195.2 Tg $CO_2$ Eq. (18 percent).

Table 1-8 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 1-9. Alternatively, emissions and sinks are aggregated by chapter in Table 1-10 and Figure 1-5.

**Figure 1-5**




## Emissions by Economic Sectors

Throughout this report, emission estimates are grouped into six sectors (i.e., chapters) defined by the IPCC: Energy, Industrial Processes, Solvent Use, Agriculture, Land-Use Change and Forestry, and Waste. While it is important to use this characterization for methodological reasons, it is also useful to allocate emissions into sectoral categories that are more intuitive. This section reports emissions by the following "economic sectors": Residential, Commercial, Industry, Transportation, Electricity Generation, and Agriculture, and U.S. Territories. Using this categorization scheme, emissions from electricity generation accounted for the largest portion (34 percent) of U.S. greenhouse gas emissions. The transportation activities, in aggregate, accounted for the second largest portion (27 percent). Additional discussion and data on these two economic sectors is provided below.

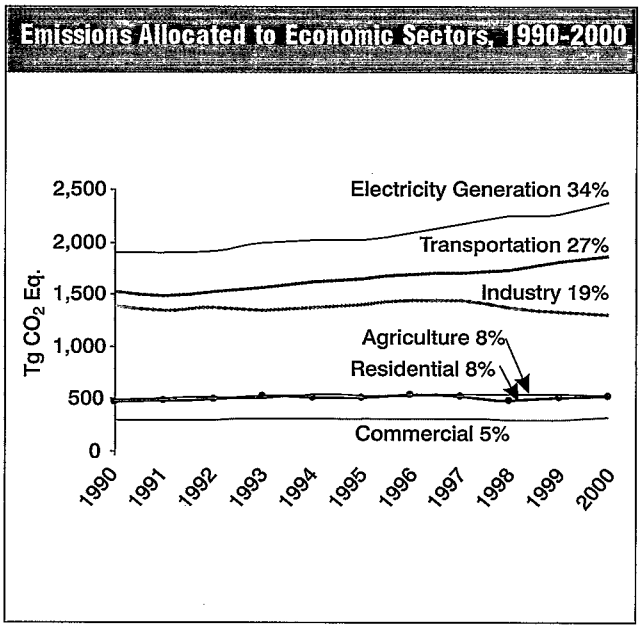
Emissions from industry accounted for 19 percent of U.S. greenhouse gas emissions in 2000. In contrast to electricity generation and transportation, emissions from industry have declined over the past decade, as structural changes have occurred in the U.S. economy (i.e., shifts from a manufacturing base to a service-based economy), fuel switching has occurred, and efficiency improvements have been made. The remaining 20 percent of U.S. greenhouse gas emissions were contributed by the residential, agriculture, commercial economic sectors, and U.S. territories. Residences accounted for about 8 percent, and primarily consisted of carbon dioxide ($CO_2$) emissions from

fossil fuel combustion. Activities related to agriculture also accounted for roughly 8 percent of U.S. emissions, but unlike all other economic sectors these emissions were dominated by nitrous oxide ($N_2O$) emissions from agricultural soils instead of $CO_2$ from fossil fuel combustion. The commercial sector accounted for about 5 percent of emissions, while U.S. territories accounted for less than 1 percent of total emissions.

Carbon dioxide was also emitted and sequestered by a variety of activities related to land-use change and forestry.

Table 1-11 presents a detailed breakdown of emissions from each of these economic sectors by source category, as they are defined in this report. Figure 1-6 shows the trend in emissions by sector from 1990 to 2000.

Figure 1-6




## 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). To distribute electricity emissions among 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 2001 and Duffield 2002). These three source categories include $CO_2$ from fossil fuel combustion, $CH_4$ and $N_2O$ from stationary sources, and $SF_6$ from electrical transmission and distribution.[24]

When emissions from electricity are distributed among these sectors, industry accounts for the largest share of U.S. greenhouse gas emissions (29 percent). Emissions from the residential and commercial sectors also increase substantially due to their relatively large share of electricity consumption. Transportation activities remain the second largest contributor to emissions. In all sectors except agriculture, $CO_2$ accounts for more than 75 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels.

Table 1-12 presents a detailed breakdown of emissions from each of these economic sectors, with emissions from electricity generation distributed to them. Figure 1-7 shows the trend in these emissions by sector from 1990 to 2000.

## Electricity Generation

Activities related to the generation, transmission, and distribution of electricity in the United States accounted for 34 percent of total U.S. greenhouse gas emissions. Emissions from this economic sector increased by 25 percent since 1990, as electricity demand to grew and fossil fuels remained the dominant energy source for generation. The electricity generation sector in the United States is composed of traditional electric utilities as well as other entities, such as power marketers and nonutility power producers. The majority of electricity generated by these entities was through the combustion of coal in boilers to produce high pressure steam that is passed through a turbine. Table 1-13 provides a detailed summary of emissions from electricity generation-related activities.

## Transportation

Transportation activities accounted 27 percent of U.S. greenhouse gas emissions. From 1990 to 2000, emissions from transportation rose by 23 percent due, in part, to increased

[24] 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 1-11: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg $CO_2$ Eq. and Percent of Total in 2000)

| Sector/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | Percent[a] |
|---|---|---|---|---|---|---|---|---|
| **Electricity Generation** | **1,898.2** | **2,024.3** | **2,096.9** | **2,171.6** | **2,256.1** | **2,271.2** | **2,376.9** | **33.9%** |
| $CO_2$ from Fossil Fuel Combustion | 1,858.9 | 1,989.3 | 2,061.2 | 2,137.9 | 2,226.4 | 2,246.2 | 2,352.5 | 33.6% |
| Transmission & Distribution[b] | 31.2 | 26.5 | 26.8 | 24.5 | 20.1 | 15.5 | 14.4 | 0.2% |
| Stationary Combustion[c] | 8.1 | 8.5 | 8.9 | 9.2 | 9.5 | 9.5 | 10.0 | 0.1% |
| **Transportation** | **1,527.7** | **1,652.4** | **1,695.2** | **1,708.5** | **1,737.4** | **1,813.3** | **1,877.0** | **26.8%** |
| $CO_2$ from Fossil Fuel Combustion | 1,471.8 | 1,579.4 | 1,618.7 | 1,628.8 | 1,655.0 | 1,728.2 | 1,789.5 | 25.6% |
| Mobile Combustion[c] | 55.8 | 65.2 | 64.8 | 64.2 | 63.6 | 63.1 | 62.7 | 0.9% |
| Substitution of ODS[d] | + | 7.9 | 11.8 | 15.4 | 18.9 | 22.0 | 24.8 | 0.4% |
| **Industry** | **1,393.9** | **1,400.9** | **1,447.6** | **1,442.7** | **1,385.9** | **1,341.1** | **1,314.6** | **18.8%** |
| $CO_2$ from Fossil Fuel Combustion | 825.3 | 838.0 | 884.5 | 876.9 | 823.5 | 798.1 | 778.8 | 11.1% |
| Natural Gas Systems | 121.2 | 125.7 | 126.6 | 122.7 | 122.2 | 118.6 | 116.4 | 1.7% |
| Iron & Steel Production | 85.4 | 74.4 | 68.3 | 76.1 | 67.4 | 64.4 | 65.7 | 0.9% |
| Coal Mining | 87.1 | 73.5 | 68.4 | 68.1 | 67.9 | 63.7 | 61.0 | 0.9% |
| Cement Manufacture | 33.3 | 36.8 | 37.1 | 38.3 | 39.2 | 40.0 | 41.1 | 0.6% |
| HCFC-22 Production[e] | 35.0 | 27.0 | 31.1 | 30.0 | 40.2 | 30.4 | 29.8 | 0.4% |
| Substitution of ODS[d] | + | 11.1 | 15.5 | 18.3 | 20.9 | 23.5 | 26.3 | 0.4% |
| Indirect $CO_2$ from $CH_4$ Oxidation | 30.9 | 29.5 | 28.9 | 28.4 | 28.2 | 27.0 | 26.3 | 0.4% |
| Petroleum Systems | 26.4 | 24.2 | 24.0 | 24.0 | 23.4 | 22.3 | 21.9 | 0.3% |
| Nitric Acid | 17.8 | 19.9 | 20.7 | 21.2 | 20.9 | 20.1 | 19.8 | 0.3% |
| Ammonia Manufacture | 18.5 | 18.9 | 19.5 | 19.5 | 20.1 | 18.9 | 18.0 | 0.3% |
| Wastewater Treatment | 12.0 | 13.7 | 13.8 | 14.2 | 14.3 | 14.6 | 14.8 | 0.2% |
| Landfills | 14.9 | 15.2 | 14.8 | 14.4 | 14.1 | 14.2 | 14.2 | 0.2% |
| Aluminum Production[f] | 24.4 | 17.1 | 18.0 | 16.6 | 14.8 | 14.8 | 13.4 | 0.2% |
| Lime Manufacture | 11.2 | 12.8 | 13.5 | 13.7 | 13.9 | 13.5 | 13.3 | 0.2% |
| Limestone & Dolomite Use | 5.2 | 7.0 | 7.4 | 8.4 | 8.2 | 9.1 | 9.2 | 0.1% |
| Adipic Acid | 14.9 | 17.9 | 17.8 | 11.5 | 7.7 | 7.7 | 8.1 | 0.1% |
| Semiconductor Manufacture[d] | 2.9 | 5.9 | 5.4 | 6.5 | 7.3 | 7.7 | 7.4 | 0.1% |
| Stationary Combustion[c] | 5.9 | 6.3 | 6.5 | 6.7 | 6.6 | 6.8 | 6.7 | 0.1% |
| Natural Gas Flaring | 5.5 | 8.7 | 8.2 | 7.6 | 6.3 | 6.7 | 6.1 | 0.1% |
| Soda Ash Manufacture & Consumption | 4.1 | 4.3 | 4.2 | 4.4 | 4.3 | 4.2 | 4.2 | 0.1% |
| Magnesium Production & Processing[b] | 5.5 | 5.5 | 5.5 | 6.9 | 6.2 | 6.1 | 4.0 | 0.1% |
| Titanium Dioxide Production | 1.3 | 1.7 | 1.7 | 1.8 | 1.8 | 1.9 | 2.0 | + |
| Ferroalloys | 2.0 | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 | 1.7 | + |
| Petrochemical Production | 1.2 | 1.5 | 1.6 | 1.6 | 1.6 | 1.7 | 1.7 | + |
| Waste Combustion[g] | 1.0 | 1.3 | 1.4 | 1.5 | 1.4 | 1.5 | 1.6 | + |
| Carbon Dioxide Consumption | 0.8 | 1.0 | 1.1 | 1.3 | 1.4 | 1.6 | 1.4 | + |
| Silicon Carbide Production | + | + | + | + | + | + | + | + |
| **Agriculture** | **494.7** | **533.3** | **533.3** | **544.2** | **545.1** | **544.9** | **535.5** | **7.6%** |
| Agricultural Soil Management | 267.1 | 283.4 | 292.6 | 297.5 | 298.4 | 296.3 | 297.6 | 4.3% |
| Enteric Fermentation | 127.9 | 133.2 | 129.6 | 126.8 | 124.9 | 124.5 | 123.9 | 1.8% |
| Manure Management[c] | 45.2 | 51.2 | 51.0 | 52.9 | 55.1 | 54.7 | 55.0 | 0.7% |
| $CO_2$ from Fossil Fuel Combustion | 46.3 | 56.9 | 52.0 | 58.3 | 57.6 | 59.9 | 50.4 | 0.7% |
| Rice Cultivation | 7.1 | 7.6 | 7.0 | 7.5 | 7.9 | 8.3 | 7.5 | 0.1% |
| Agricultural Residue Burning[c] | 1.1 | 1.0 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | + |
| Mobile Combustion[c] | + | + | + | + | + | + | + | + |
| Stationary Combustion[c] | + | + | + | + | + | + | + | + |
| **Residential** | **484.6** | **522.7** | **549.0** | **531.1** | **494.3** | **516.0** | **531.6** | **7.6%** |
| $CO_2$ from Fossil Fuel Combustion | 332.1 | 362.3 | 390.4 | 374.9 | 341.8 | 360.5 | 374.8 | 5.4% |
| Landfills | 119.5 | 121.3 | 118.4 | 115.6 | 112.6 | 113.7 | 113.9 | 1.6% |
| Wastewater Treatment | 12.3 | 13.1 | 13.2 | 13.4 | 13.5 | 13.7 | 13.9 | 0.2% |
| Waste Combustion[g] | 8.1 | 10.6 | 11.1 | 12.1 | 11.5 | 12.4 | 12.7 | 0.2% |
| Human Sewage | 7.0 | 7.7 | 7.8 | 7.9 | 8.1 | 8.4 | 8.5 | 0.1% |
| Stationary Combustion[c] | 5.7 | 5.8 | 5.9 | 4.7 | 4.2 | 4.5 | 4.7 | 0.1% |
| Substitution of ODS[d] | + | 1.9 | 2.1 | 2.5 | 2.7 | 2.9 | 3.2 | + |

**Table 1-11: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg $CO_2$ Eq. and Percent of Total in 2000) (Continued)**

| Sector/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | Percent[a] |
|---|---|---|---|---|---|---|---|---|
| **Commercial** | **303.5** | **313.0** | **320.8** | **320.9** | **302.9** | **307.1** | **327.6** | **4.7%** |
| $CO_2$ from Fossil Fuel Combustion | 217.3 | 223.9 | 232.8 | 233.7 | 217.5 | 219.8 | 239.3 | 3.4% |
| Landfills | 79.0 | 80.1 | 78.3 | 76.4 | 74.4 | 75.1 | 75.3 | 1.1% |
| Waste Combustion[g] | 5.3 | 7.0 | 7.3 | 8.0 | 7.6 | 8.2 | 8.4 | 0.1% |
| Substitution of ODS[d] | 0.9 | 0.9 | 1.3 | 1.8 | 2.4 | 2.9 | 3.5 | + |
| Stationary Combustion[c] | 1.0 | 1.1 | 1.1 | 1.1 | 1.0 | 1.1 | 1.1 | + |
| **U.S. Territories** | **28.1** | **35.3** | **27.0** | **29.1** | **34.4** | **35.8** | **38.0** | **0.5%** |
| $CO_2$ from Fossil Fuel Combustion | 28.1 | 35.3 | 27.0 | 29.1 | 34.4 | 35.8 | 38.0 | 0.5% |
| **Total** | **6,130.7** | **6,481.8** | **6,669.8** | **6,748.1** | **6,756.2** | **6,829.5** | **7,001.2** | **100%** |
| **Sinks** | **(1,097.7)** | **(1,110.0)** | **(1,108.1)** | **(887.5)** | **(885.9)** | **(896.4)** | **(902.5)** | **100%** |
| Forests | (982.7) | (979.0) | (979.0) | (759.0) | (751.7) | (762.7) | (770.0) | 85% |
| Agricultural Soils | (37.3) | (60.2) | (60.2) | (60.4) | (67.2) | (67.7) | (67.4) | 7% |
| Urban Trees | (58.7) | (58.7) | (58.7) | (58.7) | (58.7) | (58.7) | (58.7) | 7% |
| Landfilled Yard Trimmings | (19.1) | (12.2) | (10.2) | (9.5) | (8.3) | (7.3) | (6.4) | 1% |
| **Net Emissions (Sources and Sinks)** | **5,033.0** | **5,371.8** | **5,561.7** | **5,860.5** | **5,870.3** | **5,933.1** | **6,098.7** | **-** |

Note: Includes all emissions of $CO_2$, $CH_4$, $N_2O$, HFCs, PFCs, and $SF_6$. Totals may not sum due to independent rounding.
ODS (Ozone Depleting Substances)
+ Does not exceed 0.05 Tg $CO_2$ Eq. or 0.05%.
- Not applicable.
[a] Percents for year 2000.
[b] $SF_6$ emitted.
[c] Includes both $CH_4$ and $N_2O$.
[d] May include a mixture of HFCs, PFCs, and $SF_6$.
[e] HFC-23 emitted.
[f] Includes both $CO_2$ and PFCs.
[g] Includes both $CO_2$ and $N_2O$.

demand for travel and the stagnantion 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—28 percent from 1990 to 2000—and 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 1990s.

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. These emissions were primarily $CO_2$ from fuel combustion, which increased by 22 percent from 1990 to 2000. However, because of larger increases in HFC emissions during this period, overall emissions from transportation activities actually increased by 23 percent. Table 1-14 provides a detailed summary of greenhouse gas emissions from transportation-related activities.

**Table 1-12: U.S Greenhouse Gas Emissions by "Economic Sector" and Gas with Electricity-Related Emissions Distributed (Tg $CO_2$ Eq.) and Percent of Total in 2000**

| Sector/Gas | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | Percent[a] |
|---|---|---|---|---|---|---|---|---|
| **Industry** | **2,029.7** | **2,071.6** | **2,136.2** | **2,151.5** | **2,104.0** | **2,059.7** | **2,054.7** | **29.3%** |
| Direct Emissions | 1,393.9 | 1,400.9 | 1,447.6 | 1,442.7 | 1,385.9 | 1,341.1 | 1,314.6 | 18.8% |
| $CO_2$ | 1,030.9 | 1,041.5 | 1,083.4 | 1,085.4 | 1,023.6 | 994.7 | 974.7 | 13.9% |
| $CH_4$ | 265.0 | 256.1 | 251.6 | 247.5 | 245.9 | 237.5 | 232.3 | 3.3% |
| $N_2O$ | 36.6 | 41.9 | 42.7 | 37.0 | 32.9 | 32.3 | 32.2 | 0.5% |
| HFCs, PFCs, and $SF_6$ | 61.4 | 61.4 | 70.0 | 72.7 | 83.6 | 76.7 | 75.4 | 1.1% |
| Electricity-Related | 635.8 | 670.7 | 688.6 | 708.8 | 718.1 | 718.6 | 740.0 | 10.6% |
| $CO_2$ | 622.7 | 659.1 | 676.9 | 697.8 | 708.7 | 710.7 | 732.4 | 10.5% |
| $CH_4$ | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | + |
| $N_2O$ | 2.5 | 2.6 | 2.8 | 2.8 | 2.8 | 2.8 | 2.9 | + |
| $SF_6$ | 10.5 | 8.8 | 8.8 | 8.0 | 6.4 | 4.9 | 4.5 | 0.1% |
| **Transportation** | **1,530.5** | **1,655.1** | **1,697.9** | **1,711.2** | **1,740.2** | **1,816.0** | **1,879.7** | **26.8%** |
| Direct Emissions | 1,527.7 | 1,652.4 | 1,695.2 | 1,708.5 | 1,737.4 | 1,813.3 | 1,877.0 | 26.8% |
| $CO_2$ | 1,471.8 | 1,579.4 | 1,618.7 | 1,628.8 | 1,655.0 | 1,728.2 | 1,789.5 | 25.6% |
| $CH_4$ | 4.9 | 4.8 | 4.7 | 4.6 | 4.5 | 4.4 | 4.4 | 0.1% |
| $N_2O$ | 50.9 | 60.4 | 60.1 | 59.7 | 59.1 | 58.7 | 58.3 | 0.8% |
| HFCs[b] | + | 7.9 | 11.8 | 15.4 | 18.9 | 22.0 | 24.8 | 0.4% |
| Electricity-Related | 2.8 | 2.6 | 2.7 | 2.7 | 2.7 | 2.7 | 2.8 | + |
| $CO_2$ | 2.7 | 2.6 | 2.6 | 2.7 | 2.7 | 2.7 | 2.7 | + |
| $CH_4$ | + | + | + | + | + | + | + | + |
| $N_2O$ | + | + | + | + | + | + | + | + |
| $SF_6$ | + | + | + | + | + | + | + | + |
| **Residential** | **1,131.2** | **1,213.1** | **1,270.1** | **1,265.6** | **1,266.3** | **1,293.5** | **1,357.4** | **19.4%** |
| Direct Emissions | 484.6 | 522.7 | 549.0 | 531.1 | 494.3 | 516.0 | 531.6 | 7.6% |
| $CO_2$ | 340.0 | 372.8 | 401.4 | 386.8 | 353.1 | 372.7 | 387.4 | 5.5% |
| $CH_4$ | 136.4 | 139.1 | 136.4 | 132.7 | 129.4 | 131.0 | 131.5 | 1.9% |
| $N_2O$ | 8.3 | 9.0 | 9.1 | 9.0 | 9.1 | 9.4 | 9.5 | 0.1% |
| HFCs | + | 1.9 | 2.1 | 2.5 | 2.7 | 2.9 | 3.2 | + |
| Electricity-Related | 646.6 | 690.5 | 721.1 | 734.5 | 772.0 | 777.5 | 825.7 | 11.8% |
| $CO_2$ | 633.2 | 678.5 | 708.9 | 723.1 | 761.8 | 768.9 | 817.3 | 11.7% |
| $CH_4$ | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | + |
| $N_2O$ | 2.6 | 2.7 | 2.9 | 2.9 | 3.0 | 3.1 | 3.2 | + |
| $SF_6$ | 10.6 | 9.0 | 9.2 | 8.3 | 6.9 | 5.3 | 5.0 | 0.1% |
| **Commercial** | **890.7** | **944.9** | **974.3** | **1,022.4** | **1,040.0** | **1,057.5** | **1,113.8** | **15.9%** |
| Direct Emissions | 303.5 | 313.0 | 320.8 | 320.9 | 302.9 | 307.1 | 327.6 | 4.7% |
| $CO_2$ | 222.5 | 230.8 | 240.1 | 241.6 | 225.0 | 227.9 | 247.6 | 3.5% |
| $CH_4$ | 79.7 | 80.9 | 79.0 | 77.1 | 75.1 | 75.9 | 76.1 | 1.1% |
| $N_2O$ | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | + |
| HFCs | 0.9 | 0.9 | 1.3 | 1.8 | 2.4 | 2.9 | 3.5 | + |
| Electricity-Related | 587.1 | 631.9 | 653.5 | 701.5 | 737.0 | 750.4 | 786.2 | 11.2% |
| $CO_2$ | 575.0 | 621.0 | 642.4 | 690.6 | 727.3 | 742.1 | 778.1 | 11.1% |
| $CH_4$ | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | + |
| $N_2O$ | 2.3 | 2.5 | 2.6 | 2.8 | 2.9 | 3.0 | 3.1 | + |
| $SF_6$ | 9.7 | 8.3 | 8.3 | 7.9 | 6.6 | 5.1 | 4.8 | 0.1% |
| **Agriculture** | **520.5** | **561.8** | **564.3** | **568.2** | **571.4** | **567.0** | **557.7** | **8.0%** |
| Direct Emissions | 494.7 | 533.3 | 533.3 | 544.2 | 545.1 | 544.9 | 535.5 | 7.6% |
| $CO_2$ | 46.3 | 56.9 | 52.0 | 58.3 | 57.6 | 59.9 | 50.4 | 0.7% |
| $CH_4$ | 164.9 | 176.2 | 171.5 | 170.9 | 171.6 | 171.1 | 169.6 | 2.4% |
| $N_2O$ | 283.5 | 300.2 | 309.8 | 315.0 | 316.0 | 313.9 | 315.5 | 4.5% |
| Electricity-Related | 25.8 | 28.5 | 31.0 | 24.1 | 26.2 | 22.0 | 22.2 | 0.3% |
| $CO_2$ | 25.3 | 28.0 | 30.5 | 23.7 | 25.9 | 21.8 | 22.0 | 0.3% |
| $CH_4$ | + | + | + | + | + | + | + | + |
| $N_2O$ | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | + |
| $SF_6$ | 0.4 | 0.4 | 0.4 | 0.3 | 0.2 | 0.2 | 0.1 | + |
| **U.S. Territories** | 28.1 | 35.3 | 27.0 | 29.1 | 34.4 | 35.8 | 38.0 | 0.5% |
| $CO_2$ | 28.1 | 35.3 | 27.0 | 29.1 | 34.4 | 35.8 | 38.0 | 0.5% |
| **Total** | **6,130.7** | **6,481.8** | **6,669.8** | **6,748.1** | **6,756.2** | **6,829.5** | **7,001.2** | - |

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] Percents for year 2000.
[b] Includes primarily HFC-134a.

**Table 1-13: Electricity Generation-Related Greenhouse Gas Emissions (Tg $CO_2$ Eq.)**

| Gas/Fuel Type or Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | **1,858.9** | **1,989.3** | **2,061.2** | **2,137.9** | **2,226.4** | **2,246.2** | **2,352.5** |
| Coal | 1,541.5 | 1,647.9 | 1,739.1 | 1,789.0 | 1,817.0 | 1,828.0 | 1,915.4 |
| Natural Gas | 213.8 | 276.8 | 252.5 | 270.4 | 302.9 | 310.4 | 341.9 |
| Petroleum | 103.4 | 64.5 | 69.5 | 78.4 | 106.5 | 107.7 | 95.2 |
| Geothermal | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | + | + |
| **$CH_4$** | **0.5** | **0.5** | **0.5** | **0.6** | **0.6** | **0.6** | **0.6** |
| Stationary Sources* | 0.5 | 0.5 | 0.5 | 0.6 | 0.6 | 0.6 | 0.6 |
| **$N_2O$** | **7.6** | **8.0** | **8.4** | **8.7** | **8.9** | **8.9** | **9.3** |
| Stationary Sources* | 7.6 | 8.0 | 8.4 | 8.7 | 8.9 | 8.9 | 9.3 |
| **$SF_6$** | **31.2** | **26.5** | **26.8** | **24.5** | **20.1** | **15.5** | **14.4** |
| Electrical Transmission and Distribution | 31.2 | 26.5 | 26.8 | 24.5 | 20.1 | 15.5 | 14.4 |
| **Total** | **1,898.2** | **2,024.3** | **2,096.9** | **2,171.6** | **2,256.1** | **2,271.2** | **2,376.9** |

Note: Totals may not sum due to independent rounding.
* Includes only stationary source emissions related to the generation of electricity.
+ Does not exceed 0.05 Tg $CO_2$ Eq.

## 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). To the extent possible, the present U.S. Inventory 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. For some sources, IPCC default methodologies and emission factors have been employed. However, for most emission sources, the IPCC default methodologies were expanded and more comprehensive methods were applied.

Inventory emission estimates from energy consumption and production activities are based primarily on the latest official fuel consumption data from the Energy Information Administration (EIA) of the U.S. Department of Energy and augmented with additional data where available. Emission estimates for $NO_x$, CO, and NMVOCs were taken directly, except where noted, from unpublished EPA data that provide the latest estimates of regional and national emissions of local air pollutants (EPA 2001). Emissions of these pollutants are estimated by the EPA based on statistical information about each source category, emission factors, and control efficiencies. While the EPA's estimation methodologies for local air pollutants are conceptually similar to the IPCC recommended methodologies, the large number of sources EPA used in developing its local air pollutant estimates makes it difficult to reproduce the methodologies from EPA (2001) in this inventory document. In these instances, the references containing detailed documentation of the methods used are identified for the interested reader. For agricultural sources, the EPA local air pollutant emission estimates were supplemented using activity data from other agencies. Complete documentation of the methodologies and data sources used is provided in conjunction with the discussion of each source and in the various annexes.

Figure 1-7

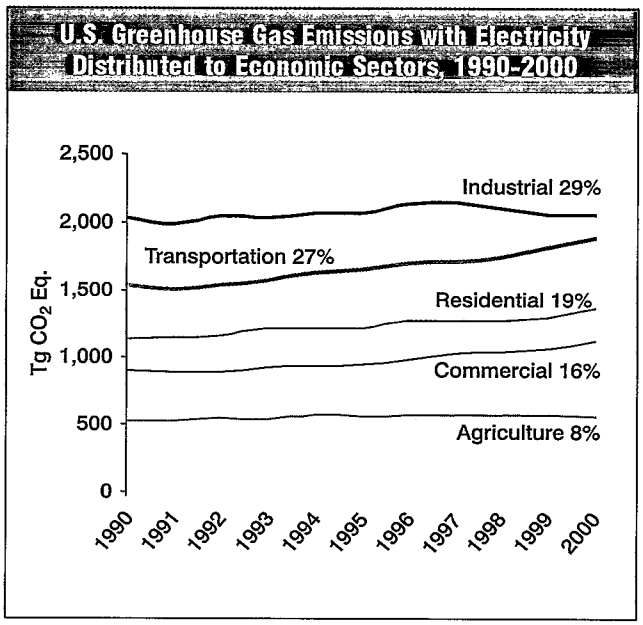


**Table 1-14: Transportation-Related Greenhouse Gas Emissions (Tg $CO_2$ Eq.)**

| Gas/Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | **1,474.5** | **1,582.0** | **1,621.3** | **1,631.5** | **1,657.7** | **1,731.0** | **1,792.2** |
| Passenger Cars | 619.9 | 641.9 | 654.1 | 660.2 | 673.5 | 687.2 | 691.7 |
| Light-Duty Trucks | 283.1 | 325.3 | 333.5 | 337.3 | 356.4 | 366.5 | 369.4 |
| Other Trucks | 206.0 | 235.9 | 248.1 | 257.0 | 257.9 | 282.4 | 294.3 |
| Buses | 10.7 | 13.5 | 11.3 | 12.0 | 12.4 | 13.1 | 13.7 |
| Aircraft[a] | 176.9 | 171.4 | 180.2 | 178.9 | 183.0 | 186.7 | 196.5 |
| Boats and Vessels | 59.4 | 66.9 | 63.8 | 50.2 | 47.8 | 63.0 | 89.9 |
| Locomotives | 28.5 | 31.6 | 33.6 | 34.5 | 33.8 | 35.3 | 36.9 |
| Other[b] | 90.1 | 95.3 | 96.8 | 101.5 | 93.0 | 96.7 | 99.9 |
| International Bunker Fuels[c] | 113.9 | 101.0 | 102.3 | 109.9 | 112.9 | 105.3 | 100.2 |
| **$CH_4$** | **4.9** | **4.8** | **4.7** | **4.6** | **4.5** | **4.4** | **4.4** |
| Passenger Cars | 2.4 | 2.0 | 2.0 | 2.0 | 1.9 | 1.9 | 1.9 |
| Light-Duty Trucks | 1.6 | 1.8 | 1.8 | 1.7 | 1.6 | 1.6 | 1.5 |
| Other Trucks and Buses | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Aircraft | 0.2 | 0.1 | 0.1 | 0.2 | 0.1 | 0.2 | 0.2 |
| Boats | 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 |
| Other[d] | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| International Bunker Fuels[c] | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **$N_2O$** | **50.9** | **60.4** | **60.1** | **59.7** | **59.1** | **58.7** | **58.3** |
| Passenger Cars | 31.1 | 33.1 | 32.7 | 32.2 | 32.0 | 31.2 | 30.7 |
| Light-Duty Trucks | 14.4 | 21.0 | 20.9 | 21.0 | 20.6 | 20.6 | 20.4 |
| Other Trucks and Buses | 2.5 | 3.3 | 3.4 | 3.5 | 3.6 | 3.8 | 3.8 |
| Aircraft | 1.7 | 1.7 | 1.8 | 1.7 | 1.8 | 1.8 | 1.9 |
| Boats | 0.4 | 0.5 | 0.4 | 0.3 | 0.3 | 0.4 | 0.6 |
| Locomotives | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| Other[d] | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| International Bunker Fuels[c] | 1.0 | 0.9 | 0.9 | 1.0 | 1.0 | 0.9 | 0.9 |
| **HFCs** | **+** | **7.9** | **11.8** | **15.4** | **18.9** | **22.0** | **24.8** |
| Mobile Air Conditioners[e] | + | 6.7 | 9.8 | 12.9 | 15.7 | 18.2 | 20.4 |
| Refrigerated Transport | + | 1.2 | 1.9 | 2.5 | 3.2 | 3.8 | 4.4 |
| **Total** | **1,530.4** | **1,655.1** | **1,697.9** | **1,711.2** | **1,740.2** | **1,816.0** | **1,879.7** |

+ 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, construction equipment, agricultural machinery, pipelines, and lubricants.
[c] Emissions from International Bunker Fuels include emissions from both civilian and military activities, but are not included in totals.
[d] "Other" $CH_4$ and $N_2O$ emissions include motorcycles, construction equipment, agricultural machinery, industrial equipment, and snowmobiles.
[e] Includes primarily HFC-134a.

Emissions from fossil fuels combusted in civilian and military ships and aircraft engaged in the international transport of passengers and cargo are not included in U.S. totals, but are reported separately as international bunkers in accordance with IPCC reporting guidelines (IPCC/UNEP/OECD/IEA 1997). Carbon dioxide emissions from fuel combusted within U.S. territories, however, are included in U.S. totals.

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

- *Agricultural $CO_2$ Emissions from Fossil Fuel Combustion, and non-$CO_2$ emissions from Stationary and Mobile Combustion.* Emissions from on-farm energy use were accounted for in the Energy chapter as part of the industrial and transportation end-use

**Box 1-3: IPCC Good Practice Guidance**

In response to a request by Parties to the United Nations Framework Convention on Climate Change (UNFCCC), the Intergovernmental Panel on Climate Change (IPCC) finalized a set of good practice guidance in May 2000 on uncertainty and good practices in inventory management. The report, entitled *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (Good Practice),* was developed with extensive participation of experts from the United States as well as many other countries.[25] It focuses on providing direction to countries to produce emission estimates that are as accurate, with the least possible uncertainty. In addition, *Good Practice* was designed as a tool to compliment the methodologies suggested in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines).* In order to obtain these goals, *Good Practice* establishes a set of guidelines for ensuring the following standards are met:

- The most appropriate estimation method is used, within the context of the *IPCC Guidelines*
- Quality control and quality assurance measures are adhered to
- Proper assessment and documentation of data and information is carried out
- Uncertainties are quantified and tracked for each source category as well as the inventory in its entirety

By providing such direction, the IPCC hopes to help countries provide inventories that are transparent, documented, and comparable, and that have been assessed for uncertainties, checked for quality control and quality assurance, and used resources efficiently.

sectors. To calculate agricultural emissions related to fossil fuel combustion, energy consumption estimates were obtained from economic survey data from the U.S. Department of Agriculture (Duffield 2002). To avoid double counting, emission estimates of $CO_2$ from fossil fuel combustion and non-$CO_2$ from stationary and mobile sources were subtracted from the industrial economic sector, although some of these fuels may have been originally be accounted for under the transportation end-use sector.

- *Landfills and Waste Combustion.* Methane emissions from landfills, as well as $CO_2$ and $N_2O$ emissions from waste combustion were allocated to the residential (56 percent), commercial (37 percent), and industrial (7 percent) economic sectors based on waste generation surveys (EPA 2000).
- *Substitution of Ozone Depleting Substances.* All greenhouse gas emissions resulting from the substitution of ozone depleting substances were placed in the industrial economic sector, with the exception of emissions from domestic, commercial, mobile and transport refrigeration/air-conditioning systems were placed in the residential, commercial, and transportation sectors, respectively. Emissions from non-MDI aerosols were attributed to the residential economic sector.

The IPCC requires 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. Section 1.3 of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reporting Instructions* states, "If a detailed, Sectoral Approach for energy has been used for the estimation of $CO_2$ from fuel combustion you are still asked to complete...the Reference Approach...for verification purposes" (IPCC/UNEP/OECD/IEA 1997). This reference method 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 U). 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.

[25] See <http://www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm>

## Uncertainty in and Limitations 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, it has several strengths and weaknesses.

First, this inventory by itself does not provide a complete picture of past or future emissions in the United States; it only provides an inventory of U.S. emissions for the years 1990 through 2000. However, the United States believes that common and consistent inventories taken over a period of time can and will contribute to understanding future emission trends. The United States produced its first comprehensive inventory of greenhouse gas emissions and sinks in 1993, and intends to update it annually, in conjunction with its commitments under the UNFCCC. The methodologies used to estimate emissions will also be updated regularly as methods and information improve and as further guidance is received from the IPCC and UNFCCC.

Secondly, 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 be fairly accurate. For some other categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated limits the scope or accuracy of the estimates presented. Despite these uncertainties, the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) require that countries provide single point estimates for each gas and emission or removal source category. Within the discussion of each emission source, specific factors affecting the accuracy of the estimates are discussed.

Finally, while the IPCC methodologies provided in the *Revised 1996 IPCC Guidelines* represent baseline methodologies for a variety of source categories, many of these methodologies continue to be improved and refined as new research and data becomes available. The current U.S. inventory uses the IPCC methodologies when applicable, and supplements them with other available methodologies and data where possible. The United States realizes that additional efforts are still needed to improve methodologies and data collection procedures. Specific areas requiring further research include:

- *Incorporating excluded emission sources.* Quantitative estimates of 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 V for a discussion of the sources of greenhouse gas emissions and sinks excluded from this report.

**Table 1-15: 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 Use | Emissions, of primarily non-methane volatile organic compounds (NMVOCs), resulting from the use of solvents. |
| Agriculture | Anthropogenic emissions from agricultural activities except fuel combustion and sewage emissions, which are addressed under Energy and Waste, respectively. |
| Land-Use Change and Forestry | Emissions and removals of carbon dioxide from forest management, other land-use activities, and land-use change. |
| Waste | Emissions from waste management activities. |

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

- *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 methane and nitrous oxide 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.
- *Applying Global Warming Potentials.* GWP values have several limitations including that they are not applicable to unevenly distributed gases and aerosols such as tropospheric ozone and its precursors. They are also intended to reflect global averages and, therefore, do not account for regional effects. Overall, the main uncertainties in developing GWP values are the estimation of atmospheric lifetimes, assessing indirect effects, choosing the appropriate integration time horizon, and assessing instantaneous radiative forcing effects which are dependent upon existing atmospheric concentrations. According to the IPCC, GWPs typically have an uncertainty of 35 percent (IPCC 1996).

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.

**Table 1-16: List of Annexes**

| | |
|---|---|
| ANNEX A | Methodology for Estimating Emissions of $CO_2$ from Fossil Fuel Combustion |
| ANNEX B | Methodology for Estimating Carbon Stored in Products from Non-Energy Uses of Fossil Fuels |
| ANNEX C | Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Ambient Air Pollutants from Stationary Combustion |
| ANNEX D | Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Ambient Air Pollutants from Mobile Combustion |
| ANNEX E | Methodology for Estimating $CH_4$ Emissions from Coal Mining |
| ANNEX F | Methodology for Estimating $CH_4$ Emissions from Natural Gas Systems |
| ANNEX G | Methodology for Estimating $CH_4$ Emissions from Petroleum Systems |
| ANNEX H | Methodology for Estimating $CO_2$ Emissions from Municipal Solid Waste Combustion |
| ANNEX I | Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military |
| ANNEX J | Methodology for Estimating HFC, PFC, and $SF_6$ Emissions from Substitution of Ozone Depleting Substances |
| ANNEX K | Methodology for Estimating $CH_4$ Emissions from Enteric Fermentation |
| ANNEX L | Methodology for Estimating $CH_4$ and $N_2O$ Emissions from Manure Management |
| ANNEX M | Methodology for Estimating $N_2O$ Emissions from Agricultural Soil Management |
| ANNEX N | Methodology for Estimating $CO_2$ Emissions and Sinks from Forest Carbon Stocks |
| ANNEX O | Methodology for Estimating $CH_4$ Emissions from Landfills |
| ANNEX P | Key Source Analysis |
| ANNEX Q | Global Warming Potential Values |
| ANNEX R | Ozone Depleting Substance Emissions |
| ANNEX S | Sulfur Dioxide Emissions |
| ANNEX T | Complete List of Source Categories |
| ANNEX U | IPCC Reference Approach for Estimating $CO_2$ Emissions from Fossil Fuel Combustion |
| ANNEX V | Sources of Greenhouse Gas Emissions Excluded |
| ANNEX W | Constants, Units, and Conversions |
| ANNEX X | Abbreviations |
| ANNEX Y | Chemical Formulas |
| ANNEX Z | Glossary |

## Organization of Report

In accordance with the IPCC guidelines for reporting contained in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997), this U.S. inventory of greenhouse gas emissions and sinks is segregated into six sector-specific chapters, listed in Table 1-15.

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
- **Data Sources:** Identification of data references, primarily for activity data and emission factors
- **Uncertainty:** Discussion of relevant issues related to the uncertainty in the emission estimates presented

Special attention is given to carbon dioxide from fossil fuel combustion relative to other sources because of its share of emissions relative to other sources 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, are treated individually. Additional information for certain source categories and other topics is also provided in several Annexes listed in Table 1-16.

# 2. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 85 percent of total emissions on a carbon equivalent basis in 2000. This included 97, 34, and 17 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 carbon equivalent basis, while the non-$CO_2$ emissions from energy-related activities represented a much smaller portion of total national emissions (4 percent collectively).

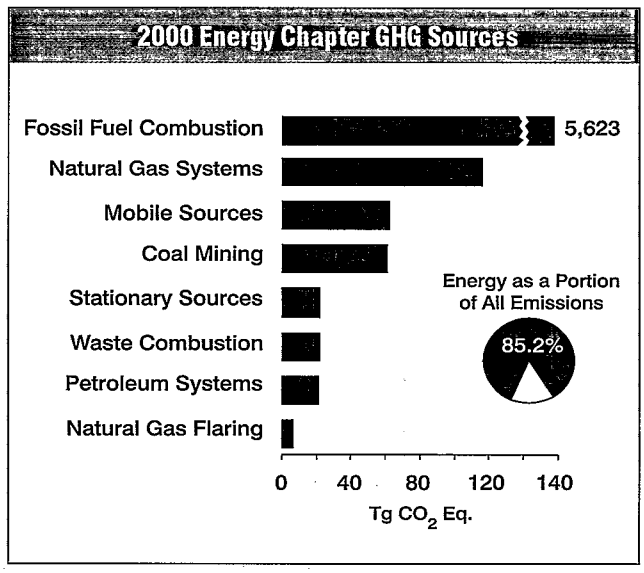
Emissions from fossil fuel combustion comprise the vast majority of energy-related emissions, with $CO_2$ being the primary gas emitted (see Figure 2-1). Globally, approximately 23,300 Tg of $CO_2$ were added to the atmosphere through the combustion of fossil fuels at the end of the 1990s, of which the United States accounted for about 24 percent (see Figure 2-2).[1] Due to the relative importance of fossil fuel combustion-related $CO_2$ emissions, they are considered separately from other emissions. Fossil fuel combustion also emits $CH_4$ and $N_2O$, as well as ambient air pollutants such as nitrogen oxides ($NO_x$), carbon monoxide (CO), and non-methane 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 ambient air pollutant emissions.

Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of $CH_4$ 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. Carbon dioxide emissions from these activities, however, are not included in national emissions totals because biomass fuels are of biogenic origin. It is assumed that the carbon released when biomass is consumed 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 carbon cycle are accounted for in the 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 2-1 summarizes emissions for the Energy chapter in units of teragrams of carbon dioxide equivalents (Tg $CO_2$ Eq.), while unweighted gas emissions in gigagrams (Gg) are provided in Table 2-2. Overall, emissions due to energy-related activities were 5,962.6 Tg $CO_2$ Eq. in 2000, an increase of 16 percent since 1990.

**Figure 2-1**




[1] Global $CO_2$ emissions from fossil fuel combustion were taken from Marland et al. (2001) <http://cdiac.esd.ornl.gov/trends/emis/meth_reg.htm>.

## Table 2-1: Emissions from Energy (Tg $CO_2$ Eq.)

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | **4,830.3** | **5,141.8** | **5,323.3** | **5,396.8** | **5,410.8** | **5,504.1** | **5,678.1** |
| Fossil Fuel Combustion | 4,779.8 | 5,085.0 | 5,266.6 | 5,339.6 | 5,356.2 | 5,448.6 | 5,623.3 |
| Indirect $CO_2$ from $CH_4$ Oxidation | 30.9 | 29.5 | 28.9 | 28.4 | 28.2 | 27.0 | 26.3 |
| Waste Combustion | 14.1 | 18.6 | 19.6 | 21.3 | 20.3 | 21.8 | 22.5 |
| Natural Gas Flaring | 5.5 | 8.7 | 8.2 | 7.6 | 6.3 | 6.7 | 6.1 |
| Biomass-Wood* | 149.6 | 163.3 | 166.6 | 159.3 | 159.6 | 173.9 | 174.8 |
| International Bunker Fuels* | 113.9 | 101.0 | 102.3 | 109.9 | 112.9 | 105.3 | 100.2 |
| Biomass-Ethanol* | 4.4 | 8.1 | 5.8 | 7.4 | 8.1 | 8.5 | 9.7 |
| Carbon Stored in Products* | 221.0 | 251.1 | 258.2 | 269.8 | 276.7 | 291.6 | 283.2 |
| **$CH_4$** | **247.6** | **236.4** | **232.1** | **226.9** | **225.0** | **216.3** | **211.1** |
| Natural Gas Systems | 121.2 | 125.7 | 126.6 | 122.7 | 122.2 | 118.6 | 116.4 |
| Coal Mining | 87.1 | 73.5 | 68.4 | 68.1 | 67.9 | 63.7 | 61.0 |
| Petroleum Systems | 26.4 | 24.2 | 24.0 | 24.0 | 23.4 | 22.3 | 21.9 |
| Stationary Sources | 7.9 | 8.2 | 8.4 | 7.5 | 7.0 | 7.3 | 7.5 |
| Mobile Sources | 4.9 | 4.8 | 4.7 | 4.6 | 4.5 | 4.4 | 4.4 |
| International Bunker Fuels* | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **$N_2O$** | **64.0** | **74.2** | **74.5** | **74.2** | **73.7** | **73.5** | **73.4** |
| Mobile Sources | 50.9 | 60.4 | 60.1 | 59.7 | 59.1 | 58.7 | 58.3 |
| Stationary Sources | 12.8 | 13.5 | 14.1 | 14.2 | 14.3 | 14.6 | 14.9 |
| Waste Combustion | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 |
| International Bunker Fuels* | 1.0 | 0.9 | 0.9 | 1.0 | 1.0 | 0.9 | 0.9 |
| **Total** | **5,141.9** | **5,452.4** | **5,629.9** | **5,697.9** | **5,709.5** | **5,793.9** | **5,962.6** |

+ Does not exceed 0.05 Tg $CO_2$ Eq.
* 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 2-2: Emissions from Energy (Gg)

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | **4,830,350** | **5,141,838** | **5,323,312** | **5,396,825** | **5,410,844** | **5,504,115** | **5,678,099** |
| Fossil Fuel Combustion | 4,779,847 | 5,085,044 | 5,266,619 | 5,339,562 | 5,356,161 | 5,448,589 | 5,623,268 |
| Indirect $CO_2$ from $CH_4$ Oxidation | 30,899 | 29,458 | 28,891 | 28,354 | 28,183 | 27,004 | 26,302 |
| Waste Combustion | 14,091 | 18,608 | 19,569 | 21,344 | 20,251 | 21,843 | 22,470 |
| Natural Gas Flaring | 5,514 | 8,729 | 8,233 | 7,565 | 6,250 | 6,679 | 6,059 |
| Biomass-Wood* | 149,609 | 163,286 | 166,617 | 159,286 | 159,610 | 173,940 | 174,770 |
| International Bunker Fuels* | 113,863 | 101,037 | 102,272 | 109,885 | 112,913 | 105,341 | 100,228 |
| Biomass-Ethanol* | 4,380 | 8,099 | 5,809 | 7,356 | 8,128 | 8,451 | 9,667 |
| Carbon Stored in Products* | 220,959 | 251,110 | 258,238 | 269,787 | 276,659 | 291,623 | 283,180 |
| **$CH_4$** | **11,789** | **11,259** | **11,052** | **10,807** | **10,715** | **10,298** | **10,050** |
| Natural Gas Systems | 5,772 | 5,984 | 6,030 | 5,845 | 5,820 | 5,646 | 5,541 |
| Coal Mining | 4,149 | 3,502 | 3,255 | 3,244 | 3,235 | 3,033 | 2,903 |
| Petroleum Systems | 1,258 | 1,154 | 1,145 | 1,144 | 1,114 | 1,061 | 1,041 |
| Stationary Sources | 376 | 392 | 400 | 356 | 334 | 350 | 357 |
| Mobile Sources | 233 | 228 | 222 | 217 | 212 | 209 | 208 |
| International Bunker Fuels* | 8 | 6 | 6 | 7 | 7 | 6 | 6 |
| **$N_2O$** | **207** | **239** | **240** | **239** | **238** | **237** | **237** |
| Mobile Combustion | 164 | 195 | 194 | 192 | 191 | 189 | 188 |
| Stationary Combustion | 41 | 43 | 45 | 46 | 46 | 47 | 48 |
| Waste Combustion | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| International Bunker Fuels* | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

+ Does not exceed 0.05 Tg
* 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.

# Carbon Dioxide Emissions from Fossil Fuel Combustion

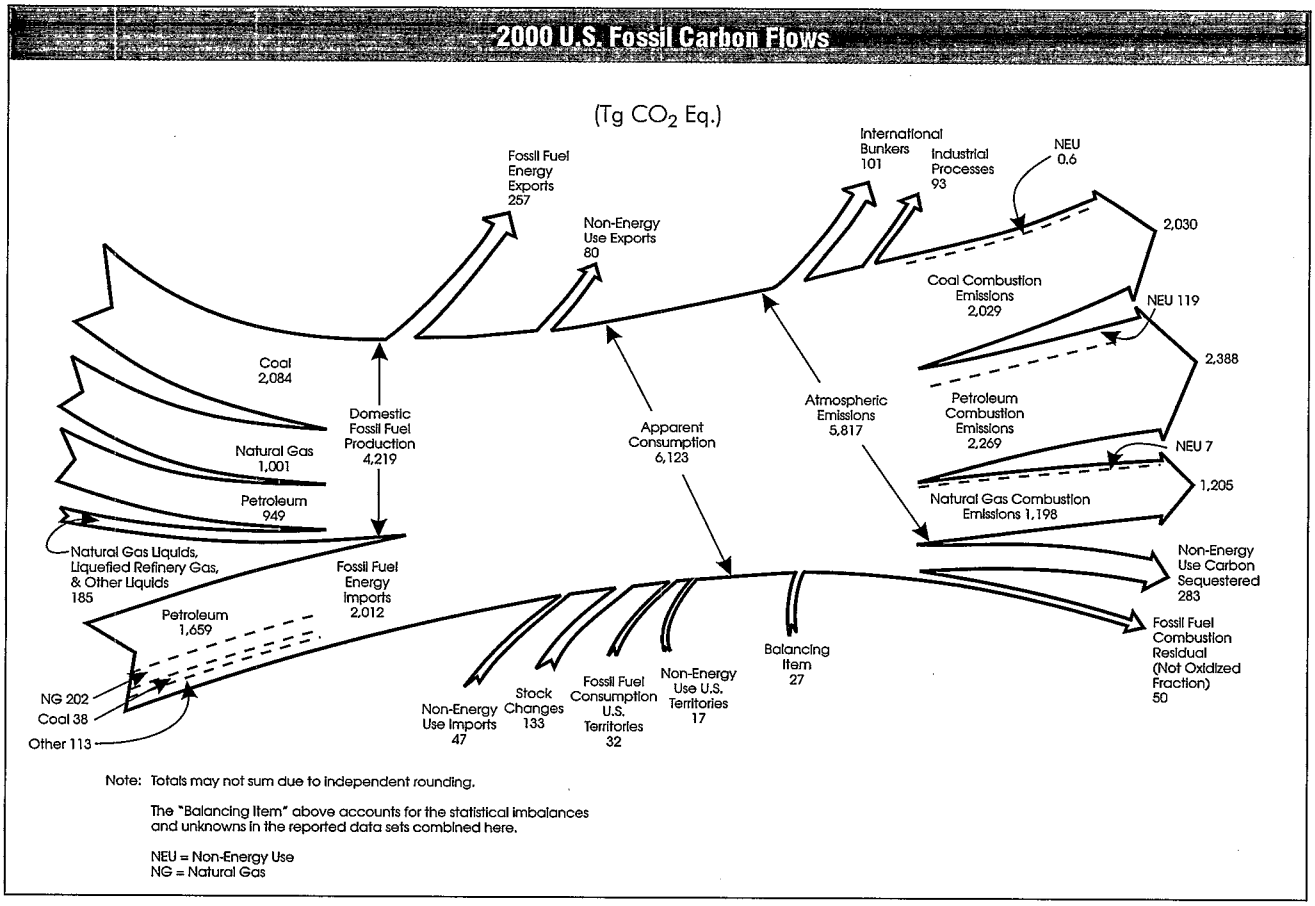
Carbon dioxide ($CO_2$) emissions from fossil fuel combustion grew by 3.2 percent from 1999 to 2000. This above average growth rate was in part due to the strong performance of the U.S. economy and continued population growth. In 2000, $CO_2$ emissions from fossil fuel combustion were 5,623.1 Tg $CO_2$ Eq., or 17.6 percent above emissions in 1990 (see Table 2-3).[2]

Trends in $CO_2$ emissions from fossil fuel combustion are influenced by many long-term and short-term factors. On a year-to-year basis, the overall demand for fossil fuels in the United States and other countries generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, 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 would be expected to have 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 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 social planning and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

Carbon dioxide emissions are also a function of the source of energy and its carbon intensity. The amount of carbon in fuels varies significantly by fuel type. For example, coal contains

**Figure 2-2**




Note: Totals may not sum due to independent rounding.

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

NEU = Non-Energy Use
NG = Natural Gas

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

**Table 2-3: $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type and Sector (Tg $CO_2$ Eq.)**

| Fuel/Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Coal** | **1,692.6** | **1,792.7** | **1,878.4** | **1,930.5** | **1,949.7** | **1,956.9** | **2,030.1** |
| Residential | 5.8 | 5.0 | 5.1 | 5.5 | 4.2 | 4.4 | 4.4 |
| Commercial | 8.7 | 7.6 | 7.7 | 8.2 | 6.3 | 6.6 | 6.6 |
| Industrial | 135.9 | 131.2 | 125.5 | 126.9 | 121.4 | 117.0 | 102.8 |
| Transportation | NE | NE | NE | NE | NE | NE | NE |
| Electricity Generation | 1,541.5 | 1,647.9 | 1,739.1 | 1,789.0 | 1,817.0 | 1,828.0 | 1,915.4 |
| U.S. Territories | 0.6 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| **Natural Gas** | **988.8** | **1,141.3** | **1,162.4** | **1,166.7** | **1,125.8** | **1,145.2** | **1,204.8** |
| Residential | 238.5 | 263.1 | 284.6 | 270.5 | 246.5 | 256.5 | 268.3 |
| Commercial | 142.4 | 164.5 | 171.6 | 174.7 | 163.6 | 165.2 | 180.8 |
| Industrial | 358.0 | 398.5 | 414.8 | 409.6 | 378.0 | 372.9 | 371.3 |
| Transportation | 36.0 | 38.3 | 38.9 | 41.5 | 34.9 | 40.2 | 41.9 |
| Electricity Generation | 213.8 | 276.8 | 252.5 | 270.4 | 302.9 | 310.4 | 341.9 |
| U.S. Territories | NO | NO | NO | NO | NO | NO | 0.6 |
| **Petroleum** | **2,098.2** | **2,150.9** | **2,225.6** | **2,242.0** | **2,280.3** | **2,346.3** | **2,388.2** |
| Residential | 87.7 | 94.2 | 100.7 | 98.9 | 91.1 | 99.6 | 102.2 |
| Commercial | 66.1 | 51.8 | 53.5 | 50.8 | 47.7 | 48.0 | 51.8 |
| Industrial | 377.8 | 365.1 | 396.2 | 398.7 | 381.7 | 368.2 | 355.1 |
| Transportation | 1,435.8 | 1,541.0 | 1,579.8 | 1,587.3 | 1,620.1 | 1,688.0 | 1,747.6 |
| Electricity Generation | 103.4 | 64.5 | 69.5 | 78.4 | 106.5 | 107.7 | 95.2 |
| U.S. Territories | 27.4 | 34.3 | 25.8 | 27.9 | 33.3 | 34.8 | 36.3 |
| **Geothermal*** | **0.2** | **0.1** | **0.1** | **0.1** | **0.1** | + | + |
| **Total** | **4,779.8** | **5,084.9** | **5,266.4** | **5,339.4** | **5,356.0** | **5,448.4** | **5,623.1** |

NE (Not estimated)
NO (Not occurring)
+ Does not exceed 0.05 Tg $CO_2$ Eq.
* 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.

the highest amount of carbon per unit of useful energy. Petroleum has roughly 75 percent of the carbon per unit of energy as coal, and natural gas has only about 55 percent.[3] Therefore, producing heat or electricity using natural gas instead of coal, for example, 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 2-1).

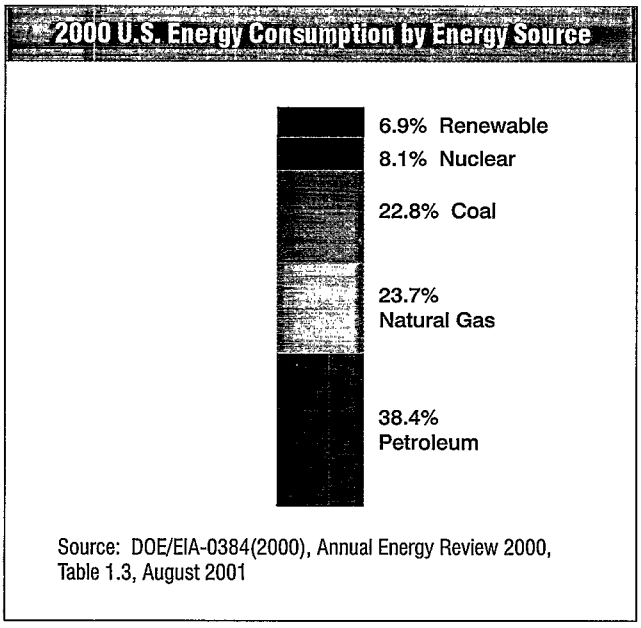
In the United States, 85 percent of the energy consumed in 2000 was produced through the combustion of fossil fuels such as coal, natural gas, and petroleum (see Figure 2-3 and Figure 2-4). The remaining portion was supplied by nuclear electric power (8 percent) and by a variety of renewable energy sources (7 percent), primarily hydroelectric power (EIA 2001). Specifically, petroleum supplied the largest share of domestic energy demands, accounting for an average of 38 percent of total energy consumption from 1990 through 2000. Natural gas and coal followed in order of importance, accounting for 28 and 26 percent of total consumption, respectively. Most petroleum was consumed in the transportation end-use sector, while the vast majority of coal was used in electricity generation, with natural gas broadly consumed in all end-use sectors except transportation (see Figure 2-5) (EIA 2001a).

Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process the carbon stored in the fuels is oxidized and emitted as $CO_2$ and smaller amounts of other gases, including methane ($CH_4$), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs).[4] These other carbon 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,

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

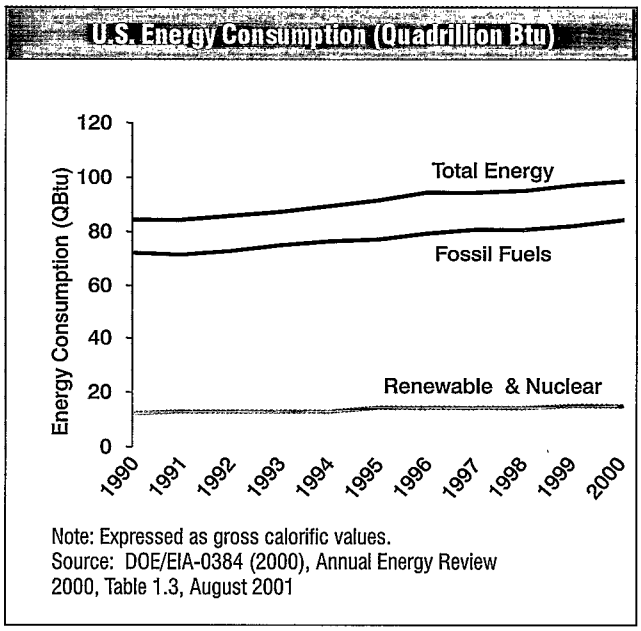
[4] See the sections entitled Stationary Combustion and Mobile Combustion in this chapter for information on non-$CO_2$ gas emissions from fossil fuel combustion.

Figure 2-3



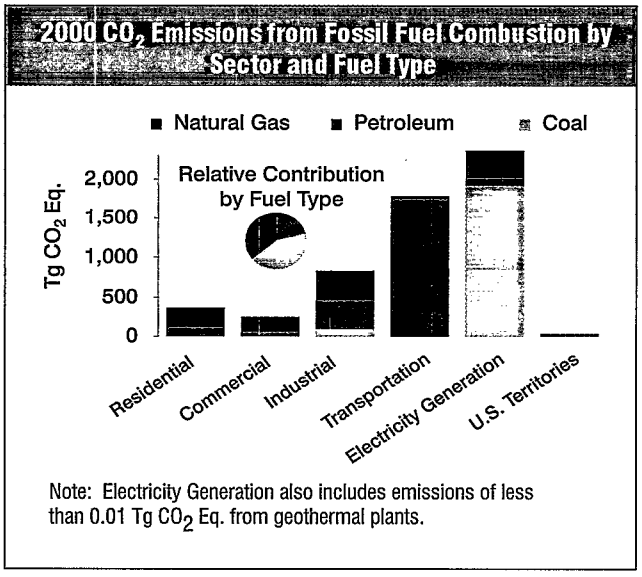

Source: DOE/EIA-0384(2000), Annual Energy Review 2000, Table 1.3, August 2001

Figure 2-4




Note: Expressed as gross calorific values.
Source: DOE/EIA-0384 (2000), Annual Energy Review 2000, Table 1.3, August 2001

Figure 2-5




Note: Electricity Generation also includes emissions of less than 0.01 Tg $CO_2$ Eq. from geothermal plants.

except for the soot an ash left behind during the combustion process, all the carbon in fossil fuels used to produce energy is eventually converted to atmospheric $CO_2$.

For the purpose of international reporting, the IPCC (IPCC/UNEP/OECD/IEA 1997) requires 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 carbon consumed for these non-energy products can be stored (i.e., sequestered) indefinitely. To account for the fact that the carbon in these fuels ends up in products instead of being combusted (i.e., oxidized and released into the atmosphere), the fraction of fossil fuel-based carbon in manufactured products is subtracted from emission estimates. (See the Carbon Stored in Products from Non-Energy Uses of Fossil Fuels section in this chapter.) The fraction of this carbon stored in products that is eventually combusted in waste incinerators or combustion plants is accounted for in the Waste Combustion section of this chapter.

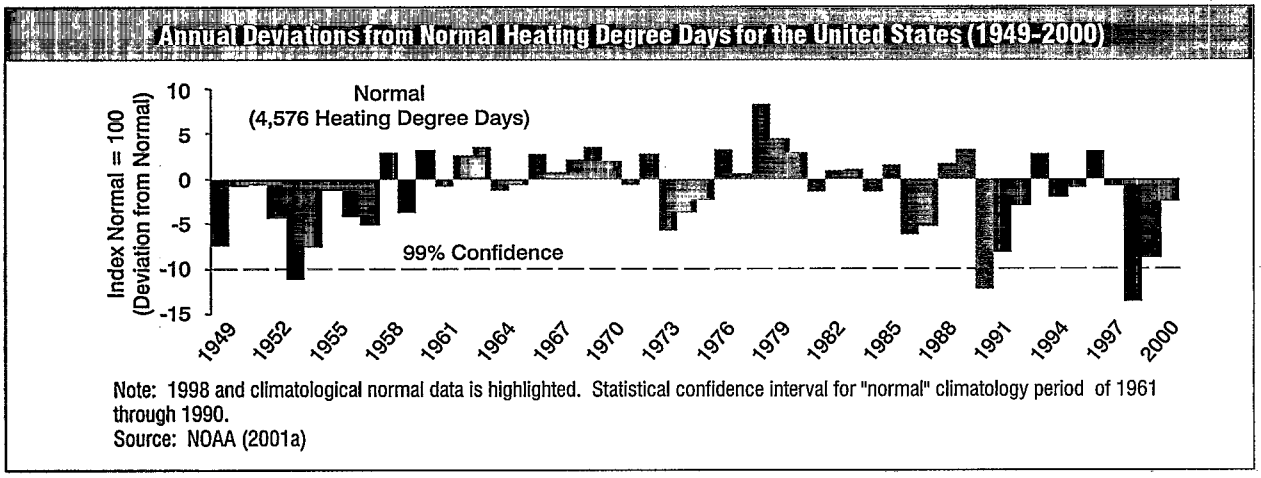
The IPCC also requires that $CO_2$ emissions from the consumption of fossil fuels for aviation and marine international transport activities (i.e., international bunker fuels) be reported separately, and not included in national emission totals. Estimates of carbon in products and international bunker fuel emissions for the United States are provided in Table 2-4 and Table 2-5.

## Box 2-1: Weather and Non-Fossil Energy Effects on $CO_2$ from Fossil Fuel Combustion Trends

After two unusually warm years in 1998 and 1999, weather conditions returned closer to normal in 2000. The colder winter conditions caused increased demand for heating fuels, while a cooler summer reduced electricity demand. Overall, however, conditions were still slightly warmer than usual. Heating degree days in the United States in 2000 were 3 percent below normal (see Figure 2-6) while cooling degree days in 2000 were 4 percent above normal (see Figure 2-7).[5]

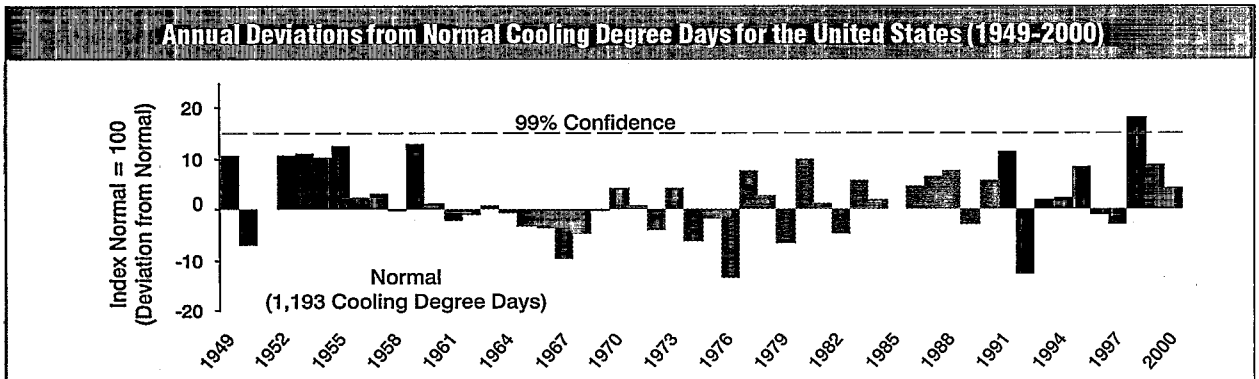
Although no new U.S. nuclear power plants have been constructed in many years, the utilization (i.e., capacity factors[6]) of existing plants reached record levels in 2000, approaching 90 percent. This increase in utilization translated into an increase in electricity output by nuclear plants of slightly more than 3 percent in 2000. This output by nuclear plants, however, was offset by reduced electricity output by hydroelectric power plants, which declined by almost 12 percent. Electricity generated by nuclear plants provides approximately twice as much of the energy consumed in the United States as hydroelectric plants. Aggregate nuclear and hydroelectric power plant capacity factors since 1973 are shown in Figure 2-8.

**Figure 2-6**




Note: 1998 and climatological normal data is highlighted. Statistical confidence interval for "normal" climatology period of 1961 through 1990.
Source: NOAA (2001a)

**Figure 2-7**



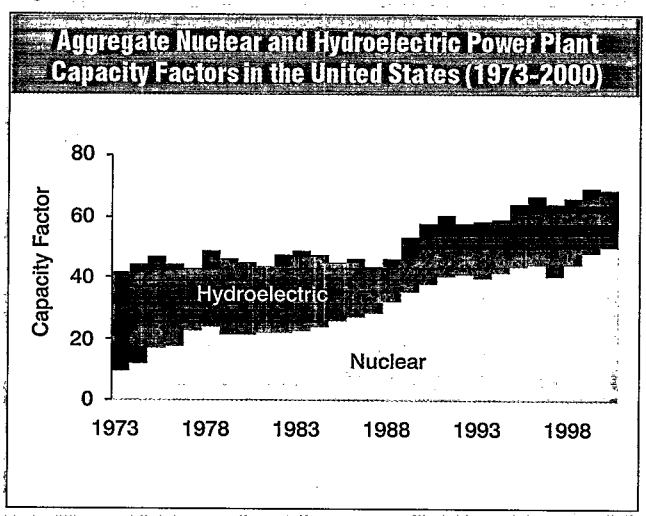

Note: 1998 and climatological normal data is highlighted. Statistical confidence interval for "normal" climatology period of 1961 through 1990.
Source: NOAA (2001b)

[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. Excludes Alaska and Hawaii. Normals are based on data from 1961 through 1990. 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 2001b).

## Box 2-1: Weather and Non-Fossil Energy Effects on $CO_2$ from Fossil Fuel Combustion Trends (Continued)

Figure 2-8




## Table 2-4: Fossil Fuel Carbon in Products (Tg $CO_2$ Eq.)*

| Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Industrial | 213.4 | 240.2 | 242.4 | 253.2 | 260.2 | 274.8 | 265.6 |
| Transportation | 1.2 | 1.2 | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 |
| Territories | 6.3 | 9.8 | 14.7 | 15.4 | 15.2 | 15.6 | 16.3 |
| **Total** | **221.0** | **251.1** | **258.2** | **269.8** | **276.7** | **291.6** | **283.2** |

* See Carbon Stored in Products from Non-Energy Uses of Fossil Fuels section for additional detail.
Note: Totals may not sum due to independent rounding.

## Table 2-5: $CO_2$ Emissions from International Bunker Fuels (Tg $CO_2$ Eq.)*

| Vehicle Mode | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Aviation | 46.6 | 51.1 | 52.1 | 55.9 | 55.0 | 58.9 | 57.3 |
| Marine | 67.3 | 49.9 | 50.1 | 54.0 | 57.9 | 46.4 | 43.0 |
| **Total** | **113.9** | **101.0** | **102.3** | **109.9** | **112.9** | **105.3** | **100.2** |

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

## End-Use Sector Consumption

When analyzing $CO_2$ emissions from fossil fuel combustion, four end-use sectors were defined: industrial, transportation, residential, and commercial.[7] Electricity generation also emits $CO_2$; however, these emissions occur as power plants combust fossil fuels 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 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. In reality, sources of electricity vary widely in carbon intensity (e.g., coal versus wind power). By giving equal carbon-intensity weight to each sector's electricity consumption, emissions attributed to one end-use sector may be somewhat overestimated, while emissions attributed to another end-use sector may be slightly underestimated. 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 2-6 and Figure 2-9 summarize $CO_2$ emissions from direct fossil fuel combustion and pro-rated electricity generation emissions from electricity consumption by end-use sector.

### Transportation End-Use Sector

The transportation end-use sector accounted for the largest share (approximately 32 percent) of $CO_2$ emissions from fossil fuel combustion—excluding international bunker fuels.[8] Almost all of the energy consumed in this end-use sector 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.[9]

Carbon dioxide emissions from fossil fuel combustion for transportation increased by 22 percent from 1990 to 2000, to 1,792.3 Tg $CO_2$ Eq. The growth in transportation end-use sector emissions has been relatively steady, including a 3.5 percent single year increase in 2000. Like overall energy demand, transportation fuel demand is a function of many short and long-term factors. In the short term only minor adjustments can generally be made through consumer behavior (e.g., not driving as far for summer vacation).

**Table 2-6: $CO_2$ Emissions from Fossil Fuel Combustion by End-Use Sector (Tg $CO_2$ Eq.)**

| End-Use Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Industrial** | **1,519.6** | **1,563.4** | **1,623.5** | **1,640.8** | **1,598.1** | **1,575.7** | **1,568.5** |
| Combustion | 871.6 | 894.9 | 936.5 | 935.2 | 881.1 | 858.1 | 829.2 |
| Electricity | 648.0 | 668.5 | 687.0 | 705.6 | 717.0 | 717.7 | 739.3 |
| **Transportation** | **1,474.5** | **1,582.0** | **1,621.3** | **1,631.6** | **1,657.7** | **1,731.0** | **1,792.3** |
| Combustion | 1,471.8 | 1,579.4 | 1,618.7 | 1,628.8 | 1,655.0 | 1,728.2 | 1,789.5 |
| Electricity | 2.7 | 2.6 | 2.7 | 2.7 | 2.7 | 2.7 | 2.8 |
| **Residential** | **965.3** | **1,050.6** | **1,109.9** | **1,106.1** | **1,112.6** | **1,136.9** | **1,199.8** |
| Combustion | 332.1 | 362.3 | 390.4 | 374.9 | 341.8 | 360.5 | 374.8 |
| Electricity | 633.2 | 688.2 | 719.5 | 731.2 | 770.8 | 776.5 | 825.0 |
| **Commercial** | **792.3** | **853.8** | **884.8** | **932.0** | **953.4** | **969.2** | **1,024.7** |
| Combustion | 217.3 | 223.9 | 232.8 | 233.7 | 217.5 | 219.8 | 239.3 |
| Electricity | 575.0 | 629.9 | 652.0 | 698.4 | 735.9 | 749.4 | 785.4 |
| **U.S. Territories** | **28.1** | **35.3** | **27** | **29.1** | **34.4** | **35.8** | **38** |
| **Total** | **4,779.8** | **5,085.0** | **5,266.4** | **5,339.6** | **5,356.2** | **5,448.6** | **5,623.3** |
| **Electricity Generation** | **1,858.9** | **1,989.3** | **2,061.2** | **2,137.9** | **2,226.4** | **2,246.2** | **2,352.5** |

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.

[7] See Glossary (Annex Z) for more detailed definitions of the industrial, residential, commercial, and transportation end-use sector, as well as electricity generation.

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

[9] See Glossary (Annex Z) for a more detailed definition of the transportation end-use sector.

Figure 2-9

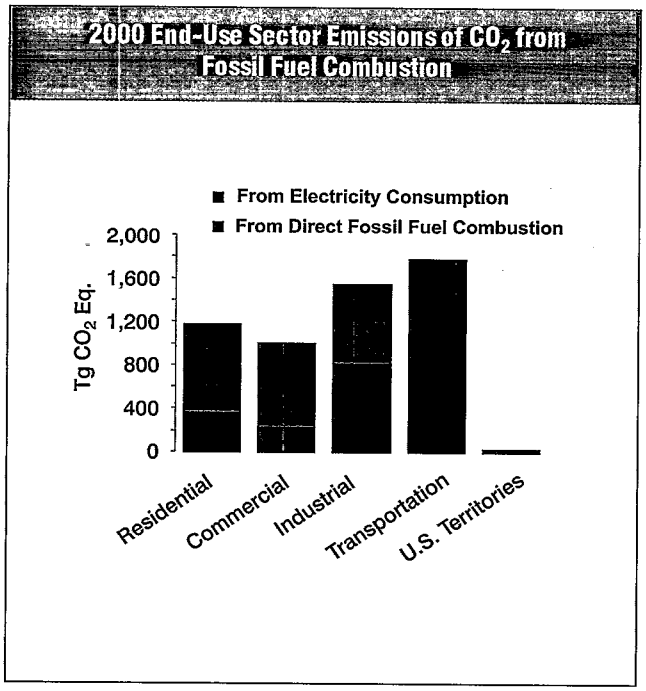
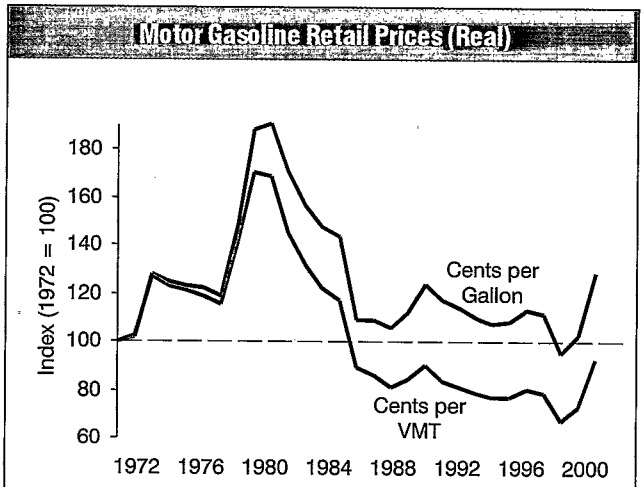



Figure 2-10

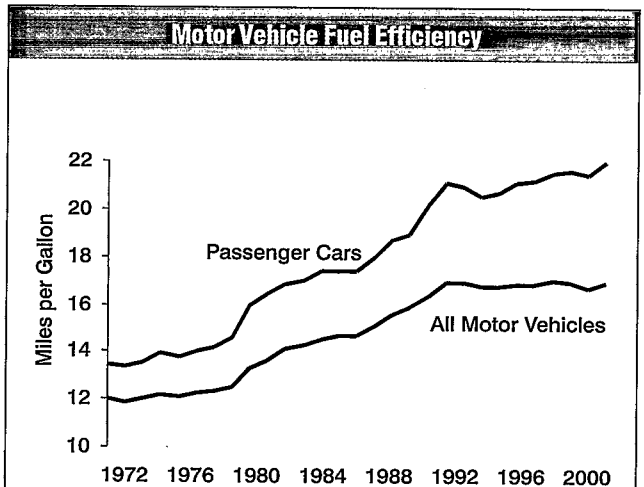



Source for gasoline prices: DOE/EIA-0384(2000), Annual Energy Review 2000, August 2001, Table 5.22 Source for motor vehicle fuel efficiency: DOT/FHWA, Highway Statistics Summary to 1995, 1996, 1997, 1998, and 2000.

However, long-term adjustments such as vehicle purchase choices, transport mode choice and access (i.e., trains versus planes), and urban planning can have a significant impact on fuel demand.

Motor gasoline and other petroleum product prices have generally declined since 1990 (see Figure 2-10). Although gasoline and other transport fuel prices did rise in 2000, an overall strong economy and short-term constraints on reductions in travel and increases in vehicle fuel efficiency were likely causes for demand for fuel from contracting. Since 1990, travel activity in the United States has grown more rapidly than population, with a 13 percent increase in vehicle miles traveled per capita. In the meantime, improvements in the average fuel efficiency of the U.S. vehicle fleet stagnated after increasing steadily since 1977 (EIA 2001a). The average miles per gallon achieved by the U.S. vehicle fleet has remained fairly constant since 1991. This trend is due, in part, to the increasing dominance of new motor vehicle sales by less fuel-efficient light-duty trucks and sport-utility vehicles (see Figure 2-11).

Figure 2-11




Source: DOT/FHWA, Highway Statistics Summary to 1995, 1996, 1997, 1998, 1999, and 2000.

Table 2-7 provides a detailed breakdown of $CO_2$ emissions by fuel category and vehicle type for the transportation end-use sector. Fifty-five percent of the emissions from this end-use sector in 2000 were the result of the combustion of motor gasoline in passenger cars and light-duty trucks. Diesel highway vehicles and jet aircraft were also significant contributors, accounting for 15 and 13 percent of $CO_2$ emissions from the transportation end-use sector, respectively.[10]

[10] These percentages include emissions from bunker fuels.

## Table 2-7: $CO_2$ Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (Tg $CO_2$ Eq.)

| Fuel/Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Motor Gasoline** | **955.3** | **1,023.0** | **1,041.4** | **1,050.6** | **1,072.5** | **1,098.7** | **1,105.7** |
| Passenger Cars | 612.8 | 634.3 | 646.6 | 652.3 | 665.9 | 682.2 | 686.5 |
| Light-Duty Trucks | 274.1 | 314.2 | 320.4 | 323.1 | 341.9 | 351.2 | 353.4 |
| Other Trucks | 41.4 | 40.0 | 40.7 | 40.5 | 32.1 | 34.7 | 34.9 |
| Motorcycles | 1.6 | 1.7 | 1.7 | 1.7 | 1.7 | 1.8 | 1.8 |
| Buses | 2.0 | 3.0 | 2.1 | 2.2 | 0.8 | 0.7 | 0.7 |
| Construction Equipment | 2.2 | 2.4 | 2.4 | 2.5 | 2.0 | 1.5 | 1.5 |
| Agricultural Machinery | 4.4 | 7.9 | 7.8 | 8.2 | 7.6 | 5.9 | 5.9 |
| Boats (Recreational) | 16.9 | 19.5 | 19.7 | 20.1 | 20.5 | 20.8 | 20.9 |
| **Distillate Fuel Oil (Diesel)** | **277.4** | **312.2** | **329.0** | **342.8** | **353.5** | **373.7** | **391.0** |
| Passenger Cars | 7.1 | 7.6 | 7.6 | 7.9 | 7.6 | 5.0 | 5.2 |
| Light-Duty Trucks | 9.0 | 11.2 | 13.1 | 14.2 | 14.4 | 15.3 | 16.0 |
| Other Trucks | 164.1 | 195.4 | 207.0 | 216.1 | 225.4 | 247.4 | 259.0 |
| Buses | 7.9 | 9.9 | 8.6 | 9.2 | 10.7 | 11.6 | 12.1 |
| Construction Equipment | 10.5 | 10.5 | 10.9 | 11.2 | 10.8 | 11.0 | 11.5 |
| Agricultural Machinery | 23.1 | 23.0 | 23.8 | 24.5 | 23.7 | 24.0 | 25.2 |
| Boats (Freight) | 18.0 | 16.1 | 18.4 | 18.3 | 17.8 | 18.1 | 18.9 |
| Locomotives | 26.3 | 29.5 | 31.5 | 32.4 | 31.6 | 33.2 | 34.8 |
| Marine Bunkers | 11.4 | 9.1 | 8.3 | 9.1 | 11.5 | 8.2 | 8.3 |
| **Jet Fuel** | **220.4** | **219.9** | **229.8** | **232.1** | **235.6** | **242.9** | **251.2** |
| General Aviation | 6.3 | 5.3 | 5.8 | 6.1 | 7.7 | 9.2 | 9.8 |
| Commercial Air Carriers | 118.2 | 121.4 | 124.9 | 129.4 | 131.4 | 137.3 | 141.0 |
| Military Vehicles | 34.8 | 24.1 | 23.1 | 21.1 | 21.7 | 21.0 | 21.4 |
| Aviation Bunkers | 46.6 | 51.1 | 52.2 | 55.9 | 55.0 | 58.9 | 57.3 |
| Other[a] | 14.6 | 17.9 | 23.9 | 19.6 | 19.7 | 16.6 | 21.8 |
| **Aviation Gasoline** | **3.1** | **2.7** | **2.6** | **2.7** | **2.4** | **2.7** | **2.5** |
| General Aviation | 3.1 | 2.7 | 2.6 | 2.7 | 2.4 | 2.7 | 2.5 |
| **Residual Fuel Oil** | **80.4** | **72.1** | **67.5** | **56.7** | **55.9** | **62.3** | **84.7** |
| Boats (Freight)[b] | 24.5 | 31.3 | 25.7 | 11.8 | 9.5 | 24.1 | 50.0 |
| Marine Bunkers[b] | 55.8 | 40.8 | 41.8 | 44.9 | 46.4 | 38.2 | 34.6 |
| **Natural Gas** | **36.0** | **38.3** | **38.9** | **41.5** | **34.9** | **40.2** | **41.9** |
| Passenger Cars | + | 0.1 | + | + | + | + | + |
| Light-Duty Trucks | + | + | + | + | + | + | + |
| Buses | + | 0.1 | 0.1 | 0.2 | 0.2 | 0.3 | 0.4 |
| Pipeline | 36.0 | 38.2 | 38.8 | 41.3 | 34.7 | 39.9 | 41.5 |
| **LPG** | **1.3** | **1.0** | **0.9** | **0.8** | **1.0** | **0.8** | **0.8** |
| Light-Duty Trucks | + | + | + | + | + | + | + |
| Other Trucks | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.3 | 0.3 |
| Buses | 0.8 | 0.5 | 0.5 | 0.4 | 0.6 | 0.5 | 0.5 |
| **Electricity** | **2.7** | **2.6** | **2.7** | **2.7** | **2.7** | **2.7** | **2.7** |
| Buses | + | + | + | + | + | + | + |
| Locomotives | 2.2 | 2.1 | 2.1 | 2.1 | 2.2 | 2.1 | 2.1 |
| Pipeline | 0.5 | 0.5 | 0.5 | 0.6 | 0.6 | 0.6 | 0.6 |
| **Lubricants** | **11.7** | **11.2** | **10.9** | **11.5** | **12.0** | **12.1** | **12.0** |
| **Total (Including Bunkers)[c]** | **1,588.4** | **1,683.0** | **1,723.6** | **1,741.4** | **1,770.6** | **1,836.3** | **1,892.5** |
| **Total (Excluding Bunkers)[c]** | **1,474.5** | **1,582.0** | **1,621.3** | **1,631.5** | **1,657.7** | **1,731.0** | **1,792.2** |

Note: Totals may not sum due to independent rounding.

[a] Including but not limited to fuel blended with heating oils and fuel used for chartered aircraft flights.

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

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

+ Does not exceed 0.05 Tg of $CO_2$ Eq.

### Industrial End-Use Sector

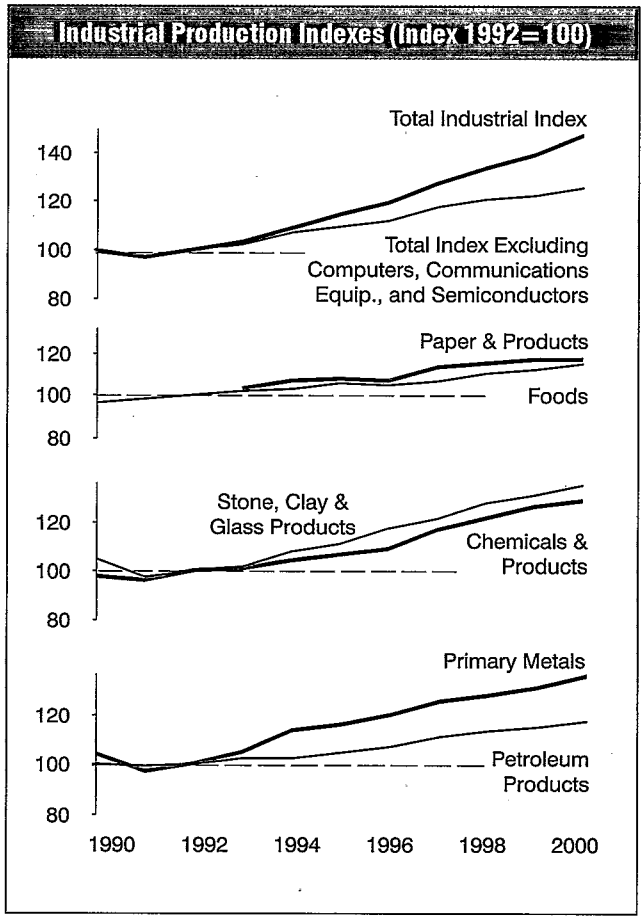
The industrial end-use sector accounted for 28 percent of $CO_2$ emissions from fossil fuel combustion. On average, 53 percent of these emissions resulted from the direct consumption of fossil fuels in order to meet industrial energy demands such as for steam and process heat. The remaining 47 percent was associated with their consumption of electricity for uses such as motors, electric furnaces, ovens, and lighting.

The industrial end-use sector includes activities such as manufacturing, construction, mining, and agriculture.[11] The largest of these activities in terms of energy consumption is manufacturing, which was estimated in 1998 to have accounted for about 84 percent of industrial energy consumption (EIA 1997). Manufacturing energy consumption was dominated by several industries, including petroleum, chemical, primary metal, paper, food, stone, clay, and glass products.

In theory, emissions from the industrial end-use sector should be highly correlated with economic growth and industrial output; however, certain activities within the sector, such as heating of industrial buildings and agricultural energy consumption, are also affected by weather conditions.[12] 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 1999 to 2000, total industrial production and manufacturing output were reported to have increased by 4.5 and 4.8 percent, respectively (FRB 2001). However, excluding the fast growing computer, communication equipment, and semiconductor industries from these indexes reduces their growth considerably—to 1.2 and 1.1 percent, respectively—and illustrates some of the structural changes occurring in the U.S. economy (see Figure 2-12).

Figure 2-12




Despite the growth in industrial output (49 percent) and the overall U.S. economy (32 percent) from 1990 to 2000, emissions from the industrial end-use sector decreased slightly (by 0.5 percent). The reasons for the disparity between rapid growth in industrial output and stagnant growth in industrial emissions are not entirely clear. It is likely, though, that several factors have influenced industrial emission trends, including: 1) more rapid growth in output from less energy-intensive industries relative to traditional manufacturing industries, 2) improvements in energy efficiency; and 3) a lowering of the carbon intensity of fossil fuel consumption as industry shifts from its historical reliance on coal and coke to heavier usage of natural gas.

[11] See Glossary (Annex Z) for a more detailed definition of the industrial end-use sector.

[12] 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.

Industry was the largest user of fossil fuels for non-energy applications. Fossil fuels can be used for producing products such as fertilizers, plastics, asphalt, or lubricants that can sequester or store carbon for long periods of time. Asphalt used in road construction, for example, stores carbon essentially indefinitely. Similarly, fossil fuels used in the manufacture of materials like plastics can also store carbon, if the material is not burned. The amount of carbon contained in industrial products made from fossil fuels rose 24 percent between 1990 and 2000, to 265.6 Tg $CO_2$ Eq.[13]

### Residential and Commercial End-Use Sectors

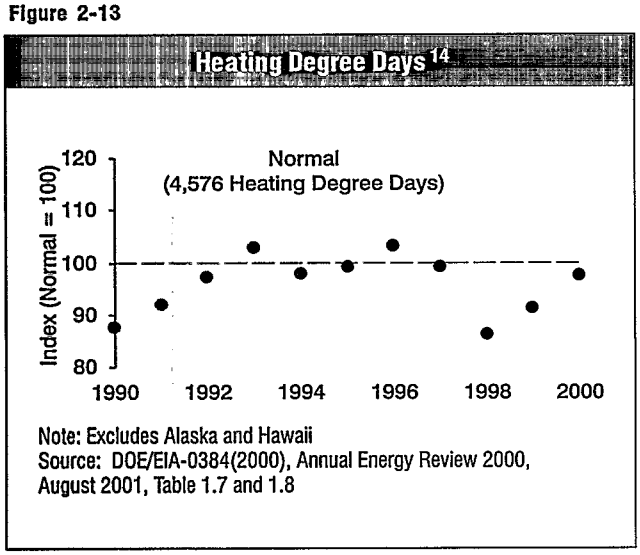
The residential and commercial end-use sectors accounted for an average 21 and 18 percent, respectively, of $CO_2$ emissions from fossil fuel combustion. Both end-use sectors were heavily reliant on electricity for meeting energy needs, with electricity consumption for lighting, heating, air conditioning, and operating appliances contributing to about 69 and 77 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 these end-use sectors.

Emissions from residences and commercial buildings generally increased throughout the 1990s, and, unlike in other end-use sectors, emissions in these sectors did not decline during the economic downturn in 1991 (see Table 2-6). This difference exists because short-term fluctuations in energy consumption in these sectors are affected proportionately more by the weather than by prevailing economic conditions. 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).

In 2000, winter conditions in the United States were slightly warmer than normal (i.e., heating degree days were 3 percent below normal), although not as warm as in 1999 (see Figure 2-13). Due, in part, to this colder winter relative to the previous year, emissions from natural gas consumption in residences and commercial establishments increased by 5 percent and 9 percent, respectively.

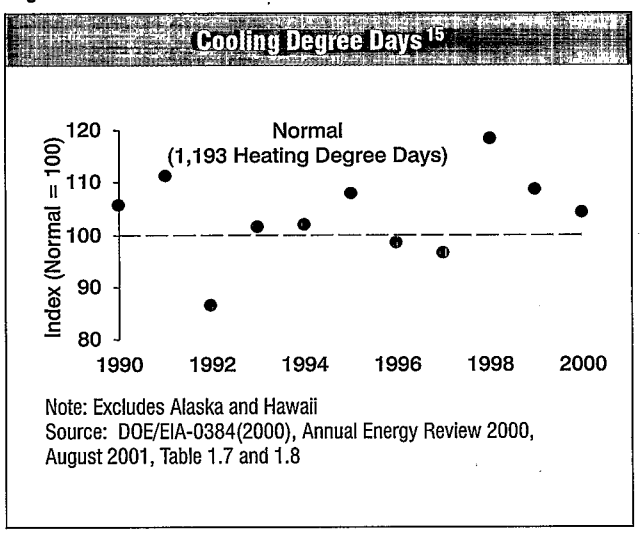
In 2000, electricity sales to the residential and commercial end-use sectors increased by 4 and 3 percent, respectively. Even though cooler summer conditions in 2000 relative to 1999 likely led to decreased air-conditioning related electricity consumption (see Figure 2-14), growth in personal

**Figure 2-13**




Note: Excludes Alaska and Hawaii
Source: DOE/EIA-0384(2000), Annual Energy Review 2000, August 2001, Table 1.7 and 1.8

**Figure 2-14**



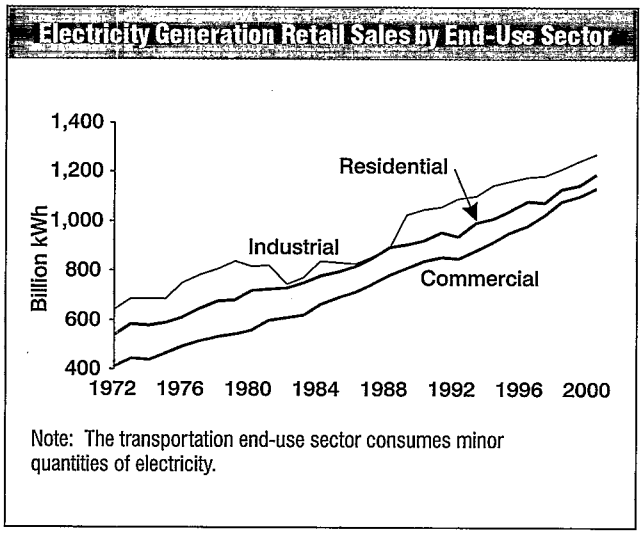

Note: Excludes Alaska and Hawaii
Source: DOE/EIA-0384(2000), Annual Energy Review 2000, August 2001, Table 1.7 and 1.8

[13] See the Carbon Stored in Products in Non-Energy Uses of Fossil Fuels for a more detailed discussion. Also, see Waste Combustion in the Waste chapter for a discussion of emissions from the incineration or combustion of fossil fuel-based products.

[14] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65° F. Excludes Alaska and Hawaii. Normals are based on data from 1961 through 1990.

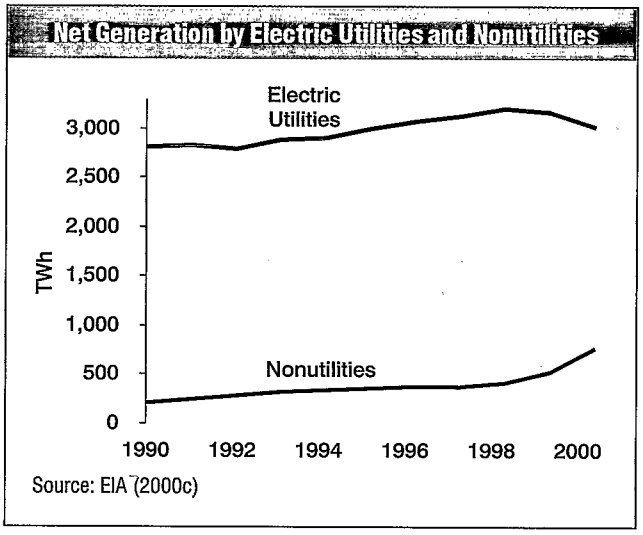
[15] Degree days are relative measurements of outdoor air temperature. Cooling degree days are deviations of the mean daily temperature above 65° F. Excludes Alaska and Hawaii. Normals are based on data from 1961 through 1990.

Figure 2-15




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

Figure 2-16




Source: EIA (2000c)

income along with other trends such as population growth led to a 6 percent increase in both residential and commercial end-use sector emissions from 1999 to 2000.

### Electricity Generation

The process of generating electricity is the single largest source of greenhouse gas emissions in the United States (34 percent), which relies on electricity to meet a significant portion of its energy requirements. Electricity was consumed primarily in the residential, commercial, and industrial end-use sectors for uses such as lighting, heating, electric motors, appliances, electronics, and air conditioning (see Figure 2-15). Electricity generation also accounted for the largest share of $CO_2$ emissions from fossil fuel combustion, approximately 42 percent in 2000.

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). While utilities primarily generate power for the U.S. electric grid for sale to retail customers, nonutilities produce electricity for their own use, to sell to large consumers, or to sell on the wholesale electricity market (e.g., to utilities for distribution and resale to customers). The net generation of electricity by utilities and nonutilities is shown in Figure 2-16.

The electric power industry in the United States is currently undergoing significant changes. Both Federal and State government agencies are modifying regulations to create a competitive market for electricity generation from what was a market dominated by vertically integrated and regulated monopolies (i.e., electric utilities). These changes have led to the growth of nonutility power producers, including the sale of generating capacity by electric utilities to nonutilities.[16] As a result, the proportion of electricity in the United States generated by nonutilities has grown from about 7 percent in 1990 to 21 percent in 2000 (EIA 2001b).

In 2000, $CO_2$ emissions from electricity generation increased by 4.7 percent relative to the previous year, coinciding with increased electricity consumption and robust growth in the U.S. economy. An additional factor leading to this above average increase in emissions was the decreased generation of electricity from renewable resources, including a 12 percent reduction in output from hydroelectric dams. This generation was primarily replaced by additional fossil fuel consumption for producing electricity, thus increasing the overall the carbon intensity from energy consumption for electricity generation (see Table 2-9).

Coal is consumed primarily by the electric power sector in the United States, which accounted for 94 percent of total coal consumption in 2000. Consequently, changes in

[16] In 2000, 47,710 megawatts of electrical generating capacity was sold by electric utilities to nonutilities, or 5.9 percent of total electric power industry capacity (EIA 2001b).

## Box 2-2: Sectoral Carbon Intensity Trends Related to Fossil Fuel and Overall Energy Consumption

Fossil fuels are the dominant source of energy in the United States, and carbon dioxide ($CO_2$) is emitted as a product from their combustion. Useful energy, however, can be generated from many other sources that do not emit $CO_2$ in the energy conversion process. In the United States, useful energy is also produced from renewable (i.e., hydropower, biofuels, geothermal, solar, and wind) and nuclear sources.[17]

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 carbon intensity of the energy sources employed (e.g., fuel switching from coal to natural gas). The amount of carbon emitted—in the form of $CO_2$—from the combustion of fossil fuels is dependent upon the carbon content of the fuel and the fraction of that carbon that is oxidized.[18] Fossil fuels vary in their average carbon content, ranging from about 53 Tg $CO_2$ Eq./EJ for natural gas to upwards of 95 Tg $CO_2$ Eq./EJ for coal and petroleum coke.[19] In general, the carbon intensity 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 carbon neutral (i.e., 0 Tg $CO_2$ Eq./EJ). 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 carbon neutral, as the $CO_2$ emitted during their combustion is assumed to be offset by the carbon sequestered in the growth of new biomass.[20] The overall carbon intensity of the U.S. economy is thus dependent upon the quantity and combination of fuels and other energy sources employed to meet demand.

Table 2-8 provides a time series of the carbon 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 carbon 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 carbon intensity, which is related to the large percentage of its energy derived from natural gas for heating. The carbon intensity of the commercial sector was greater than the residential sector for the period from 1990 to 1997, but then declined to a comparable level as commercial businesses shifted away from petroleum to natural gas. The industrial sector was more dependent on petroleum and coal than either the residential or commercial sectors, and thus had higher carbon intensities over this period. The carbon intensity of the transportation sector was closely related to the carbon content of petroleum products (e.g., motor gasoline and jet fuel, both around 67 Tg $CO_2$ Eq./EJ), which were the primary sources of energy. Lastly, the electricity generation sector had the highest carbon intensity due to its heavy reliance on coal for generating electricity.

In contrast to Table 2-8, Table 2-9 presents carbon 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.[21] This table, therefore, provides a more complete picture of the actual carbon intensity of each end-use sector per unit of energy consumed. The transportation end-use sector in Table 2-9 emerges as the most carbon 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 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 carbon intensity. The carbon intensity of the electricity generation sector differs greatly from the scenario in Table 2-8, where only the energy consumed from the direct combustion of fossil fuels was included. This difference is due almost entirely to the inclusion of electricity generation from nuclear and hydropower sources, which do not emit carbon dioxide.

By comparing the values in Table 2-8 and Table 2-9, a couple of observations can be made. The usage of renewable and nuclear energy sources has resulted in a significantly lower carbon intensity of the U.S. economy. However, over the eleven year period of 1990 through 2000, the carbon intensity of U.S. energy consumption has been fairly constant, as the proportion of renewable and nuclear energy technologies has not changed significantly.

Although the carbon intensity of total energy consumption has remained fairly constant, per capita energy consumption has increased, leading to a greater energy-related $CO_2$ emissions per capita in the United States since 1990 (see Figure 2-17). Due to structural changes and the strong growth in the U.S. economy, though, energy consumption and energy-related $CO_2$ emissions per dollar of gross domestic product (GDP) declined in the 1990s.

[17] 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.

[18] Generally, more than 97 percent of the carbon in fossil fuel is oxidized to $CO_2$ with most carbon combustion technologies used in the United States.

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

[20] This statement assumes that there is no net loss of biomass-based carbon associated with the land use practices used to produce these biomass fuels.

[21] 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.

## Table 2-8: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (Tg $CO_2$ Eq./EJ)

| Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Residential[a] | 53.8 | 53.7 | 53.6 | 53.7 | 53.7 | 53.7 | 53.7 |
| Commercial[a] | 55.7 | 54.2 | 54.2 | 54.0 | 53.8 | 53.8 | 53.8 |
| Industrial[a] | 60.5 | 59.6 | 59.5 | 59.6 | 59.7 | 59.2 | 58.9 |
| Transportation[a] | 66.9 | 66.8 | 66.7 | 66.6 | 66.7 | 66.7 | 66.8 |
| Electricity Generation[b] | 80.4 | 79.6 | 80.5 | 80.2 | 79.6 | 79.5 | 79.2 |
| **All Sectors[c]** | **68.4** | **67.9** | **68.0** | **68.2** | **68.4** | **68.3** | **68.3** |

[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. Exajoule (EJ) = $10^{18}$ joules = 0.9479 QBtu.

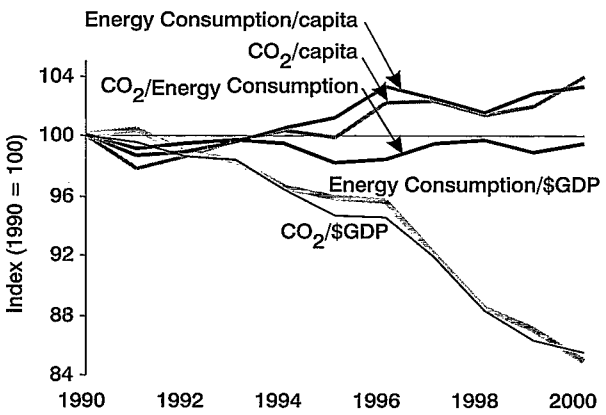
## Table 2-9: Carbon Intensity from Energy Consumption by Sector (Tg $CO_2$ Eq./EJ)

| Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Transportation[a] | 66.7 | 66.4 | 66.5 | 66.3 | 66.4 | 66.3 | 66.4 |
| Other End-Use Sectors[a,b] | 54.0 | 52.8 | 52.9 | 53.8 | 53.9 | 53.2 | 53.6 |
| Electricity Generation[c] | 55.0 | 53.4 | 53.8 | 55.1 | 55.3 | 54.5 | 55.3 |
| **All Sectors[d]** | **57.6** | **56.6** | **56.7** | **57.3** | **57.5** | **57.0** | **57.3** |

[a] Includes electricity (from fossil fuel, nuclear, and renewable sources) and direct renewable energy consumption.
[b] Other End-Use Sectors include 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. Exajoule (EJ) = $10^{18}$ joules = 0.9479 QBtu.

**Figure 2-17**

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




Source: BEA (2001), Census (2000), Emission and energy consumption estimates in this report.

**Figure 2-18**

### Change in $CO_2$ Emissions from Fossil Fuel Combustion Since 1990 by End-Use Sector

Dark shaded columns relate to changes in emissions from electricity consumption. Lightly shaded columns relate to changes in emissions from both electricity and direct fossil fuel combustion.

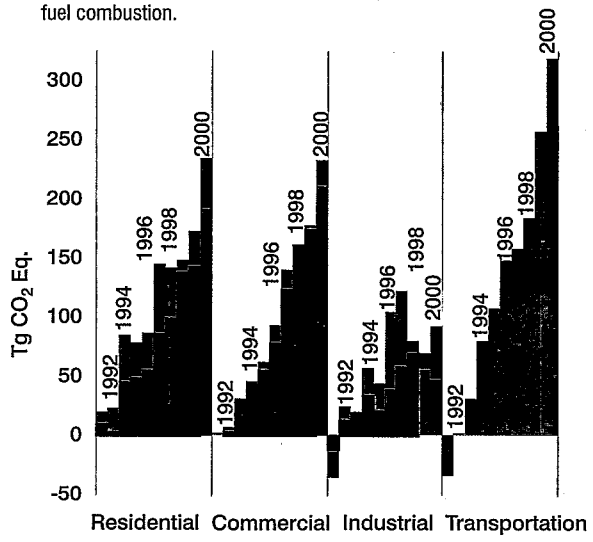



Figure 2-18 and Table 2-10 present the detailed $CO_2$ emission trends underlying the carbon intensity differences and changes described in Table 2-8. In Figure 2-18, changes over time in both overall end-use sector-related emissions and electricity-related emissions for each year since 1990 are highlighted. In Table 2-10 changes in emissions since 1990 are presented by sector and fuel type to provide a more detailed accounting.

**Table 2-10: Change in $CO_2$ Emissions from Direct Fossil Fuel Combustion Since 1990 (Tg $CO_2$ Eq.)**

| Sector/Fuel Type | 1991 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Residential** | **9.9** | **30.2** | **58.3** | **42.8** | **9.7** | **28.4** | **42.7** |
| Coal | (0.5) | (0.8) | (0.7) | (0.4) | (1.6) | (1.4) | (1.4) |
| Natural Gas | 8.8 | 24.6 | 46.0 | 32.0 | 8.0 | 17.9 | 29.7 |
| Petroleum | 1.7 | 6.4 | 13.0 | 11.2 | 3.4 | 11.9 | 14.4 |
| **Commercial** | **1.5** | **6.6** | **15.5** | **16.4** | **0.3** | **2.5** | **22.0** |
| Coal | (0.8) | (1.2) | (1.0) | (0.5) | (2.5) | (2.1) | (2.1) |
| Natural Gas | 5.8 | 22.1 | 29.2 | 32.3 | 21.1 | 22.8 | 38.4 |
| Petroleum | (3.5) | (14.3) | (12.6) | (15.3) | (18.4) | (18.1) | (14.3) |
| **Industrial** | **(24.3)** | **23.2** | **64.9** | **63.5** | **9.4** | **(13.6)** | **(42.4)** |
| Coal | (1.5) | (4.6) | (10.4) | (8.9) | (14.5) | (18.9) | (33.0) |
| Natural Gas | (1.4) | 40.5 | 56.8 | 51.6 | 20.0 | 14.9 | 13.3 |
| Petroleum | (21.4) | (12.7) | 18.4 | 20.9 | 3.9 | (9.6) | (22.7) |
| **Transportation** | **(34.1)** | **107.5** | **146.9** | **157.0** | **183.2** | **256.4** | **317.7** |
| Coal | NE | NE | NE | NE | NE | NE | NE |
| Natural Gas | (3.2) | 2.3 | 2.9 | 5.5 | (1.1) | 4.2 | 5.9 |
| Petroleum | (30.9) | 105.3 | 144.0 | 151.6 | 184.3 | 252.3 | 311.9 |
| **Electricity Generation** | **(3.7)** | **130.3** | **202.3** | **279.0** | **367.5** | **387.3** | **493.6** |
| Coal | (5.8) | 106.4 | 197.6 | 247.5 | 275.4 | 286.5 | 373.8 |
| Natural Gas | 7.4 | 63.0 | 38.7 | 56.6 | 89.1 | 96.6 | 128.1 |
| Petroleum | (5.2) | (38.9) | (33.9) | (25.0) | 3.1 | 4.3 | (8.2) |
| Geothermal | + | (0.1) | (0.1) | (0.1) | (0.1) | (0.2) | (0.2) |
| **U.S. Territories** | **3.7** | **7.2** | **(1.2)** | **0.9** | **6.1** | **7.6** | **9.8** |
| Coal | 0.1 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Natural Gas | NE | NE | NE | NE | NE | NE | 0.6 |
| Petroleum | 3.7 | 6.9 | (1.5) | 0.6 | 5.9 | 7.4 | 8.9 |
| **All Sectors** | **(46.8)** | **305.1** | **486.6** | **559.6** | **576.2** | **668.6** | **843.3** |

+ Does not exceed 0.05 Tg $CO_2$ Eq.
NE (Not Estimated)
Note: Totals may not sum due to independent rounding.

electricity demand have a significant impact on coal consumption and associated U.S. $CO_2$ emissions. Coal consumption for electricity generation increased by 5 percent in 2000, due to 1) increased electricity demand, 2) decreased electricity output of from hydropower, and 3) the relatively stable price of coal. In 2000, the price of coal decreased 2 percent, while petroleum and natural gas prices increased 68 and 63 percent, respectively.

## 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/UNEP/OECD/IEA 1997). A detailed description of the U.S. methodology is presented in Annex A, and is characterized by the following steps:

1. *Determine fuel consumption by fuel type and sector.* 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.), estimates of total U.S. fossil fuel consumption for a particular year were made. The United States does not include territories in its national energy statistics; therefore, fuel consumption data for territories was collected separately.[22] Portions of the fuel consumption data for three fuel categories – coking coal, petroleum coke, and natural gas – were reallocated to the

[22] Fuel consumption by U.S. territories (i.e. American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report and contributed emissions of 53 Tg $CO_2$ Eq. in 2000.

industrial processes chapter, as these portions were actually consumed during a non-energy related industrial activity. [23]

2. *Determine the total carbon content of fuels consumed.* Total carbon was estimated by multiplying the amount of fuel consumed by the amount of carbon in each fuel. This total carbon estimate defines the maximum amount of carbon that could potentially be released to the atmosphere if all of the carbon in each fuel was converted to $CO_2$. The carbon content coefficients used by the United States are presented in Annex A.

3. *Subtract the amount of carbon stored in products.* Non-energy uses of fossil fuels can result in storage of some or all of the carbon contained in the fuel for some period of time, depending on the end-use. For example, asphalt made from petroleum can sequester up to 100 percent of the carbon for extended periods of time, while other fossil fuel products, such as lubricants or plastics, lose or emit some carbon when they are used and/or burned as waste. Aggregate U.S. energy statistics include consumption of fossil fuels for non-energy uses; therefore, the portion of carbon that remains in products after they are manufactured was subtracted from potential carbon emission estimates.[24] The amount of carbon remaining in products was based on the best available data on the end-uses and fossil fuel products. These non-energy uses occurred in the industrial and transportation end-use sectors and U.S. territories. Emissions of $CO_2$ associated with the disposal of these fossil fuel-based products are not accounted for here, but are instead accounted for under the Waste Combustion section in this chapter.

4. *Subtract the amount of carbon from international bunker fuels.* According to the IPCC guidelines (IPCC/UNEP/OECD/IEA 1997) emissions from international transport activities, or bunker fuels, should not be included in national totals. Because U.S. energy consumption statistics include these bunker fuels—distillate fuel oil, residual fuel oil, and jet fuel—as part of consumption by the transportation end-use sector, emissions from international transport activities were calculated separately and the carbon content of these fuels was subtracted from the transportation end-use sector. The calculations for emissions from bunker fuels follow the same procedures used for emissions from consumption of all fossil fuels (i.e., estimation of consumption, determination of carbon content, and adjustment for the fraction of carbon not oxidized).[25]

5. *Adjust for carbon that does not oxidize during combustion.* Because combustion processes are not 100 percent efficient, some of the carbon contained in fuels is not emitted to the atmosphere. Rather, it remains behind as soot and ash. The estimated amount of carbon not oxidized due to inefficiencies during the combustion process was assumed to be 1 percent for petroleum and coal and 0.5 percent for natural gas (see Annex A). Unoxidized or partially oxidized organic (i.e., carbon containing) combustion products were assumed to have eventually oxidized to $CO_2$ in the atmosphere.[26]

6. *Allocate transportation emissions by vehicle type.* Because the transportation end-use sector was such a large consumer of fossil fuels in the United States,[27] a more detailed accounting of carbon dioxide emissions is provided. 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. Specific data by vehicle type were not available for 2000; therefore, the 1999 percentage allocations were applied to 2000 fuel consumption data in order to estimate emissions in 2000. Military vehicle jet fuel consumption was provided by the Defense Energy Support Center, under Department of Defense's (DoD) Defense Logistics Agency and the Office of the Undersecretary of Defense (Environmental Security). The difference between total U.S. jet fuel consumption (as reported by

[23] See sections on Iron and Steel Production, Ammonia Manufacture, Titanium Dioxide Production, Ferroalloy Production, and Aluminum Production in the Industrial Proceses chapter.

[24] See Carbon Stored in Products from Non-Energy Uses of Fossil Fuels section in this chapter for a more detailed discussion.

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

[26] See Indirect $CO_2$ from $CH_4$ Oxidation section in this chapter for a more detailed discussion.

[27] Electricity generation is not considered a final end-use sector, because energy is consumed solely to provide electricity to the other sectors.

EIA) and civilian air carrier consumption for both domestic and international flights (as reported by DOT and BEA) plus military jet fuel consumption is reported as "other" under the jet fuel category in Table 2-7, and includes such fuel uses as blending with heating oils and fuel used for chartered aircraft flights.

## Data Sources

Data on fuel consumption for the United States and its territories, and carbon content of fuels were obtained directly from the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE). Fuel consumption data were obtained primarily from the *Annual Energy Review* and other EIA databases (EIA 2001a). Data on military jet fuel use was supplied by the Office of the Under Secretary of Defense (Environmental Security) and the Defense Energy Support Center (Defense Logistics Agency) of the U.S. Department of Defense (DoD) (DESC 2001). Estimates of international bunker fuel emissions are discussed in the section entitled International Bunker Fuels. Estimates of carbon stored in products are discussed in the section entitled Carbon Stored in Products from Non-fuel Uses of Fossil Fuels.

IPCC provided fraction oxidized values for petroleum and natural gas (IPCC/UNEP/OECD/IEA 1997). Bechtel (1993) provided the fraction oxidation value for coal. Vehicle type fuel consumption data for the allocation of transportation end-use sector emissions were primarily taken from the *Transportation Energy Data Book* prepared by the Center for Transportation Analysis at Oak Ridge National Laboratory (DOE 1993 through 2001). Specific data on military fuel consumption were taken from DESC (2001). Densities for each military jet fuel type were obtained from the Air Force (USAF 1998).

Carbon intensity estimates were developed using nuclear and renewable energy data from EIA (2001a) and fossil fuel consumption data as discussed above and presented in Annex A.

For consistency of reporting, the IPCC has recommended that national inventories report energy data—and emissions from energy—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.[28]

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).[29]

## Uncertainty

For estimates of $CO_2$ from fossil fuel combustion, the amount of $CO_2$ emitted is – in principle – 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.

There are uncertainties, however, 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.

[28] See IPCC Reference Approach for estimating $CO_2$ emissions from fossil fuel combustion in Annex R for a comparison of U.S. estimates using top-down and bottom-up approaches.

[29] 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.

Although statistics of total fossil fuel and other energy consumption are considered to be relatively accurate, the allocation of this consumption to individual end-use sectors (i.e., residential, commercial, industrial, and transportation) is considerably more uncertain. For example, for some fuels the sectoral allocations are based on price rates (i.e., tariffs). However, 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.

Non-energy uses of the fuel can also create situations where the carbon is not emitted to the atmosphere (e.g., plastics, asphalt, etc.) or is emitted at a delayed rate. The proportions of fuels used in these non-energy production processes that result in the sequestration of carbon have been assumed. Additionally, inefficiencies in the combustion process, which can result in ash or soot remaining unoxidized for long periods, were also assumed. These factors all contribute to the uncertainty in the $CO_2$ estimates. More detailed discussions on the uncertainties associated with Carbon Stored in Products from Non-Energy Uses of Fossil Fuels are provided this section in this chapter.

Various uncertainties surround the estimation of emissions from international bunker fuels, which are subtracted from U.S. totals. These uncertainties are primarily due to the difficulty in collecting accurate fuel consumption data for international transport activities. Small aircraft and many marine vessels often carry enough fuel to complete multiple voyages without refueling, which, if used for both domestic and international trips, may be classified as solely international. The data collected for aviation does not include some smaller planes making international voyages, and also designates some flights departing to Canada and Mexico as domestic. More detailed discussions on these uncertainties are 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.

For Table 2-7, uncertainties also exist as to 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 better allocate 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.

For the United States, however, the impact of these uncertainties on overall $CO_2$ emission estimates is believed to be relatively small. For the United States, $CO_2$ emission estimates from fossil fuel combustion are considered accurate within several percent. See, for example, Marland and Pippin (1990).

## Carbon Stored in Products from Non-Energy Uses of Fossil Fuels

Besides being combusted for energy, fossil fuels are also consumed for non-energy purposes. The types of fuels used for non-energy uses are listed in Table 2-11. These fuels are used in the industrial and transportation end-use sectors and are quite diverse, including natural gas, 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 fuel uses are equally diverse, and include application as solvents, lubricants, and waxes, or as raw materials in the manufacture of plastics, rubber, synthetic fibers, and fertilizers.

Carbon dioxide emissions arise from non-energy uses via several pathways. Emissions may occur during the manufacture of a product, as is the case in producing plastics or rubber from fuel-derived feedstocks. Additionally, in the case of solvents or lubricants, for example, emissions may occur during the product's lifetime. Overall, more than 65 percent of the total carbon consumed for non-energy purposes is stored in products, and not released to the atmosphere. However, some of the products release $CO_2$ at the end of their commercial life when they are disposed. These emissions are covered separately in this chapter in the Waste Combustion section.

In 2000, fossil fuel consumption for non-energy uses constituted 6 percent (5,915.6 TBtu) of overall fossil fuel consumption, approximately the same as 1990. In 2000, the carbon contained in fuels consumed for non-energy uses was approximately 410 Tg $CO_2$ Eq., an increase of 28 percent since 1990. About 283 Tg $CO_2$ Eq. of this carbon was stored, while the remaining 126 Tg $CO_2$ Eq. was emitted. The proportion of carbon emitted has remained about the same, at 31 percent of total non-energy consumption, since 1990. Table 2-12 shows the fate of the non-energy fossil fuel carbon for 1990 and 1995 through 2000.

## Methodology

The first step in estimating carbon stored in products was to determine the aggregate quantity of fossil fuels consumed for non-energy uses. The carbon content of these feedstock fuels is equivalent to potential emissions, or the product of consumption and the fuel-specific carbon content values (see Annex A). Consumption of natural gas, LPG, pentanes plus, naphthas, and other oils were adjusted to account for net exports of these products. Approximately 8 percent of the U.S. production of these products is exported. Consumption values

**Table 2-11: 2000 Non-Energy Fossil Fuel Consumption, Storage, and Emissions (Tg $CO_2$ Eq. unless otherwise noted)**

| Sector/Fuel Type | Consumption (TBtu) Total | Consumption (TBtu) Adjusted[a] | Carbon Content | Storage Factor | Carbon Stored | Emissions |
|---|---|---|---|---|---|---|
| **Industry** | **6,675.0** | **5,512.4** | **379.8** | - | **265.6** | **114.2** |
| Industrial Coking Coal | 793.1 | 26.4 | 2.5 | 0.8 | 1.9 | 0.6 |
| Natural Gas to Chemical Plants | 372.3 | 342.4 | 18.2 | 0.6 | 11.5 | 6.7 |
| Asphalt & Road Oil | 1,275.7 | 1,275.7 | 96.4 | 1.0 | 96.4 | - |
| LPG | 1,856.7 | 1,707.3 | 105.6 | 0.6 | 66.8 | 38.8 |
| Lubricants | 189.9 | 189.9 | 14.1 | 0.1 | 1.3 | 12.8 |
| Pentanes Plus | 311.9 | 286.8 | 19.2 | 0.6 | 12.1 | 7.0 |
| Petrochemical Feedstocks | | | | | | |
| Naphtha (<401 deg. F) | 613.5 | 564.2 | 37.5 | 0.6 | 23.7 | 13.8 |
| Other Oil (>401 deg. F) | 722.2 | 664.1 | 48.6 | 0.6 | 30.7 | 17.8 |
| Still Gas | 7.4 | 7.4 | 0.5 | 0.8 | 0.4 | 0.1 |
| Petroleum Coke | 225.5 | 141.4 | 14.4 | 0.5 | 7.2 | 7.2 |
| Special Naphtha | 97.4 | 97.4 | 7.1 | - | - | 7.1 |
| Distillate Fuel Oil | 7.0 | 7.0 | 0.5 | 0.5 | 0.3 | 0.3 |
| Residual Fuel | 50.3 | 50.3 | 4.0 | 0.5 | 2.0 | 2.0 |
| Waxes | 33.1 | 33.1 | 2.4 | 1.0 | 2.4 | - |
| Miscellaneous Products | 119.2 | 119.2 | 8.8 | 1.0 | 8.8 | - |
| **Transportation** | **179.4** | **179.4** | **13.3** | | **1.2** | **12.1** |
| Lubricants | 179.4 | 179.4 | 13.3 | 0.1 | 1.2 | 12.1 |
| **U.S. Territories** | **223.8** | **223.8** | **16.4** | | **16.3** | **0.1** |
| Lubricants | 1.4 | 1.4 | 0.1 | 0.1 | + | 0.1 |
| Other Petroleum (Misc. Prod.) | 222.5 | 222.5 | 16.3 | 1.0 | 16.3 | - |
| **Total** | **7,078.3** | **5,915.6** | **409.6** | - | **283.2** | **126.4** |

[a] Natural gas, LPG, Pentanes Plus, Naphthas, and Other Oils are adjusted to account for exports of chemical intermediates derived from these fuels. To avoid double-counting, coal coke, petroleum coke, and natural gas consumption are adjusted for industrial process consumption addressed in the Industrial Process chapter.
- Not applicable.
Note: Totals may not sum due to independent rounding.

**Table 2-12: Storage and Emissions from Non-Energy Fossil Fuel Consumption (Tg $CO_2$ Eq.)**

| Variable | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Potential Emissions | 319.9 | 362.9 | 371.9 | 388.0 | 402.7 | 428.1 | 409.6 |
| Carbon Stored | 221.0 | 251.1 | 258.2 | 269.8 | 276.7 | 291.6 | 283.2 |
| Emissions | 99.0 | 111.8 | 113.7 | 118.2 | 126.1 | 136.4 | 126.4 |

for industrial coking coal, petroleum coke, and natural gas in Table 2-11 are adjusted to subtract non-energy uses that are addressed in the Industrial Process chapter.[30]

For the remaining non-energy uses, the amount of carbon stored was estimated by multiplying the potential emissions by a storage factor. For several fuel types—asphalt and road oil, lubricants, petrochemical feedstocks, liquid petroleum gases (LPG), pentanes plus, and natural gas for non-fertilizer uses—U.S. data on carbon stocks and flows were used to develop carbon storage factors, calculated as the ratio of (a) the carbon stored by the fuel's non-energy products to (b) the total carbon content of the fuel consumed. A lifecycle approach was used in the development of these factors in order to account for losses in the production process—from raw material acquisition through manufacturing and processing—and during use. Details of these calculations are shown in Annex B. Because losses associated with municipal solid waste management are handled separately in this chapter under Waste Combustion, the storage factors do not account for losses at the disposal end of the life cycle. For the other fuel types, the storage factors were taken directly from Marland and Rotty (1984).

Lastly, emissions were estimated by subtracting the carbon stored from the potential emissions.

## Data Sources

Non-energy fuel consumption and carbon content data were supplied by the EIA (2001a).

Where storage factors were calculated specifically for the United States, data was obtained on fuel products such as asphalt, plastics, synthetic rubber, synthetic fibers, pesticides, and solvents. Data was taken from a variety of industry sources, government reports, and expert communications. Sources include EPA compilations of air emission factors (EPA 1995, EPA 2001), the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 2001b), the National Petrochemical & Refiners Association (NPRA 2001), the National Asphalt Pavement Association (Connolly 2000), the Emissions Inventory Improvement Program (EIIP 1999), the U.S. Census Bureau (1999), the American Plastics Council (APC 2000), the International Institute of Synthetic Rubber Products (IISRP 2000), the Fiber Economics Bureau (FEB 2000), and the Chemical Manufacturer's Handbook (CMA 1999). For the other fuel types, storage factors were taken from Marland and Rotty (1984). Specific data sources are listed in full detail in Annex B.

## Uncertainty

The fuel consumption data for non-energy uses and the carbon content values employed here were taken from the same references as the data used for estimating overall $CO_2$ emissions from fossil fuel combustion. In addition, data used to make adjustments to the fuel consumption estimates were taken from several sources. Given that the uncertainty in these data is expected to be small, the uncertainty of the estimate for the *potential* carbon emissions is also expected to be small. However, there is a large degree of uncertainty in the storage factors employed, depending upon the fuel type. For each of the calculated storage factors, the uncertainty is discussed in detail in Annex B. Generally, uncertainty arises from assumptions made to link fuel types with their derivative products and in determining the fuel products' carbon contents and emission or storage fates. The storage factors from Marland and Rotty (1984) are also highly uncertain.

# Stationary Combustion (excluding $CO_2$)

Stationary combustion encompasses all fuel combustion activities except those related to transportation (i.e., mobile combustion). Other than carbon dioxide ($CO_2$), which was addressed in the previous section, gases from stationary combustion include the greenhouse gases methane ($CH_4$) and nitrous oxide ($N_2O$) and the ambient air pollutants nitrogen oxides ($NO_x$), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs).[31] Emissions of these gases from stationary combustion sources depend upon fuel characteristics, size and vintage to the combustion technology, pollution control equipment, and ambient environmental conditions. Emissions also vary with operation and maintenance practices.

[30] These source categories include Iron and Steel Production, Ammonia Manufacture, Titanium Dioxide Production, Ferroalloy Production, and Aluminum Production.

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

Nitrous oxide and $NO_x$ emissions from stationary combustion are closely related to air-fuel mixes and combustion temperatures, as well as the characteristics of any pollution control equipment that is employed. Carbon monoxide emissions from stationary combustion are generally a function of the efficiency of combustion; they are highest when less oxygen is present in the air-fuel mixture than is necessary for complete combustion. These conditions are most likely to occur during start-up, shutdown and during fuel switching (e.g., the switching of coal grades at a coal-burning electric utility plant). Methane and NMVOC emissions from stationary combustion are primarily a function of the $CH_4$ and NMVOC content of the fuel and combustion efficiency.

Emissions of $CH_4$ decreased 5 percent overall from 7.9 Tg $CO_2$ Eq. (376 Gg) in 1990 to 7.5 Tg $CO_2$ Eq. (357 Gg) in 2000. This decrease in $CH_4$ emissions was primarily due to lower wood consumption in the residential sector. Conversely, nitrous oxide emissions rose 16 percent since 1990 to 14.9 Tg $CO_2$ Eq. (48 Gg) in 2000. The largest source of $N_2O$ emissions was coal combustion by electricity generators, which alone accounted for 60 percent of total $N_2O$ emissions from stationary combustion in 2000. Overall, though, stationary combustion is a small source of $CH_4$ and $N_2O$ in the United States.

In contrast, stationary combustion was a significant source of $NO_x$ emissions, but a smaller source of CO and NMVOCs. In 2000, emissions of $NO_x$ from stationary combustion represented 35 percent of national $NO_x$ emissions, while CO and NMVOC emissions from stationary combustion contributed approximately 4 and 6 percent, respectively, to the national totals. From 1990 to 2000, emissions of $NO_x$ and CO from stationary combustion decreased by 12 and 17 percent, respectively, and emissions of NMVOCs increased by 19 percent.

The decrease in $NO_x$ emissions from 1990 to 2000 are mainly due to decreased emissions from electricity generation. The decrease in CO and increase in NMVOC emissions over this time period can largely be attributed to changes in residential wood consumption, which is the most significant source of these pollutants from stationary combustion. Table 2-13 through Table 2-16 provide $CH_4$ and $N_2O$ emission estimates from stationary combustion by sector and fuel type. Estimates of $NO_x$, CO, and NMVOC emissions in 2000 are given in Table 2-17.[32]

## Methodology

Methane and $N_2O$ emissions were estimated by multiplying emission factors (by sector and fuel type) by fossil fuel and wood consumption data. National coal, natural gas, fuel oil, and wood consumption data were grouped into four sectors—industrial, commercial, residential, and electricity generation.

For $NO_x$, CO, and NMVOCs, the major categories included in this section are those used in EPA (2001): coal, fuel oil, natural gas, wood, other fuels (including LPG, coke, coke oven gas, and others), and stationary internal combustion. The EPA estimates emissions of $NO_x$, CO, and NMVOCs by sector and fuel source using a "bottom-up" estimating procedure. In other words, emissions were calculated either for individual sources (e.g., industrial boilers) or for multiple sources combined, using basic activity data as indicators of emissions. Depending on the source category, these basic activity data may include fuel consumption, fuel deliveries, tons of refuse burned, raw material processed, etc.

The EPA derived the overall emission control efficiency of a source category from published reports, the 1985 National Acid Precipitation and Assessment Program (NAPAP) emissions inventory, and other EPA databases. The U.S. approach for estimating emissions of $NO_x$, CO, and NMVOCs from stationary combustion, as described above, is consistent with the methodology recommended by the IPCC (IPCC/UNEP/OECD/IEA 1997).

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

## Data Sources

Emissions estimates for $NO_x$, CO, and NMVOCs in this section were taken directly from unpublished EPA data (2001). Fuel consumption data for $CH_4$ and $N_2O$ estimates were provided by the U.S. Energy Information Administration's *Annual Energy Review* (EIA 2001). 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 were provided by the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997).

[32] See Annex C for a complete time series of ambient air pollutant emission estimates for 1990 through 2000.

## Table 2-13: $CH_4$ Emissions from Stationary Combustion (Tg $CO_2$ Eq.)

| Sector/Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Electricity Generation** | **0.5** | **0.5** | **0.5** | **0.6** | **0.6** | **0.6** | **0.6** |
| Coal | 0.3 | 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 |
| Wood | + | + | + | + | + | + | + |
| **Industrial** | **2.1** | **2.3** | **2.3** | **2.4** | **2.3** | **2.4** | **2.3** |
| Coal | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 |
| Fuel Oil | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Natural gas | 0.7 | 0.8 | 0.8 | 0.8 | 0.7 | 0.7 | 0.7 |
| Wood | 0.8 | 0.8 | 0.8 | 0.9 | 0.9 | 1.0 | 1.0 |
| **Commercial** | **0.7** | **0.7** | **0.8** | **0.8** | **0.7** | **0.8** | **0.8** |
| Coal | + | + | + | + | + | + | + |
| Fuel Oil | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.2 |
| Natural gas | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Wood | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| **Residential** | **4.6** | **4.7** | **4.7** | **3.8** | **3.3** | **3.6** | **3.7** |
| Coal | 0.4 | 0.3 | 0.3 | 0.4 | 0.3 | 0.3 | 0.3 |
| Fuel Oil | 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 |
| Wood | 3.5 | 3.6 | 3.6 | 2.6 | 2.3 | 2.5 | 2.6 |
| **Total** | **7.9** | **8.2** | **8.4** | **7.5** | **7.0** | **7.3** | **7.5** |

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

## Table 2-14: $N_2O$ Emissions from Stationary Combustion (Tg $CO_2$ Eq.)

| Sector/Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Electricity Generation** | **7.6** | **8.0** | **8.4** | **8.7** | **8.9** | **8.9** | **9.3** |
| Coal | 7.2 | 7.7 | 8.1 | 8.3 | 8.5 | 8.5 | 8.9 |
| Fuel Oil | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.2 |
| Natural Gas | 0.1 | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 |
| Wood | + | + | + | + | + | + | + |
| **Industrial** | **3.8** | **4.1** | **4.2** | **4.3** | **4.3** | **4.4** | **4.3** |
| Coal | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.5 |
| Fuel Oil | 1.5 | 1.6 | 1.7 | 1.7 | 1.7 | 1.7 | 1.6 |
| Natural Gas | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Wood | 1.5 | 1.7 | 1.7 | 1.8 | 1.8 | 2.0 | 2.0 |
| **Commercial** | **0.3** | **0.3** | **0.3** | **0.3** | **0.3** | **0.3** | **0.3** |
| Coal | + | + | + | + | + | + | + |
| Fuel Oil | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Natural Gas | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Wood | + | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Residential** | **1.1** | **1.1** | **1.2** | **1.0** | **0.9** | **0.9** | **1.0** |
| Coal | + | + | + | + | + | + | + |
| Fuel Oil | 0.2 | 0.3 | 0.3 | 0.3 | 0.2 | 0.3 | 0.3 |
| Natural Gas | 0.1 | 0.1 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 |
| Wood | 0.7 | 0.7 | 0.7 | 0.5 | 0.5 | 0.5 | 0.5 |
| **Total** | **12.8** | **13.5** | **14.1** | **14.2** | **14.3** | **14.6** | **14.9** |

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

## Table 2-15: $CH_4$ Emissions from Stationary Combustion (Gg)

| Sector/Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Electricity Generation** | **24** | **25** | **26** | **27** | **29** | **29** | **30** |
| Coal | 17 | 18 | 19 | 19 | 19 | 20 | 21 |
| Fuel Oil | 4 | 2 | 3 | 3 | 4 | 4 | 4 |
| Natural Gas | 4 | 5 | 5 | 5 | 5 | 6 | 6 |
| Wood | + | + | + | + | + | + | + |
| **Industrial** | **100** | **108** | **111** | **113** | **110** | **114** | **111** |
| Coal | 15 | 14 | 14 | 14 | 13 | 13 | 11 |
| Fuel Oil | 16 | 17 | 18 | 18 | 18 | 18 | 17 |
| Natural Gas | 33 | 37 | 38 | 38 | 35 | 35 | 34 |
| Wood | 36 | 40 | 41 | 43 | 45 | 49 | 48 |
| **Commercial** | **33** | **36** | **38** | **37** | **35** | **37** | **39** |
| Coal | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Fuel Oil | 9 | 7 | 7 | 7 | 7 | 7 | 7 |
| Natural Gas | 13 | 15 | 15 | 16 | 15 | 15 | 16 |
| Wood | 11 | 13 | 14 | 13 | 13 | 15 | 15 |
| **Residential** | **218** | **223** | **226** | **179** | **159** | **170** | **177** |
| Coal | 19 | 16 | 16 | 17 | 13 | 14 | 14 |
| Fuel Oil | 13 | 14 | 15 | 14 | 13 | 15 | 15 |
| Natural Gas | 21 | 24 | 26 | 24 | 22 | 23 | 24 |
| Wood | 166 | 170 | 170 | 123 | 110 | 118 | 123 |
| **Total** | **376** | **392** | **400** | **356** | **334** | **350** | **357** |

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

## Table 2-16: $N_2O$ Emissions from Stationary Combustion (Gg)

| Sector/Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Electricity Generation** | **24** | **26** | **27** | **28** | **29** | **29** | **30** |
| Coal | 23 | 25 | 26 | 27 | 27 | 27 | 29 |
| Fuel Oil | 1 | + | + | 1 | 1 | 1 | 1 |
| Natural Gas | + | + | + | + | 1 | 1 | 1 |
| Wood | + | + | + | + | + | + | + |
| **Industrial** | **12** | **13** | **13** | **14** | **14** | **14** | **14** |
| Coal | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Fuel Oil | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Natural Gas | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Wood | 5 | 5 | 5 | 6 | 6 | 7 | 6 |
| **Commercial** | **1** | **1** | **1** | **1** | **1** | **1** | **1** |
| Coal | + | + | + | + | + | + | + |
| Fuel Oil | 1 | + | + | + | + | + | + |
| Natural Gas | + | + | + | + | + | + | + |
| Wood | + | + | + | + | + | + | + |
| **Residential** | **3** | **4** | **4** | **3** | **3** | **3** | **3** |
| Coal | + | + | + | + | + | + | + |
| Fuel Oil | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Natural Gas | + | + | 1 | + | + | + | + |
| Wood | 2 | 2 | 2 | 2 | 1 | 2 | 2 |
| **Total** | **41** | **43** | **45** | **46** | **46** | **47** | **48** |

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

**Table 2-17: $NO_x$, CO, and NMVOC Emissions from Stationary Combustion in 2000 (Gg)**

| Sector/Fuel Type | $NO_x$ | CO | NMVOC |
|---|---|---|---|
| **Electricity Generation** | **4,763** | **380** | **51** |
| Coal | 4,149 | 212 | 27 |
| Fuel Oil | 140 | 16 | 4 |
| Natural Gas | 320 | 95 | 10 |
| Internal Combustion | 154 | 56 | 10 |
| **Industrial** | **2,924** | **1,108** | **169** |
| Coal | 493 | 100 | 6 |
| Fuel Oil | 207 | 50 | 8 |
| Natural Gas | 1,137 | 327 | 57 |
| Other Fuels[a] | 112 | 322 | 34 |
| Internal Combustion | 976 | 308 | 64 |
| **Commercial** | **376** | **137** | **26** |
| Coal | 34 | 14 | 1 |
| Fuel Oil | 73 | 15 | 3 |
| Natural Gas | 244 | 63 | 14 |
| Other Fuels[a] | 26 | 46 | 9 |
| **Residential** | **677** | **2,515** | **843** |
| Wood | 30 | 2,292 | 812 |
| Other Fuels[b] | 647 | 223 | 31 |
| **Total** | **8,740** | **4,140** | **1,089** |

NA (Not Available)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2001).
[b] "Other Fuels" include LPG, waste oil, coke oven gas, and coke (EPA 2001).
Note: Totals may not sum due to independent rounding. See Annex C for emissions in 1990 through 2000.

## Uncertainty

Methane emission estimates from stationary sources are highly uncertain, 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). The uncertainties associated with the emission estimates of these gases are greater than 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 ambient air pollutants, uncertainties are partly due to assumptions concerning combustion technology types, age of equipment, emission factors used, and activity data projections.

# Mobile Combustion (excluding $CO_2$)

Mobile combustion emits greenhouse gases other than $CO_2$, including methane ($CH_4$), nitrous oxide ($N_2O$), and the ambient air pollutants carbon monoxide (CO), nitrogen oxides ($NO_x$), and non-methane volatile organic compounds (NMVOCs). As with stationary combustion, $N_2O$ and $NO_x$ emissions are closely related to fuel characteristics, air-fuel mixes, combustion temperatures, as well as usage of pollution control equipment. Nitrous oxide, 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 presence of post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. These emissions occur especially in idle, low speed and cold start conditions. Methane and NMVOC emissions from motor vehicles are a function of the $CH_4$ content of the motor fuel, the amount of hydrocarbons passing uncombusted through the engine, and any post-combustion control of hydrocarbon emissions, such as catalytic converters.

Emissions from mobile combustion were estimated by transport mode (e.g., highway, air, rail, and water) and fuel type—motor gasoline, diesel fuel, jet fuel, aviation gas, natural gas, liquefied petroleum gas (LPG), and residual fuel oil—and vehicle type. Road transport accounted for the majority of mobile source fuel consumption, and hence, the majority of mobile combustion emissions. Table 2-18 through Table 2-21 provide $CH_4$ and $N_2O$ emission estimates from mobile combustion by vehicle type, fuel type, and transport mode. Estimates of $NO_x$, CO, and NMVOC emissions in 2000 are given in Table 2-22.[33]

Mobile combustion was responsible for a small portion of national $CH_4$ emissions but was the second largest source of $N_2O$ in the United States. From 1990 to 2000, $CH_4$ emissions declined by 11 percent, to 4.4 Tg $CO_2$ Eq. (208 Gg). Nitrous oxide emissions, however, rose 14 percent to 58.3 Tg $CO_2$ Eq. (188 Gg) (see Figure 2-19). The reason for this conflicting trend was that the control technologies employed on highway vehicles in the United States lowered CO, $NO_x$, NMVOC, and $CH_4$ emissions, but resulted in higher average

[33] See Annex D for a complete time series of emission estimates for 1990 through 2000.

## Table 2-18: $CH_4$ Emissions from Mobile Combustion (Tg $CO_2$ Eq.)

| Fuel Type/Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Gasoline Highway** | **4.2** | **4.1** | **3.9** | **3.8** | **3.8** | **3.7** | **3.6** |
| Passenger Cars | 2.4 | 2.0 | 2.0 | 1.9 | 1.9 | 1.9 | 1.9 |
| Light-Duty Trucks | 1.6 | 1.8 | 1.7 | 1.7 | 1.6 | 1.6 | 1.5 |
| Heavy-Duty Vehicles | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Motorcycles | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Diesel Highway** | **0.2** | **0.3** | **0.3** | **0.3** | **0.3** | **0.3** | **0.3** |
| Passenger Cars | + | + | + | + | + | + | + |
| Light-Duty Trucks | + | + | + | + | + | + | + |
| Heavy-Duty Vehicles | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| **Non-Highway** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.5** |
| Ships and Boats | 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 |
| Farm Equipment | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Construction Equipment | + | + | + | + | + | + | + |
| Aircraft | 0.2 | 0.1 | 0.1 | 0.2 | 0.1 | 0.2 | 0.2 |
| Other* | + | + | + | + | + | + | + |
| **Total** | **4.9** | **4.8** | **4.7** | **4.6** | **4.5** | **4.4** | **4.4** |

+ Does not exceed 0.05 Tg $CO_2$ Eq.
Note: Totals may not sum due to independent rounding.
* "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

## Table 2-19: $N_2O$ Emissions from Mobile Combustion (Tg $CO_2$ Eq.)

| Fuel Type/Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Gasoline Highway** | **46.0** | **54.9** | **54.4** | **54.0** | **53.4** | **52.7** | **51.9** |
| Passenger Cars | 31.0 | 33.1 | 32.7 | 32.2 | 32.0 | 31.2 | 30.6 |
| Light-Duty Trucks | 14.2 | 20.8 | 20.7 | 20.7 | 20.3 | 20.4 | 20.1 |
| Heavy-Duty Vehicles | 0.7 | 1.0 | 1.0 | 1.0 | 1.1 | 1.1 | 1.1 |
| Motorcycles | + | + | + | + | + | + | + |
| **Diesel Highway** | **2.1** | **2.6** | **2.7** | **2.8** | **2.9** | **3.0** | **3.1** |
| Passenger Cars | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | + | + |
| Light-Duty Trucks | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 |
| Heavy-Duty Vehicles | 1.8 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.7 |
| **Non-Highway** | **2.9** | **3.0** | **3.0** | **2.9** | **2.8** | **3.0** | **3.4** |
| Ships and Boats | 0.4 | 0.5 | 0.4 | 0.3 | 0.3 | 0.4 | 0.6 |
| Locomotives | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| Farm Equipment | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Construction Equipment | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.1 | 0.2 |
| Aircraft | 1.7 | 1.7 | 1.8 | 1.7 | 1.8 | 1.8 | 1.9 |
| Other* | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Total** | **50.9** | **60.4** | **60.1** | **59.7** | **59.1** | **58.7** | **58.3** |

+ Does not exceed 0.05 Tg $CO_2$ Eq.
Note: Totals may not sum due to independent rounding.
* "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

## Table 2-20: $CH_4$ Emissions from Mobile Combustion (Gg)

| Fuel Type/Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Gasoline Highway** | **202** | **193** | **188** | **183** | **179** | **175** | **171** |
| Passenger Cars | 115 | 96 | 94 | 93 | 93 | 91 | 90 |
| Light-Duty Trucks | 74 | 86 | 83 | 81 | 77 | 75 | 72 |
| Heavy-Duty Vehicles | 9 | 7 | 6 | 6 | 6 | 6 | 6 |
| Motorcycles | 4 | 4 | 4 | 3 | 3 | 3 | 3 |
| **Diesel Highway** | **11** | **13** | **13** | **14** | **14** | **14** | **14** |
| Passenger Cars | + | + | + | + | + | + | + |
| Light-Duty Trucks | + | + | + | + | + | + | + |
| Heavy-Duty Vehicles | 10 | 13 | 13 | 13 | 13 | 13 | 13 |
| **Non-Highway** | **21** | **21** | **21** | **20** | **19** | **20** | **23** |
| Ships and Boats | 3 | 4 | 4 | 3 | 2 | 4 | 6 |
| Locomotives | 3 | 3 | 3 | 2 | 2 | 2 | 2 |
| Farm Equipment | 6 | 6 | 6 | 6 | 5 | 5 | 5 |
| Construction Equipment | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Aircraft | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Other* | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Total** | **233** | **228** | **222** | **217** | **212** | **209** | **208** |

+ Does not exceed 0.5 Gg
Note: Totals may not sum due to independent rounding.
* "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

## Table 2-21: $N_2O$ Emissions from Mobile Combustion (Gg)

| Fuel Type/Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Gasoline Highway** | **148** | **177** | **176** | **174** | **172** | **170** | **167** |
| Passenger Cars | 100 | 107 | 105 | 104 | 103 | 101 | 99 |
| Light-Duty Trucks | 46 | 67 | 67 | 67 | 66 | 66 | 65 |
| Heavy-Duty Vehicles | 2 | 3 | 3 | 3 | 3 | 4 | 3 |
| Motorcycles | + | + | + | + | + | + | + |
| **Diesel Highway** | **7** | **8** | **9** | **9** | **9** | **10** | **10** |
| Passenger Cars | + | + | + | + | + | + | + |
| Light-Duty Trucks | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Heavy-Duty Vehicles | 6 | 7 | 8 | 8 | 8 | 9 | 9 |
| **Non-Highway** | **9** | **10** | **10** | **9** | **9** | **10** | **11** |
| Ships and Boats | 1 | 1 | 1 | 1 | 1 | 1 | 2 |
| Locomotives | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Farm Equipment | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Construction Equipment | + | + | + | + | + | + | 1 |
| Aircraft | 6 | 5 | 6 | 6 | 6 | 6 | 6 |
| Other* | + | + | + | + | + | + | + |
| **Total** | **164** | **195** | **194** | **192** | **191** | **189** | **188** |

+ Does not exceed 0.5 Gg
Note: Totals may not sum due to independent rounding.
* "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

**Table 2-22: $NO_x$, CO, and NMVOC Emissions from Mobile Combustion in 2000 (Gg)**

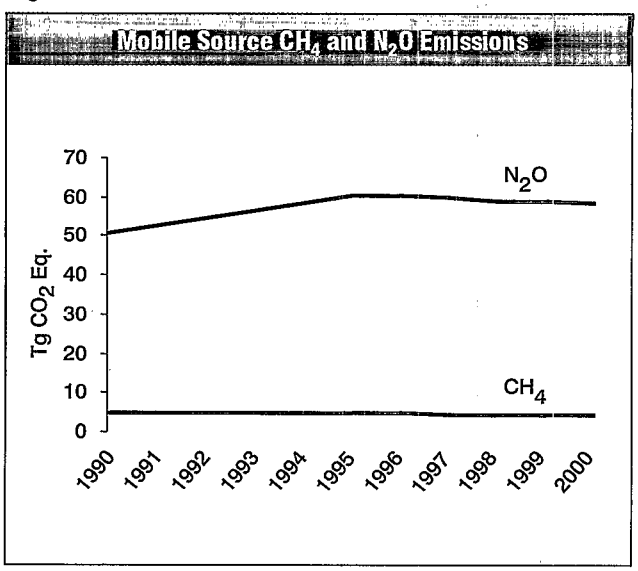
| Fuel Type/Vehicle Type | $NO_x$ | CO | NMVOCs |
|---|---|---|---|
| **Gasoline Highway** | **4,388** | **41,944** | **4,333** |
| Passenger Cars | 2,519 | 24,058 | 2,500 |
| Light-Duty Trucks | 1,459 | 14,367 | 1,501 |
| Heavy-Duty Vehicles | 398 | 3,338 | 293 |
| Motorcycles | 12 | 181 | 38 |
| **Diesel Highway** | **3,004** | **2,026** | **236** |
| Passenger Cars | 6 | 5 | 2 |
| Light-Duty Trucks | 4 | 4 | 2 |
| Heavy-Duty Vehicles | 2,994 | 2,017 | 232 |
| **Non-Highway** | **7,549** | **25,326** | **3,069** |
| Ships and Boats | 1,041 | 2,070 | 833 |
| Locomotives | 704 | 70 | 27 |
| Farm Equipment | 815 | 465 | 93 |
| Construction Equipment | 1,114 | 1,290 | 199 |
| Aircraft[a] | 76 | 331 | 26 |
| Other[b] | 3,799 | 21,100 | 1,891 |
| **Total** | **14,941** | **69,296** | **7,638** |

[a] Aircraft estimates include only emissions related to landing and take-off (LTO) cycles, and therefore do not include cruise altitude emissions.
[b] "Other" includes gasoline powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel powered recreational, industrial, lawn and garden, light construction, airport service.
Note: Totals may not sum due to independent rounding. See Annex D for emissions from 1990 through 2000.

$N_2O$ emission rates. Fortunately, since 1994 improvements in the emission control technologies installed on new vehicles have reduced emission rates of both $NO_x$ and $N_2O$ per vehicle mile traveled. Overall, $CH_4$ and $N_2O$ emissions were predominantly from gasoline-fueled passenger cars and light-duty gasoline trucks.

Fossil-fueled motor vehicles comprise the single largest source of CO emissions in the United States and are a significant contributor to $NO_x$ and NMVOC emissions. In 2000, mobile combustion contributed to 74 percent of national CO emissions and 60 and 43 percent of $NO_x$ and NMVOC emissions, respectively. Since 1990, emissions of

Figure 2-19




NMVOCs from mobile combustion decreased by 6 percent, while emissions of $NO_x$ increased by 37 percent. Carbon monoxide emissions remained unchanged.

## Methodology

Estimates for $CH_4$ and $N_2O$ emissions from mobile combustion were calculated by multiplying emission factors by measures of activity for each category. Depending upon the category, activity data included such information as fuel consumption, fuel deliveries, and vehicle miles traveled (VMT). Emission estimates from highway vehicles were based on VMT and emission factors by vehicle type, fuel type, model year, and control technology. Fuel consumption data were employed as a measure of activity for non-highway vehicles and then fuel-specific emission factors were applied.[34] A complete discussion of the methodology used to estimate emissions from mobile combustion is provided in Annex D.

EPA (2001) provided emissions estimates of $NO_x$, CO, and NMVOCs for eight categories of highway vehicles,[35] aircraft, and seven categories of off-highway vehicles.[36]

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

[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: gasoline and diesel farm tractors, other gasoline and diesel farm machinery, gasoline and diesel construction equipment, snowmobiles, small gasoline utility engines, and heavy-duty gasoline and diesel general utility engines.

## Data Sources

Emission factors used in the calculations of $CH_4$ and $N_2O$ emissions are presented in Annex D. The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) provided emission factors for $CH_4$, and were developed using MOBILE5a, a model used by the Environmental Protection Agency (EPA) to estimate exhaust and running loss emissions from highway vehicles. The MOBILE5a model uses information on ambient temperature, vehicle speeds, national vehicle registration distributions, gasoline volatility, and other variables in order to produce these factors (EPA 1997).

Emission factors for $N_2O$ from gasoline passenger cars are from EPA (1998). This report contains emission factors for older passenger cars—roughly pre-1992 in California and pre-1994 in the rest of the United States—from published references, and for newer cars from a recent testing program at EPA's National Vehicle and Fuel Emissions Laboratory (NVFEL). These emission factors for gasoline highway vehicles are lower than the U.S. default values in the *Revised 1996 IPCC Guidelines*, but are higher than the European default values, both of which were published before the more recent tests and literature review conducted by the NVFEL. The U.S. default values in the *Revised 1996 IPCC Guidelines* were based on three studies that tested a total of five cars using European rather than U.S. test protocols. More details may be found in EPA (1998).

Nitrous oxide emission factors for gasoline vehicles other than passenger cars (i.e., light-duty gasoline trucks, heavy-duty gasoline vehicles, and motorcycles) were scaled from $N_2O$ factors from passenger cars with the same control technology, based on their relative fuel economy. Fuel economy for each vehicle category was derived from data in DOE (1993 through 2001), (FHWA 1996 through 2001), (EPA, DOE 2001), and (Census 1997). This scaling was supported by limited data showing that light-duty trucks emit more $N_2O$ than passenger cars with equivalent control technology. The use of fuel consumption ratios to determine emission factors is considered a temporary measure only, and will be replaced as additional testing data become available.

Nitrous oxide emission factors for diesel highway vehicles were taken from the European default values found in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Little data exists addressing $N_2O$ emissions from U.S. diesel-fueled vehicles, and in general, European countries have had more experience with diesel-fueled vehicles. U.S. default values in the *Revised 1996 IPCC Guidelines* were used for non-highway vehicles.

Activity data were gathered from several U.S. government sources including BEA (1991 through 2001), Census (1997), DESC (2001), DOC (1991 through 2001), DOT (1991 through 2001), EIA (2001a), EIA (1991-2001), EIA (2001c), EIA (2001e), EPA/DOE (2001), FAA (1995 through 2001), and FHWA (1996 through 20001). Control technology and standards data for highway vehicles were obtained from the EPA's Office of Transportation and Air Quality (EPA 1997 and 2000). These technologies and standards are defined in Annex D, and were compiled from EPA (1993), EPA (1994a), EPA (1994b), EPA (1998), EPA (1999), and IPCC/UNEP/OECD/IEA (1997). Annual VMT data for 1990 through 2000 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in *Highway Statistics* (FHWA 1996 through 20001).

Emissions estimates for $NO_x$, CO, NMVOCs were taken directly from the EPA (2001).

## Uncertainty

Mobile combustion emissions from each vehicle mile traveled can vary significantly due to assumptions concerning fuel type and composition, technology type, average speeds, type of emission control equipment, equipment age, and operating and maintenance practices. Fortunately, detailed activity data for mobile combustion were available, including VMT by vehicle type for highway vehicles. The allocation of this VMT to individual model years was done using temporally variable profiles of both vehicle usage by age and vehicle usage by model year in the United States. Data for these profiles were provided by EPA (2000).

Average emission factors were developed based on numerous assumptions concerning the age and model of vehicle; percent driving in cold start, warm start, and cruise conditions; average driving speed; ambient temperature; and maintenance practices. The factors for regulated emissions from mobile combustion (i.e., CO, $NO_x$, and hydrocarbons) have been extensively researched, and thus involve lower uncertainty than emissions of unregulated gases. Although $CH_4$ has not been singled out for regulation

in the United States, overall hydrocarbon emissions from mobile combustion—a component of which is methane—are regulated.

In calculating $CH_4$ and $N_2O$ emissions from highway vehicles, only data for Low Emission Vehicles (LEVs) in California has been obtained. Data on the number of LEVs in the rest of the United States will be researched and may be included in future inventories.

Compared to $CH_4$, CO, $NO_x$, and NMVOCs, there is relatively little data available to estimate emission factors for $N_2O$. Nitrous oxide is not a regulated air pollutant, and measurements of it in automobile exhaust have not been routinely collected. Research data has shown that $N_2O$ emissions from vehicles with catalytic converters are greater than those without emission controls, and vehicles with aged catalysts emit more than new vehicles. The emission factors used were, therefore, derived from aged cars (EPA 1998). The emission factors used for Tier 0 and older cars were based on tests of 28 vehicles; those for newer vehicles were based on tests of 22 vehicles. This sample is small considering that it is being used to characterize the entire U.S. fleet, and the associated uncertainty is therefore large. Currently, $N_2O$ gasoline highway emission factors for vehicles other than passenger cars are scaled based on those for passenger cars and their relative fuel economy. Actual measurements should be substituted for this procedure when they become available. Further testing is needed to reduce the uncertainty in emission factors for all classes of vehicles, using realistic driving regimes, environmental conditions, and fuels.

Overall, uncertainty for $N_2O$ emissions estimates is considerably higher than for $CH_4$, CO, $NO_x$, or NMVOC; however, all these gases involve far more uncertainty than $CO_2$ emissions from fossil fuel combustion.

U.S. jet fuel and aviation gasoline consumption is currently all attributed to the transportation sector by EIA, and it is assumed that it is all used to fuel aircraft. However, some fuel purchased by airlines is not necessarily used in aircraft, but instead used to power auxiliary power units, in 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. While some evidence exists that fuel emissions in cruise conditions may actually destroy $CH_4$, the average emission factor used does not take this into account.

Lastly, in EPA (2000b), U.S. aircraft emission estimates for CO, NOx, and NMVOCs are based upon landing and take-off (LTO) cycles and, consequently, only estimate near ground-level emissions, which are more relevant for air quality evaluations. These estimates also include both domestic and international flights. Therefore, estimates presented here overestimate IPCC-defined domestic CO, $NO_x$, and NMVOC emissions by including LTO cycles by aircraft on international flights but underestimate total emissions because they exclude emissions from aircraft on domestic flight segments at cruising altitudes.

## Coal Mining

All underground and surface coal mining liberates methane as part of the normal mining operations. The amount of methane liberated depends upon the amount that remains in the coal ("*in situ*") and surrounding strata when mining occurs. The in-situ methane content depends upon the amount of methane created during the coal formation (i.e., coalification) process, and the geologic characteristics of the coal seams. During coalification, deeper deposits tend to generate more methane and retain more of the gas afterwards. Accordingly, deep underground coal seams generally have higher methane contents than shallow coal seams or surface deposits.

Three types of coal mining related activities release methane to the atmosphere: underground mining, surface mining, and post-mining (i.e. coal-handling) activities. Underground coal mines contribute the largest share of methane emissions. All underground coal mines employ ventilation systems to ensure that methane levels remain within safe concentrations. These systems can exhaust significant amounts of methane to the atmosphere in low concentrations. Additionally, seventeen 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 methane before, during or after mining. In 2000, ten coal mines collected methane from degasification systems and sold this gas to a pipeline, thus reducing emissions to the atmosphere. Surface coal mines also release methane as the overburden is removed and the coal is exposed; however, the level of emissions is much lower than from underground mines. Finally, some of the methane retained in the coal after mining is released during processing, storage, and transport of the coal.

Total methane emissions in 2000 were estimated to be 61.0 Tg $CO_2$ Eq. (2,903 Gg), declining 30 percent since 1990 (see Table 2-23 and Table 2-24). Of this amount, underground mines accounted for 65 percent, surface mines accounted for 14 percent, and post-mining emissions accounted for 21 percent. With the exception of 1994 and 1995, total methane emissions declined in each successive year during this period. In 1993, methane generated from underground mining dropped, primarily due to labor strikes at many large underground mines. In 1995, there was an increase in methane emissions from underground mining due to significantly increased emissions at the highest-emitting coal mine in the country. The decline in methane emissions from underground mines in 2000 is the result of a decrease in coal production, the mining of less gassy coal, and an increase in methane recovered and used. Surface mine emissions and post-mining emissions remained relatively constant from 1990 to 2000.

## Methodology

The methodology for estimating methane emissions from coal mining consists of two parts. The first part involves estimating methane 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

**Table 2-23: $CH_4$ Emissions from Coal Mining (Tg $CO_2$ Eq.)**

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Underground Mining | 62.1 | 51.2 | 45.3 | 44.3 | 44.4 | 41.6 | 39.4 |
| Liberated | 67.6 | 63.3 | 59.8 | 55.7 | 58.6 | 54.4 | 54.1 |
| Recovered & Used | (5.6) | (12.0) | (14.5) | (11.4) | (14.2) | (12.7) | (14.7) |
| Surface Mining | 10.2 | 8.9 | 9.2 | 9.5 | 9.4 | 8.9 | 8.8 |
| Post-Mining (Underground) | 13.1 | 11.9 | 12.4 | 12.8 | 12.6 | 11.7 | 11.3 |
| Post-Mining (Surface) | 1.7 | 1.5 | 1.5 | 1.5 | 1.5 | 1.4 | 1.4 |
| **Total** | **87.1** | **73.5** | **68.4** | **68.1** | **67.9** | **63.7** | **61.0** |

Note: Totals may not sum due to independent rounding.

**Table 2-24: $CH_4$ Emissions from Coal Mining (Gg)**

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Underground Mining | 2,956 | 2,439 | 2,158 | 2,111 | 2,117 | 1,982 | 1,877 |
| Liberated | 3,220 | 3,012 | 2,850 | 2,654 | 2,791 | 2,589 | 2,575 |
| Recovered & Used | (265) | (574) | (692) | (543) | (674) | (607) | (698) |
| Surface Mining | 488 | 425 | 436 | 451 | 446 | 424 | 420 |
| Post-Mining (Underground) | 626 | 569 | 590 | 609 | 600 | 557 | 538 |
| Post-Mining (Surface) | 79 | 69 | 71 | 73 | 72 | 69 | 68 |
| **Total** | **4,149** | **3,502** | **3,255** | **3,244** | **3,235** | **3,033** | **2,903** |

Note: Totals may not sum due to independent rounding.

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 emissions factors.

*Underground mines.* Total methane emitted from underground mines was estimated as the sum of methane liberated from ventilation systems, plus methane liberated by means of degasification systems, minus methane recovered and used. The Mine Safety and Heath Administration (MSHA) samples methane emissions from ventilation systems for all mines with detectable[37] methane concentrations. These mine-by-mine measurements are used to estimate methane emissions from ventilation systems.

Some of the higher-emitting underground mines also use degasification systems (e.g., wells or boreholes) that remove methane before, during, or after mining. This methane can then be collected for use or vented to the atmosphere. Various approaches were employed to estimate the quantity of methane collected by each of the seventeen mines using these systems, depending on available data. For example, some mines report to EPA the amounts of methane liberated from their degasification systems. For mines that sell recovered methane to a pipeline, pipeline sales data 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 methane recovered by degasification systems and then used (i.e., not vented) was estimated. This calculation was complicated by the fact that most methane is not recovered and used during the same year in which the particular coal seam is mined. In 2000, ten active coal mines sold recovered methane into the local gas pipeline networks. Emissions avoided for these projects were estimated using gas sales data reported by various State agencies. For most mines with recovery systems, companies and state agencies provided individual well production information, which was used to assign gas sales to a particular year. For the few remaining mines, coal mine operators supplied information regarding the number of years in advance of mining that gas recovery occurs.

*Surface Mines and Post-Mining Emissions.* Surface mining and post-mining methane emissions were estimated by multiplying basin-specific coal production by basin-specific emissions factors. Surface mining emissions factors were developed by assuming that surface mines emit two times as much methane as the average *in situ* methane content of the coal. This accounts for methane 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* methane content of coals mined in the basin.

## Data Sources

The Mine Safety and Health Administration provided mine-specific information on methane liberated from ventilation systems at underground mines. The primary sources of data for estimating emissions avoided at underground mines were gas sales data published by State petroleum and natural gas agencies, information supplied by mine operators regarding the number of years in advance of mining that gas recovery occurred, and reports of gas used on-site. Annual coal production data were taken from the Energy Information Administration's *Coal Industry Annual* (see Table 2-25) (EIA 2000). Data on *in situ* methane content and emissions factors are taken from EPA (1990).

## Uncertainty

The emission estimates from underground ventilation systems were based upon actual measurement data, which are believed to have relatively low uncertainty. A degree of imprecision was introduced because the measurements were not continuous but rather an average of quarterly instantaneous readings. Additionally, the measurement equipment used possibly resulted in an average of ten percent overestimation of annual methane emissions (Mutmansky and Wang 2000). Estimates of methane liberated and recovered by degasification systems are also 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. A level of uncertainty currently

[37] MSHA records coal mine methane readings with concentrations of greater than 50 ppm (parts per million) methane. Readings below this threshold are considered non-detectable.

exists concerning the radius of influence of each well. The number of wells counted, and thus the avoided emissions, may increase if the drainage area is found to be larger than currently estimated. EPA is currently working to determine the proper drainage radius and may include additional mines in the recovery estimate in the future. Compared to underground mines, there is considerably more uncertainty associated with surface mining and post-mining emissions because of the difficulty in developing accurate emissions factors from field measurements. The EPA plans to update the basin-specific surface mining emission factors. Additionally, EPA plans to re-evaluate the post-mining emission factors for the impact of methane not released before combustion. Because underground emissions comprise the majority of total coal mining emissions, the overall uncertainty is preliminarily estimated to be roughly ±15 percent. Currently, the estimate does not include emissions from abandoned coal mines because of limited data. The EPA is conducting research on the feasibility of including an estimate in future years.

## Natural Gas Systems

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 116.4 Tg $CO_2$ Eq. (5,541 Gg) of methane in 2000, a slight decrease over emissions in 1990 (see Table 2-26 and Table 2-27).

**Table 2-25: Coal Production (Thousand Metric Tons)**

| Year | Underground | Surface | Total |
|---|---|---|---|
| 1990 | 384,250 | 546,818 | 931,068 |
| 1991 | 368,635 | 532,656 | 901,291 |
| 1992 | 368,627 | 534,290 | 902,917 |
| 1993 | 318,478 | 539,214 | 857,692 |
| 1994 | 362,065 | 575,529 | 937,594 |
| 1995 | 359,477 | 577,638 | 937,115 |
| 1996 | 371,816 | 593,315 | 965,131 |
| 1997 | 381,620 | 607,163 | 988,783 |
| 1998 | 378,964 | 634,864 | 1,013,828 |
| 1999 | 355,433 | 642,877 | 998,310 |
| 2000[38] | 338,173 | 635,592 | 973,765 |

Improvements in management practices and technology, along with the normal replacement of older equipment, have helped to stabilize emissions.

Methane 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 combusting engine and turbine 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 methane 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 emissions. Emissions from field production accounted for approximately 25 percent of methane emissions from natural gas systems between 1990 and 2000.

*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 emissions from compressors, including compressor seals, are the primary emission source from this stage. Processing plants account for about 12 percent of methane 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 emissions from these compressor stations and from metering and regulating stations account for

[38] The EIA Coalndustry Annual 2000 was not yet available; however, EIA provided preliminary production statistics from MSHA (EIA 2001).

**Table 2-26: $CH_4$ Emissions from Natural Gas Systems (Tg $CO_2$ Eq.)**

| Stage | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Field Production | 29.6 | 31.0 | 30.9 | 29.5 | 31.7 | 28.3 | 26.2 |
| Processing | 14.7 | 15.0 | 14.9 | 14.9 | 14.6 | 14.5 | 14.8 |
| Transmission and Storage | 46.7 | 46.7 | 47.1 | 46.2 | 45.1 | 44.1 | 43.3 |
| Distribution | 30.2 | 33.0 | 33.6 | 32.1 | 30.8 | 31.5 | 32.0 |
| **Total** | **121.2** | **125.7** | **126.6** | **122.7** | **122.2** | **118.6** | **116.4** |

Note: Totals may not sum due to independent rounding.

**Table 2-27: $CH_4$ Emissions from Natural Gas Systems (Gg)**

| Stage | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Field Production | 1,407 | 1,477 | 1,474 | 1,407 | 1,511 | 1,350 | 1,248 |
| Processing | 702 | 712 | 711 | 710 | 693 | 693 | 707 |
| Transmission and Storage | 2,223 | 2,225 | 2,243 | 2,198 | 2,150 | 2,102 | 2,061 |
| Distribution | 1,440 | 1,570 | 1,602 | 1,530 | 1,467 | 1,501 | 1,526 |
| **Total** | **5,772** | **5,984** | **6,030** | **5,845** | **5,820** | **5,646** | **5,541** |

Note: Totals may not sum due to independent rounding.

the majority of the emissions from this stage. Pneumatic devices and engine exhaust are also sources of emissions from transmission facilities. Methane emissions from transmission account for approximately 37 percent of the emissions from natural gas systems.

Natural gas is also injected and stored in underground formations 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. Approximately one percent of total emissions from natural gas systems can be attributed to storage facilities.

*Distribution.* Distribution pipelines take the high-pressure gas from the transmission system at "city gate" stations, reduce the pressure and distribute the gas through mains and service lines to individual end users. There were over 1,043,000 miles of distribution mains in 2000, an increase from just over 837,000 miles in 1990 (AGA 1998). Distribution system emissions, which account for approximately 25 percent of emissions from natural gas systems, resulted mainly from fugitive emissions from gate stations and non-plastic piping (cast iron, steel).[39] An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced the growth in emissions from this stage. Distribution system emissions in 1999 were only slightly higher than 1990 levels.

## Methodology

The basis for estimates of methane 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 100 emission and activity factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system. The study was based on a combination of process engineering studies and measurements at representative gas facilities. From this analysis, the EPA developed a 1992 base year emissions estimate using the emission and activity factors. For other years, the EPA has developed a set of industry activity factor drivers 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.

[39] The percentages of total emissions from each stage may not add to 100 because of independent rounding.

The methodology also adjusts the emission factors to reflect underlying technological improvement through both innovation and normal replacement of equipment. For the period 1990 through 1995, the emission factors were held constant. Thereafter, emission factors are reduced at a rate of 0.2 percent per year such that by 2020, emission factors will have declined by 5 percent from 1995. Emission reductions, as reported by EPA's Natural Gas STAR partners, were also incorporated into the analysis. Emission reductions associated with each stage of the natural gas system (production, processing, transmission and distribution) were subtracted from the corresponding total emissions estimates for each operating stage. See Annex F for more detailed information on the methodology and data used to calculate methane emissions from natural gas systems.

## Data Sources

Activity factor data were obtained from the following sources: American Gas Association (AGA 1991 through 1999); *Natural Gas Annual* (EIA 1999); *Natural Gas Monthly* (EIA 2001); *Oil and Gas Journal* (PennWell Corporation 1999, 2000, 2001); Independent Petroleum Association of America (IPAA 1998, 1999, 2000); and the Department of Transportation's Office of Pipeline Safety (OPS 2001a,b). The Minerals Management Service (DOI 1998 through 2001) supplied offshore platform data. All emission factors were taken from EPA/GRI (1996).

## Uncertainty

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. Despite the difficulties associated with estimating emissions from this source, the uncertainty in the total estimated emissions is preliminarily believed to be on the order of ±40 percent.

# Petroleum Systems

Methane emissions from petroleum systems are primarily associated with crude oil production, transportation, and refining operations. During each of these activities, methane is released to the atmosphere as fugitive emissions, vented emissions, emissions from operational upsets, and emissions from fuel combustion. Methane emissions from petroleum systems in 2000 were 21.9 Tg $CO_2$ Eq. (1,041 Gg). Since 1990, emissions declined gradually, primarily due to a decline in domestic oil production. (See Table 2-28 and Table 2-29.) The activities associated with petroleum systems are detailed below.

*Production Field Operations*. Production field operations account for approximately 97 percent of total methane emissions from petroleum systems. Vented methane from oil wells, storage tanks, and related production field processing equipment account for the vast majority of the emissions from production, with field storage tanks and natural-gas-powered pneumatic devices being the dominant sources. The emissions from storage tanks occur when the methane entrained in crude oil under high pressure volatilizes once the crude oil is dumped into storage tanks at atmospheric pressure. The next most dominant sources of vented emissions are chemical injection pumps and vessel blowdown. The remaining emissions from production can be attributed to fugitives and combustion.

*Crude Oil Transportation*. Crude transportation activities account for approximately one-half percent of total methane emissions from the oil industry. Venting from tanks and marine vessel loading operations accounts for the majority of methane emissions from crude oil transportation. Fugitive emissions, almost entirely from floating roof tanks, account for the remainder.

*Crude Oil Refining*. Crude oil refining processes and systems account for only two percent of total methane emissions from the oil industry because most of the methane in crude oil is removed or escapes before the crude oil is delivered to the refineries. Within refineries, vented emissions account for about 87 percent of the emissions from refining, while fugitive and combustion emissions

**Table 2-28: $CH_4$ Emissions from Petroleum Systems (Tg $CO_2$ Eq.)**

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Production Field Operations** | **25.8** | **23.6** | **23.4** | **23.3** | **22.7** | **21.6** | **21.2** |
| Tank venting | 11.8 | 10.4 | 10.2 | 10.2 | 9.8 | 9.1 | 8.9 |
| Pneumatic device venting | 11.0 | 10.4 | 10.4 | 10.4 | 10.2 | 9.9 | 9.7 |
| Wellhead fugitives | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 | 0.4 |
| Combustion & process upsets | 1.0 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| Misc. venting & fugitives | 1.4 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| **Crude Oil Transportation** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** |
| **Refining** | **0.5** | **0.5** | **0.5** | **0.6** | **0.6** | **0.6** | **0.6** |
| **Total** | **26.4** | **24.2** | **24.0** | **24.0** | **23.4** | **22.3** | **21.9** |

Note: Totals may not sum due to independent rounding.

**Table 2-29: $CH_4$ Emissions from Petroleum Systems (Gg)**

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Production Field Operations** | **1,227** | **1,122** | **1,114** | **1,112** | **1,081** | **1,028** | **1,008** |
| Tank venting | 564 | 493 | 485 | 484 | 466 | 433 | 425 |
| Pneumatic device venting | 525 | 497 | 496 | 495 | 485 | 470 | 460 |
| Wellhead fugitives | 25 | 25 | 25 | 24 | 23 | 21 | 20 |
| Combustion & process upsets | 47 | 44 | 45 | 45 | 44 | 42 | 42 |
| Misc. venting & fugitives | 66 | 63 | 63 | 63 | 63 | 62 | 61 |
| **Crude Oil Transportation** | **7** | **6** | **6** | **6** | **6** | **6** | **5** |
| **Refining** | **25** | **25** | **26** | **27** | **27** | **27** | **28** |
| **Total** | **1,258** | **1,154** | **1,145** | **1,144** | **1,114** | **1,061** | **1,041** |

Note: Totals may not sum due to independent rounding.

account for approximately six percent each. Refinery system blowdowns for maintenance and the process of asphalt blowing—with air to harden it—are the primary venting contributors. Most of the fugitive emissions from refineries are from leaks in the fuel gas system. Refinery combustion emissions accumulate from small amounts of unburned methane in process heater stacks as well as from unburned methane in engine exhausts and flares. The very slight increase in emissions from refining, relative to the decline in emissions from field production operations, is due to increasing imports of crude oil.

## Methodology

The methodology for estimating methane emissions from petroleum systems is based on a comprehensive studies of methane emissions from U.S. petroleum systems, *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report)* (EPA 1999) and *Methane Emissions from the U.S. Petroleum Industry* (Radian 1996). The studies estimated emissions from 70 activities occurring in petroleum systems from the oil wellhead through crude oil refining, including 39 activities for crude oil production field operations, 11 for crude oil transportation activities, and 20 for refining operations. Annex F explains the emission estimates for these 70 activities in greater detail. The estimates of methane emissions from petroleum systems do not include emissions downstream from oil refineries because these emissions are very small compared to methane emissions upstream from oil refineries.

The methodology for estimating methane emissions from the 70 oil industry activities employs emission and activity factors initially developed in EPA (1999) and Radian (1996). Emissions were estimated for each activity by multiplying emission factors (e.g., emission rate per equipment item or per activity) by their corresponding activity data (e.g., equipment count or frequency of activity). The report provides emission factors and activity factors for all activities except those related to offshore oil production. For offshore oil production, an emission factor was calculated by dividing an emission estimate from the Minerals Management Service (MMS) by the number of platforms. Emission factors were held constant for the period 1990 through 2000.

Activity data for 1990 through 2000 from a wide variety of statistical resources. For some years, complete activity factor data are not available. In these cases, the activity data was evaluated in the same manner as in Radian (1996), by arithmetic mean of component estimates based on annual oil production and producing wells. Alternatively, the activity data was held constant.

Annex F provides a more detailed discussion of the methodology for petroleum systems.

## Data Sources

Nearly all emission factors were taken from Radian (1996e). Other emission factors were taken from an American Petroleum Institute publication (API 1996), EPA default values, MMS reports (MMS 1995 and 1999), the Exploration and Production (E&P) Tank model (API and GRI), reports by the Canadian Association of Petroleum Producers (CAPP 1992 and 1993), and consensus of industry peer review panels.

Among the more important references used to obtain activity data are Energy Information Administration annual and monthly reports (EIA 1998, 2001), the API *Basic Petroleum Data Book* (API 1997 and 1999), *Methane Emissions from the Natural Gas Industry* prepared for the Gas Research Institute (GRI) and EPA (Radian 1996a-d), consensus of industry peer review panels, MMS reports (MMS 1995 and 1999), and the *Oil & Gas Journal* (OGJ 2000a,b).

## Uncertainty

There is uncertainty associated with the estimate of annual venting emissions in production field operations because a recent census of tanks and other tank battery equipment, such as separators and pneumatic devices, were not available. These uncertainties are significant because storage tanks and pneumatic devices accounted for 85 percent of methane emissions from petroleum systems. Emission rates can also vary widely from reservoir to reservoir and well to well. A single average emission factor cannot reflect this variation. Pneumatic devices were estimated by assuming that the devices were a function of number of heater/treaters and separators, and that 35 percent of the total pneumatic devices were high bleed and 65 percent were low bleed. These assumptions may overestimate the numbers of high bleed pneumatic devices, and thus overestimate emissions. Finally, because the majority of methane emissions occur during production field operations, where methane can first escape from crude oil, a better understanding of tanks, tank equipment and vapor recovery practices would reduce that uncertainty. Because of the dominance of crude storage tank venting and pneumatics, Table 2-30 provides preliminary emission estimate ranges for these sources. For tank venting, these ranges include numbers that are 25 percent higher than or lower than the given point estimates. For pneumatics, the range is between 33 percent lower or 25 percent higher than the point estimates.

# Municipal Solid Waste Combustion

Combustion is used to manage about 7 to 17 percent of the municipal solid wastes (MSW) generated in the United States (EPA 2000c, Glenn 1999). Almost all combustion of MSW in the United States occurs at waste-to-energy facilities where energy is recovered, and thus emissions from waste combustion are accounted for in the Energy chapter. Combustion of MSW results in conversion of the organic inputs to $CO_2$. According to the IPCC Guidelines, when the $CO_2$ emitted is of fossil origin, it is counted as a net anthropogenic emission of $CO_2$ to the atmosphere. Thus, the emissions from waste combustion are calculated by estimating the quantity of waste combusted and the fraction of the waste that is carbon derived from fossil sources.

Most of the organic materials in MSW are of biogenic origin (e.g., paper, yard trimmings), and have their net carbon flows accounted for under the Land-Use Change and Forestry chapter (see Box 2-3). However, some components—plastics, synthetic rubber, and synthetic fibers—are of fossil origin. Plastics in the U.S. waste stream are primarily in the form of containers, packaging, and durable goods. Rubber is found in durable goods, such as carpets, and in non-durable goods, such as clothing and footwear. Fibers in MSW are predominantly from clothing and home furnishings. Tires are also considered a "non-hazardous" waste and are included in the MSW combustion estimate, though waste disposal practices for tires differ from the rest of MSW.

**Table 2-30: Uncertainty in $CH_4$ Emissions from Production Field Operations (Gg)**

| Activity | 1990 | | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|
| **Tank venting (point estimate)** | **564** | | **493** | **485** | **484** | **466** | **433** | **425** |
| Low | 423 | | 370 | 364 | 363 | 349 | 325 | 319 |
| High | 705 | | 617 | 606 | 605 | 582 | 541 | 531 |
| **Pneumatic devices (point estimate)** | **525** | | **497** | **496** | **495** | **485** | **470** | **460** |
| Low | 352 | | 333 | 332 | 332 | 325 | 315 | 308 |
| High | 656 | | 621 | 620 | 619 | 606 | 588 | 575 |

It was estimated that approximately 24 million metric tons of MSW were combusted in the United States in 2000. Carbon dioxide emissions from combustion of MSW rose 63 percent since 1990, to an estimated 22.5 Tg $CO_2$ Eq. (22,470 Gg) in 2000, as the volume of plastics in MSW increased (see Table 2-31 and Table 2-32). Waste combustion is also a source of nitrous oxide ($N_2O$) emissions (De Soete 1993). Nitrous oxide emissions from MSW combustion were estimated to be 0.3 Tg $CO_2$ Eq. (1 Gg) in 2000, and have not changed significantly since 1990.

## Methodology

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

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 MSW combusted and an emission factor.

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

## Data Sources

For each of the methods used to calculate $CO_2$ emissions from MSW combustion, data on the quantity of product combusted and the carbon content of the product are needed. It was estimated that approximately 24 million metric tons of MSW were combusted in the United States in 2000, based on an extrapolation of data from 1998 and earlier years (EPA 2000c, Glenn 1999). Waste combustion for 2000 was assumed to be the same as for 1999. For plastics, synthetic rubber, and synthetic fibers, the amount of material in MSW and its portion combusted was taken from the *Characterization of Municipal Solid Waste in the United States* (EPA 2000c). For synthetic rubber and carbon black in scrap tires, this information was provided by the *Scrap Tire Use/Disposal Study 1998/1999 Update* (STMC 1999) and the *Scrap Tires, Facts and Figures* (STMC 2000).

Average carbon contents for the "Other" plastics category, synthetic rubber in scrap tires, synthetic rubber in MSW, and synthetic fibers were calculated from recent production statistics which divide their respective markets by chemical compound. The plastics production data set was taken from the website of the American Plastics Council (APC 2000); synthetic rubber production was taken from the website of the International Institute of Synthetic Rubber Producers (IISRP 2000); and synthetic fiber production was taken from the website of the Fiber Economics Bureau (FEB 2000). Personal communications with the APC (Eldredge-Roebuck 2000) and the FEB (DeZan 2000) validated the website information. All three sets of production data can also be found in Chemical and Engineering News, "Facts & Figures for the Chemical Industry." Lastly, information about scrap tire composition was taken from the Scrap Tire Management Council's Internet web site entitled "Scrap Tire Facts and Figures" (STMC 2000).

### Box 2-3: Biogenic Emissions and Sinks of Carbon

For many countries, $CO_2$ emissions from the combustion or degradation of biogenic materials are important because of the significant amount of energy they derive from biomass (e.g., burning fuelwood). The fate of biogenic materials is also important when evaluating waste management emissions (e.g., the decomposition of paper). The carbon contained in paper was originally stored in trees during photosynthesis. Under natural conditions, this material would eventually degrade and cycle back to the atmosphere as $CO_2$. The quantity of carbon that these degradation processes cycle through the Earth's atmosphere, waters, soils, and biota is much greater than the quantity added by anthropogenic greenhouse gas sources. But the focus of the United Nations Framework Convention on Climate Change is on anthropogenic emissions—emissions resulting from human activities and subject to human control—because it is these emissions that have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle, and enhancing the atmosphere's natural greenhouse effect.

Carbon dioxide emissions from 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. However, $CH_4$ 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.

The removal of carbon from the natural cycling of carbon between the atmosphere and biogenic materials—which occurs when wastes of biogenic origin are deposited in landfills—sequesters carbon. When wastes of sustainable, biogenic origin are landfilled, and do not completely decompose, the carbon that remains is effectively removed from the global carbon cycle. Landfilling of forest products and yard trimmings results in long-term storage of 154 Tg $CO_2$ Eq. and 13 Tg $CO_2$ Eq. on average per year, respectively. Carbon storage that results from forest products and yard trimmings disposed in landfills is accounted for in the Land-Use Change and Forestry chapter, as recommended in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) regarding the tracking of carbon flows.

### Table 2-31: $CO_2$ and $N_2O$ Emissions from Municipal Solid Waste Combustion (Tg $CO_2$ Eq.)

| Gas/Waste Product | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | **14.1** | **18.6** | **19.6** | **21.3** | **20.3** | **21.8** | **22.5** |
| Plastics | 10.3 | 11.1 | 11.5 | 12.5 | 12.9 | 13.3 | 13.7 |
| Synthetic Rubber in Tires | 0.3 | 1.5 | 1.7 | 1.9 | 1.3 | 1.7 | 1.8 |
| Carbon Black in Tires | 0.4 | 2.4 | 2.7 | 3.0 | 2.0 | 2.7 | 2.8 |
| Synthetic Rubber in MSW | 1.6 | 1.7 | 1.7 | 1.8 | 1.8 | 1.9 | 1.9 |
| Synthetic Fibers | 1.5 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 | 2.3 |
| **$N_2O$** | **0.3** | **0.3** | **0.3** | **0.3** | **0.2** | **0.2** | **0.2** |
| **Total** | **14.4** | **18.9** | **19.8** | **21.6** | **20.5** | **22.1** | **22.7** |

### Table 2-32: $CO_2$ and $N_2O$ Emissions from Municipal Solid Waste Combustion (Gg)

| Gas/Waste Product | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | **14,014** | **18,608** | **19,569** | **21,344** | **20,251** | **21,843** | **22,470** |
| Plastics | 10,320 | 11,077 | 11,459 | 12,484 | 12,929 | 13,297 | 13,653 |
| Synthetic Rubber in Tires | 253 | 1,507 | 1,689 | 1,906 | 1,263 | 1,703 | 1,771 |
| Carbon Black in Tires | 399 | 2,377 | 2,666 | 3,006 | 1,993 | 2,687 | 2,795 |
| Synthetic Rubber in MSW | 1,584 | 1,708 | 1,737 | 1,807 | 1,833 | 1,870 | 1,905 |
| Synthetic Fibers | 1,535 | 1,938 | 2,018 | 2,141 | 2,233 | 2,285 | 2,346 |
| **$N_2O$** | **1** | **1** | **1** | **1** | **1** | **1** | **1** |

The use of the value 98 as the fraction of carbon oxidized, which applies to all municipal solid waste combustion categories for $CO_2$ emissions, was reported in the EPA's life cycle analysis of greenhouse gas emissions and sinks from management of solid waste (EPA 1998).

The $N_2O$ emission estimates are based on different data sources. The $N_2O$ emissions are a function of total waste combusted, as reported in the November 2000 issue of *BioCycle* (Goldstein N. and C. Matdes 2000). Table 2-33 provides MSW generation and percentage combustion data for the total waste stream. The emission factor of $N_2O$ emissions per quantity of MSW combusted was taken from Olivier (1993).

**Table 2-33: Municipal Solid Waste Generation (Metric Tons) and Percent Combusted**

| Year | Waste Generation | Combusted (%) |
|---|---|---|
| 1990 | 266,541,881 | 11.5 |
| 1991 | 254,796,765 | 10.0 |
| 1992 | 264,843,388 | 11.0 |
| 1993 | 278,572,955 | 10.0 |
| 1994 | 293,109,556 | 10.0 |
| 1995 | 296,586,430 | 10.0 |
| 1996 | 297,268,188 | 10.0 |
| 1997 | 309,075,035 | 9.0 |
| 1998 | 340,090,022 | 7.5 |
| 1999 | 347,318,833 | 7.0 |
| 2000 | 347,318,833 | 7.0 |

## Uncertainty

Uncertainties in the waste combustion emission estimates arise from both the assumptions applied to the data and from the quality of the data.

- *MSW Combustion Rate.* A source of uncertainty affecting both fossil $CO_2$ and $N_2O$ emissions is the estimate of the MSW combustion rate. The EPA (2000c) estimates of materials generated, discarded, and combusted carry considerable uncertainty associated with the material flows methodology used to generate them. Similarly, *BioCycle* (Glenn 1999, Goldstein and Matdes 2000) estimate of total waste combustion — used for the $N_2O$ emissions estimate—is based on a survey of State officials, who use differing definitions of solid waste and who draw from a variety of sources of varying reliability and accuracy. Despite the differences in methodology and data sources, the two references—the EPA's Office of Solid Waste (EPA 2000c) and *BioCycle* (Glenn 1999, Goldstein and Matdes 2000)—provide estimates of total solid waste combusted that are relatively consistent (see Table 2-34).
- *Fraction Oxidized.* Another source of uncertainty for the $CO_2$ emissions estimate is fraction oxidized. Municipal waste combustors vary considerably in their efficiency as a function of waste type, moisture content, combustion conditions, and other factors. The value of 98 percent assumed here may not be representative of typical conditions.
- *Use of 1998 Data on MSW Composition.* Emissions have been calculated from activity that has been extrapolated from reported 1998 values using average annual growth rates. In addition, the ratio of landfilling to combustion was assumed to be constant for the entire period (1990 to 2000) based on the 1998 ratio (EPA 2000c).
- *Average Carbon Contents.* Average carbon contents were applied to the mass of "Other" plastics combusted, synthetic rubber in tires and MSW, and synthetic fibers. These average values were estimated from the average carbon content of the known products recently produced. The true carbon content of the combusted waste may differ from this estimate depending on differences in the formula between the known and unspecified materials, and differences between the composition of the material disposed and that produced. For rubber, this uncertainty is probably small since the major elastomers' carbon contents range from 77 to 91 percent; for plastics, where carbon contents range from 29 to 92 percent, it may be more significant. Overall, this is a small source of uncertainty.
- *Synthetic/Biogenic Assumptions.* A portion of the fiber and rubber in MSW is biogenic in origin. Assumptions have been made concerning the allocation between synthetic and biogenic materials based primarily on expert judgment.
- *Combustion Conditions Affecting $N_2O$ Emissions.* Because insufficient data exist to provide detailed estimates of $N_2O$ emissions for individual combustion facilities, the estimates presented are highly uncertain. The emission factor for $N_2O$ from MSW combustion facilities used in the analysis is a default value used to

**Table 2-34: U.S. Municipal Solid Waste Combusted by Data Source (Metric Tons)**

| Year | EPA | BioCycle |
|---|---|---|
| 1990 | 28,939,680 | 30,652,316 |
| 1991 | 30,236,976 | 25,479,677 |
| 1992 | 29,656,638 | 29,132,773 |
| 1993 | 29,865,024 | 27,857,295 |
| 1994 | 29,474,928 | 29,310,956 |
| 1995 | 32,241,888 | 29,658,643 |
| 1996 | 32,740,848 | 29,726,819 |
| 1997 | 32,294,240 | 27,816,753 |
| 1998 | 31,218,818 | 25,506,752 |
| 1999 | 30,945,455 | NA |
| 2000 | NA | NA |

NA (Not Available)

estimate $N_2O$ emissions from facilities worldwide (Olivier 1993). As such, it has a range of uncertainty that spans an order of magnitude (between 25 and 293 g $N_2O$/metric ton MSW combusted) (Watanabe, et al. 1992). Due to a lack of information on the control of $N_2O$ emissions from MSW combustion facilities in the United States, the estimate of zero percent for $N_2O$ emissions control removal efficiency is also uncertain.

## Natural Gas Flaring and Ambient Air Pollutant Emissions from Oil and Gas Activities

The flaring of natural gas from oil wells is a small source of carbon dioxide ($CO_2$). In addition, oil and gas activities also release small amounts of nitrogen oxides ($NO_x$), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs). This source accounts for only a small proportion of overall emissions of each of these gases. Emissions of $NO_x$, and CO from petroleum and natural gas production activities were both less than 1 percent of national totals, while NMVOC and $SO_2$ emissions were roughly 2 percent of national totals.

Carbon dioxide emissions from petroleum production result from natural gas that is flared (i.e., combusted) at the production site. Barns and Edmonds (1990) noted that of total reported U.S. venting and flaring, approximately 20 percent may be vented, with the remaining 80 percent flared; however, it is now believed that flaring accounts for an even greater proportion, although some venting still occurs. Methane emissions from venting are accounted for under Petroleum Systems. For 2000, $CO_2$ emissions from flaring were estimated to be approximately 6.1 Tg $CO_2$ Eq. (6,059 Gg), an increase of 10 percent since 1990 (see Table 2-35).

Ambient air pollutant emissions from oil and gas production, transportation, and storage, constituted a relatively small and stable portion of the total emissions of these gases from the 1990 to 2000 (see Table 2-36).

### Methodology

Estimates of $CO_2$ emissions were prepared using an emission factor of 54.71 Tg $CO_2$ Eq./QBtu of flared gas, and an assumed flaring efficiency of 100 percent.

Ambient air pollutant emission estimates for $NO_x$, CO, and NMVOCs were determined using industry-published production data and applying average emission factors.

### Data Sources

Total natural gas vented and flared was taken from EIA's *Natural Gas Annual* (EIA 2001). It was assumed that all reported vented and flared gas was flared. This assumption is consistent with that used by EIA in preparing their emission estimates, under the assumption that many states require flaring of natural gas (EIA 2000b).

There is a discrepancy in the time series for natural gas vented and flared as reported in EIA (2001). One facility in Wyoming had been incorrectly reporting $CO_2$ vented as $CH_4$. EIA has corrected these data in the *Natural Gas Annual* (EIA 2001a) for the years 1998 and 1999 only. Data for 1990 through 1997 were adjusted by assuming a proportionate share of $CO_2$ in the flare gas for those years as for 1998 and 1999. The adjusted values are provided in Table 2-37. The emission and thermal conversion factors were also provided by EIA (2001) and are included in Table 2-37.

**Table 2-35: $CO_2$ Emissions from Natural Gas Flaring**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 5.5 | 5,514 |
| 1995 | 8.7 | 8,729 |
| 1996 | 8.2 | 8,233 |
| 1997 | 7.6 | 7,565 |
| 1998 | 6.3 | 6,250 |
| 1999 | 6.7 | 6,679 |
| 2000 | 6.1 | 6,059 |

EPA (2001) provided emission estimates for $NO_x$, CO, and NMVOCs from petroleum refining, petroleum product storage and transfer, and petroleum marketing operations. Included are gasoline, crude oil and distillate fuel oil storage and transfer operations, gasoline bulk terminal and bulk plants operations, and retail gasoline service stations operations.

## Uncertainty

Uncertainties in $CO_2$ emission estimates primarily arise from assumptions concerning the flaring efficiency and the correction factor applied to 1990-1997 venting and flaring data. Uncertainties in ambient air pollutant emission estimates are partly due to the accuracy of the emission factors used and projections of growth.

## Indirect $CO_2$ from $CH_4$ Oxidation

Indirect $CO_2$ emissions are formed in the atmosphere from the oxidation of methane ($CH_4$). Although this indirect $CO_2$ is a greenhouse gas, its generation is not accounted for within the global warming potential (GWP) of $CH_4$. Thus for the sake of completion, it is necessary to account for these indirect emissions whenever anthropogenic sources of $CH_4$ are calculated.

Indirect $CO_2$ emissions from $CH_4$ oxidation originating from non-combustion fossil sources—coal mining, natural gas systems, petroleum systems, petrochemical production, and silicon carbide production—are included in this estimate. Methane is also emitted from stationary and mobile combustion sources (e.g., natural gas-fired boilers, gasoline fueled vehicles), and from several managed biological

**Table 2-36: $NO_x$, NMVOCs, and CO Emissions from Oil and Gas Activities (Gg)**

| Year | $NO_x$ | CO | NMVOCs |
|---|---|---|---|
| 1990 | 139 | 302 | 555 |
| 1995 | 100 | 316 | 582 |
| 1996 | 126 | 321 | 433 |
| 1997 | 130 | 333 | 442 |
| 1998 | 130 | 332 | 440 |
| 1999 | 130 | 332 | 385 |
| 2000 | 132 | 335 | 393 |

**Table 2-37: Total Natural Gas Reported Vented and Flared (Million $Ft^3$) and Thermal Conversion Factor (Btu/$Ft^3$)**

| Year | Vented and Flared (original) | Vented and Flared (revised)* | Thermal Conversion Factor |
|---|---|---|---|
| 1990 | 150,415 | 91,130 | 1,106 |
| 1991 | 169,909 | 92,207 | 1,108 |
| 1992 | 167,519 | 83,363 | 1,110 |
| 1993 | 226,743 | 108,238 | 1,106 |
| 1994 | 228,336 | 109,493 | 1,105 |
| 1995 | 283,739 | 144,265 | 1,106 |
| 1996 | 272,117 | 135,709 | 1,109 |
| 1997 | 256,351 | 124,918 | 1,107 |
| 1998 | 103,019 | 103,019 | 1,109 |
| 1999 | 110,285 | 110,285 | 1,107 |
| 2000 | 100,048 | 100,048 | 1,107 |

* Wyoming venting and flaring estimates were revised. See text for further explanation.

systems (e.g., livestock, rice cultivation), but $CO_2$ produced through oxidation of $CH_4$ from these sources is excluded because:

- Indirect $CO_2$ emissions from $CH_4$ emitted by combustion sources are accounted for within the Carbon Dioxide from Fossil Fuel Combustion section in the assumption that all carbon containing gaseous combustion products are eventually oxidized to $CO_2$ in the atmosphere (see Annex A).
- Methane from biological systems is derived from rapidly cycling (non-fossil) sources. For example, the carbon content of methane from enteric fermentation is derived from plant matter, which has converted atmospheric $CO_2$ to organic compounds. Anthropogenic activity (e.g., management of a biological system) converts the atmospheric $CO_2$ to $CH_4$ and thus is counted in the Inventory. The subsequent atmospheric oxidation of $CH_4$ merely completes the natural cycle.

In addition to oxidation of $CH_4$, indirect $CO_2$ emissions can also result from emissions of carbon monoxide (CO) and non-methane volatile organic compounds (NMVOCs). However, $CO_2$ from non-combustion emissions of CO and NMVOCs are not included in this section because they are explicitly included in the mass balance used in calculating the storage and emissions from non-energy uses of fossil fuels, with the carbon components of CO and NMVOC counted as $CO_2$ emissions in the mass balance. Thus, it would be double-counting to include them in the indirect $CO_2$ emissions estimates presented in this section.[40] If reported separately, indirect $CO_2$ emissions from applicable CO and NMVOC sources—primarily from industrial processes and solvent use—would be 31.1 and 28.1 Tg of $CO_2$ in 2000.

Total $CH_4$ emissions from non-combustion fossil sources, gathered from the respective sections of this Inventory, are presented in Table 2-38. Indirect $CO_2$ emissions from those sources are summarized in Table 2-39 and Table 2-40.

## Methodology

Indirect emissions of $CO_2$ are calculated by applying a factor of 44/16, which is the ratio of molecular weight of $CO_2$ to the molecular weight of $CH_4$, to the appropriate methane emissions. The methodology for calculating the methane emissions is presented within the respective sections of this Inventory. For the purposes of the calculation, it is assumed that $CH_4$ emitted to the atmosphere from non-combustion fossil processes is oxidized to $CO_2$ in the same year that it is emitted. This is a simplification, because the average atmospheric lifetime of methane is actually on the order of 12 years.

The IPCC Guidelines for Greenhouse Gas Inventories (IPCC/UNEP/OECD/IEA 1997) makes passing references to issues of "double counting carbon" in estimating $CO_2$ emissions from fossil fuel combustion. In one case, by double counting, the IPCC is referring to the fact that some carbon during the combustion is actually emitted as $CH_4$, CO, and NMVOCs. The IPCC also assumes that the carbon in these compounds is assumed to eventually oxidizes to $CO_2$ in the atmosphere. Therefore in the case of emissions from fossil fuel combustion, the carbon is intentionally double counted (e.g., once as an atom in a $CH_4$ molecule and once in a $CO_2$ molecule) in order to develop a more comprehensive estimate of the long-term $CO_2$ burden in the atmosphere and the radiative forcing effects of fossil fuel combustion emissions.

**Table 2-38: $CH_4$ Emissions from Non-Combustion Fossil Sources (Gg)**

| Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Coal Mining | 4,149 | 3,502 | 3,255 | 3,244 | 3,235 | 3,033 | 2,903 |
| Natural Gas Systems | 5,772 | 5,984 | 6,030 | 5,845 | 5,820 | 5,646 | 5,541 |
| Petroleum Systems | 1,258 | 1,154 | 1,145 | 1,144 | 1,114 | 1,061 | 1,041 |
| Petrochemical Production | 56 | 72 | 75 | 77 | 78 | 79 | 79 |
| Silicon Carbide Production | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Total** | **11,236** | **10,712** | **10,506** | **10,311** | **10,248** | **9,820** | **9,564** |

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

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

**Table 2-39: Indirect $CO_2$ Emissions from Non-Combustion Fossil Methane Sources (Gg)**

| Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Coal Mining | 11,409 | 9,630 | 8,951 | 8,922 | 8,897 | 8,340 | 7,984 |
| Natural Gas Systems | 15,873 | 16,456 | 16,581 | 16,073 | 16,005 | 15,527 | 15,237 |
| Petroleum Systems | 3,460 | 3,173 | 3,149 | 3,146 | 3,063 | 2,917 | 2,862 |
| Petrochemical Production | 153 | 197 | 207 | 211 | 215 | 218 | 217 |
| Silicon Carbide Production | 3 | 2 | 2 | 2 | 2 | 2 | 1 |
| **Total** | **30,899** | **29,458** | **28,891** | **28,354** | **28,183** | **27,004** | **26,302** |

Note: Totals may not sum due to independent rounding.

**Table 2-40: Indirect $CO_2$ Emissions from Non-Combustion Fossil Methane Sources (Tg $CO_2$ Eq.)**

| Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Coal Mining | 11.4 | 9.6 | 9.0 | 8.9 | 8.9 | 8.3 | 8.0 |
| Natural Gas Systems | 15.9 | 16.5 | 16.6 | 16.1 | 16.0 | 15.5 | 15.2 |
| Petroleum Systems | 3.5 | 3.2 | 3.1 | 3.1 | 3.1 | 2.9 | 2.9 |
| Petrochemical Production | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Silicon Carbide Production | + | + | + | + | + | + | + |
| **Total** | **30.9** | **29.5** | **28.9** | **28.4** | **28.2** | **27.0** | **26.3** |

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

The IPCC, though, points out that this approach misses the indirect $CO_2$ emitted from sources other than fossil fuel combustion, such as venting of $CH_4$ from natural gas and petroleum systems and coal mines. It also misses biogenic sources of $CH_4$, CO and NMVOCs, such as enteric fermentation in ruminant livestock and decomposition of organic wastes in landfills. The exclusion of biogenic emissions is appropriate, however, given the cyclical nature and probable net zero effect on the atmospheric $CO_2$ burden.

It should be noted that the climate forcing caused by $CO_2$ produced from the oxidation of $CH_4$ is not included in these GWP estimates. As discussed in IPCC (1996), it is often the case that this $CO_2$ is included in national carbon production inventories. Therefore, depending on how the inventories are combined, including $CO_2$ production from $CH_4$ could result in double counting this $CO_2$ (IPCC 2001).

## Data Sources

Data sources for estimating methane emissions from non-combustion processes are summarized in other sections of this Inventory. Methane emissions from coal mining, natural gas systems, and petroleum systems are summarized in this chapter and described in detail in Annexes E, F, and G, respectively. Methane emissions from petrochemicals production and from silicon carbide production are discussed in the Industrial Processes chapter.

## Uncertainty

The two principal sources of uncertainty in the estimate of indirect $CO_2$ emissions are the extent to which methane emissions are included in the overall carbon emissions calculated as $CO_2$ for combustion sources, and the time frame in which the methane is assumed to oxidize to $CO_2$ once emitted to the atmosphere. It is assumed that 100 percent of the methane emissions from combustion sources are accounted for in the overall carbon emissions calculated as $CO_2$ for sources using emission factors and carbon mass balances. However, it may be the case for some types of combustion sources that the oxidation factors used for calculating $CO_2$ emissions do not accurately account for the full mass of carbon emitted in gaseous form (i.e., partially oxidized or still in hydrocarbon form). Also, the indirect $CO_2$ emission calculation is based on the assumption that the methane is completely oxidized to $CO_2$ in the same year that it is emitted to the atmosphere, but its average atmospheric lifetime is approximately 12 years.

## International Bunker Fuels

Emissions resulting from the combustion of fuels used for international transport activities, termed international bunker fuels under the United Nations Framework Convention on Climate Change (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.[41] These decisions are reflected in the *Revised 1996 IPCC Guidelines*, in which countries are requested to report emissions from ships or aircraft that depart from their ports with fuel purchased within national boundaries and are engaged in international transport separately from national totals (IPCC/UNEP/OECD/IEA 1997).[42]

Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), carbon monoxide (CO), oxides of nitrogen ($NO_x$), non-methane volatile organic compounds (NMVOCs), particulate matter, and sulfur dioxide ($SO_2$).[43] Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine. Emissions from ground transport activities—by road vehicles and trains—even when crossing international borders are allocated to the country where the fuel was loaded into the vehicle and, therefore, are not counted as bunker fuel emissions.

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.[44]

Emissions of $CO_2$ from aircraft are essentially a function of fuel use. Methane, $N_2O$, CO, $NO_x$, and NMVOC emissions also depend upon engine characteristics, flight conditions, and flight phase (i.e., take-off, climb, cruise, decent, and landing). Methane, CO, and NMVOCs are the product of incomplete combustion and occur mainly during the landing and take-off phases. In jet engines, $N_2O$ and $NO_x$ are primarily produced by the oxidation of atmospheric nitrogen, and the majority of emissions occur during the cruise phase. The impact of $NO_x$ on atmospheric chemistry depends on the altitude of the actual emission. The cruising altitude of supersonic aircraft, near or in the ozone layer, is higher than that of subsonic aircraft. At this higher altitude, $NO_x$ emissions contribute to stratospheric ozone depletion.[45] At the cruising altitudes of subsonic aircraft, however, $NO_x$ emissions contribute to the formation of tropospheric ozone. At these lower altitudes, the positive radiative forcing effect of ozone has enhanced the anthropogenic greenhouse gas forcing.[46] The vast majority of aircraft $NO_x$ emissions occur at these lower cruising altitudes of commercial subsonic aircraft (NASA 1996).[47]

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

[41] 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) (contact secretariat@unfccc.de).

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

[43] Sulfur dioxide emissions from jet aircraft and marine vessels, although not estimated here, are mainly determined by the sulfur content of the fuel. In the U.S., jet fuel, distillate diesel fuel, and residual fuel oil average sulfur contents of 0.05, 0.3, and 2.3 percent, respectively. These percentages are generally lower than global averages.

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

[45] In 1996, there were only around a dozen civilian supersonic aircraft in service around the world which flew at these altitudes, however.

[46] However, at this lower altitude, ozone does little to shield the earth from ultraviolet radiation.

[47] Cruise altitudes for civilian subsonic aircraft generally range from 8.2 to 12.5 km (27,000 to 41,000 feet).

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. Carbon dioxide is the primary greenhouse gas emitted from marine shipping. In comparison to aviation, the atmospheric impacts of $NO_x$ from shipping are relatively minor, as the emissions occur at ground level.

Overall, aggregate greenhouse gas emissions in 2000 from the combustion of international bunker fuels from both aviation and marine activities were 101.2 Tg $CO_2$ Eq., or 12 percent below emissions in 1990 (see Table 2-41). Although emissions from international flights departing from the United States have increased significantly (23 percent), emissions from international shipping voyages departing the United States have decreased by 36 percent since 1990. Increased military activity during the Persian Gulf War resulted in an increased level of military marine emissions in 1990 and 1991; civilian marine emissions during this period exhibited a similar trend.[48] The majority of these emissions were in the form of carbon dioxide; however, small amounts of $CH_4$ and $N_2O$ were also emitted. Emissions of $NO_x$ by aircraft during idle, take-off, landing and at cruising altitudes are of primary concern because of their effects on ground-level ozone formation (see Table 2-42).

Emissions from both aviation and marine international transport activities are expected to grow in the future, as both air traffic and trade increase, although emission rates should decrease over time due to technological changes.[49]

## Methodology

Emissions of $CO_2$ were estimated through the application of carbon content and fraction oxidized factors to fuel consumption activity data. This approach is analogous to that described under $CO_2$ from Fossil Fuel Combustion. A complete description of the methodology and a listing of the various factors employed can be found in Annex A. See Annex I for a specific discussion on the methodology used for estimating emissions from international bunker fuel use by the U.S. military.

Emission estimates for $CH_4$, $N_2O$, CO, $NO_x$, and NMVOCs were calculated by multiplying emission factors by measures of fuel consumption by fuel type and mode. Activity data for aviation included solely jet fuel consumption statistics, while the marine mode included both distillate diesel and residual fuel oil.

## Data Sources

Carbon content and fraction oxidized factors for jet fuel, distillate fuel oil, and residual fuel oil were taken directly from the Energy Information Administration (EIA) of the U.S. Department of Energy and are presented in Annex A. Heat content and density conversions were taken from EIA (2001) and USAF (1998). Emission factors used in the calculations of $CH_4$, $N_2O$, CO, $NO_x$, and NMVOC 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 $CH_4$, 0.1 for $N_2O$, 5.2 for CO, 12.5 for $NO_x$, and 0.78 for NMVOCs. For marine vessels consuming either distillate diesel or residual fuel oil the following values, in the same units, except where noted, were employed: 0.32 for $CH_4$, 0.08 for $N_2O$, 1.9 for CO, 87 for $NO_x$, and 0.052 g/MJ for NMVOCs.

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 2001). 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

[48] See Uncertainty section for a discussion of data quality issues.

[49] Most emission related international aviation and marine regulations are under the rubric of the International Civil Aviation Organization (ICAO) or the International Maritime Organization (IMO), which develop international codes, recommendations, and conventions, such as the International Convention of the Prevention of Pollution from Ships (MARPOL).

**Table 2-41: Emissions from International Bunker Fuels (Tg $CO_2$ Eq.)**

| Gas/Mode | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | **113.9** | **101.0** | **102.3** | **109.9** | **112.9** | **105.3** | **100.2** |
| Aviation | 46.6 | 51.1 | 52.2 | 55.9 | 55.0 | 58.9 | 57.3 |
| Marine | 67.3 | 49.9 | 50.1 | 54.0 | 57.9 | 46.4 | 43.0 |
| **$CH_4$** | **0.2** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** |
| Aviation | + | + | + | + | + | + | + |
| Marine | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **$N_2O$** | **1.0** | **0.9** | **0.9** | **1.0** | **1.0** | **0.9** | **0.9** |
| Aviation | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.6 | 0.6 |
| Marine | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.3 |
| **Total** | **115.0** | **102.1** | **103.3** | **111.0** | **114.0** | **106.4** | **101.2** |

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

**Table 2-42: Emissions from International Bunker Fuels (Gg)**

| Gas/Mode | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | **113,863** | **101,037** | **102,272** | **109,885** | **112,913** | **105,341** | **100,228** |
| Aviation | 46,591 | 51,117 | 52,164 | 55,925 | 55,012 | 58,913 | 57,274 |
| Marine | 67,272 | 49,921 | 50,109 | 53,960 | 57,900 | 46,429 | 42,954 |
| **$CH_4$** | **8** | **6** | **6** | **7** | **7** | **6** | **6** |
| Aviation | 1 | 1 | 1 | 2 | 2 | 2 | 2 |
| Marine | 7 | 5 | 5 | 5 | 6 | 5 | 4 |
| **$N_2O$** | **3** | **3** | **3** | **3** | **3** | **3** | **3** |
| Aviation | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| Marine | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| **CO** | **116** | **113** | **115** | **124** | **125** | **124** | **120** |
| Aviation | 77 | 84 | 86 | 92 | 91 | 97 | 94 |
| Marine | 39 | 29 | 29 | 32 | 34 | 27 | 25 |
| **$NO_x$** | **1,987** | **1,541** | **1,549** | **1,667** | **1,771** | **1,478** | **1,379** |
| Aviation | 184 | 202 | 207 | 222 | 218 | 233 | 227 |
| Marine | 1,803 | 1,339 | 1,343 | 1,446 | 1,553 | 1,244 | 1,152 |
| **NMVOC** | **59** | **48** | **49** | **52** | **55** | **48** | **45** |
| Aviation | 11 | 13 | 13 | 14 | 14 | 15 | 14 |
| Marine | 48 | 36 | 36 | 38 | 41 | 33 | 31 |

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

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 2001). Approximate average fuel prices paid by air carriers for aircraft on international flights was taken from DOT (1991 through 2001) 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 services' 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 2001), and by the Naval Operations Navy Strategic Mobility/Combat Logistics Division (N42

2001). 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 2-43. See Annex I 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 2001). Activity data on distillate diesel consumption by military vessels departing from U.S. ports were provided by DESC (2001) and N42 (2001). 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 2-44.

## 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.[50] 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 2001) 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 2001) 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

**Table 2-43: Aviation Jet Fuel Consumption for International Transport (Million Gallons)**

| Nationality | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| U.S. Carriers | 1,982 | 2,256 | 2,329 | 2,482 | 2,363 | 2,638 | 2,740 |
| Foreign Carriers | 2,062 | 2,549 | 2,629 | 2,918 | 2,935 | 3,085 | 2,818 |
| U.S. Military | 862 | 581 | 540 | 496 | 502 | 488 | 480 |
| **Total** | **4,905** | **5,385** | **5,497** | **5,895** | **5,799** | **6,211** | **6,038** |

Note: Totals may not sum due to independent rounding.

**Table 2-44: Marine Fuel Consumption for International Transport (Million Gallons)**

| End-Use Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Residual Fuel Oil | 4,781 | 3,495 | 3,583 | 3,843 | 3,974 | 3,272 | 2,967 |
| Distillate Diesel Fuel & Other | 617 | 573 | 456 | 421 | 627 | 308 | 290 |
| U.S. Military Naval Fuels | 522 | 334 | 367 | 484 | 518 | 511 | 537 |
| **Total** | **5,920** | **4,402** | **4,406** | **4,748** | **5,119** | **4,091** | **3,794** |

Note: Totals may not sum due to independent rounding.

[50] See uncertainty discussions under $CO_2$ from Fossil Fuel Combustion and Mobile Combustion.

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.[51]

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. 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. 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 emissions estimates could be reduced through additional data collection.

Aircraft and ship fuel data were developed from DoD records, which document fuel sold to the Navy and Air Force by the Defense Logistics Agency. This data may slightly over or under estimate actual fuel use in aircraft and ships because each service may have procured fuel from, sold to, traded, or given fuel to other ships, aircraft, governments, or other entities. Small fuel quantities may have been used in vehicles or equipment other than that which was assumed for each fuel type. In particular, the marine fuel data provided by the Navy Fuels and Logistics office (N42 2001) were inconsistent with previous years' data.

There are also uncertainties in aircraft operations and training activity data. Estimates for the quantity of fuel used in Navy and Air Force flying activities reported as bunker fuel emissions was 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 that 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 also uncertainty in the methodology used to estimate emissions for 1990 through 1994. These emissions were estimated based on the 1995 values of the original data set and extrapolated back in time based on a closely correlated data set of fuel usage.

Although aggregate fuel consumption data has 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

[51] 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.

[52] It should be noted that in the EPA's *National Air Pollutant Emissions Trends, 1900-2000* (EPA 2001), U.S. aviation emission estimates for CO, NOx, and NMVOCs 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 given under Mobile Source Fossil Fuel Combustion 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. EPA (2001) is also likely to include emissions from ocean-going vessels departing from U.S. ports on international voyages.

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 $CO_2$.[52]

There is also concern as to the reliability of the existing DOC (1991 through 2001) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

## Wood Biomass and Ethanol Consumption

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 carbon dioxide ($CO_2$). However, in the long run the carbon dioxide emitted from biomass consumption does not increase atmospheric carbon dioxide concentrations, assuming the biogenic carbon emitted is offset by the uptake of $CO_2$ resulting 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 carbon fluxes from changes in biogenic carbon reservoirs in wooded or crop lands are accounted for in the Land-Use Change and Forestry chapter.

In 2000, $CO_2$ emissions due to burning of woody biomass within the industrial and residential/commercial sectors and by electricity generation were about 174.8 Tg $CO_2$ Eq. (174,770 Gg) (see Table 2-45 and Table 2-46). As the largest consumer of woody biomass, the industrial sector in 2000 was responsible for 78 percent of the $CO_2$ emissions from this source. The residential sector was the second largest emitter, making up 20 percent of total emissions from woody biomass. The commercial end-use sector and electricity generation accounted for the remainder.

Biomass-derived fuel consumption in the United States consisted mainly 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. Ethanol and ethanol blends 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 $CO_2$.

**Table 2-45: $CO_2$ Emissions from Wood Consumption by End-Use Sector (Tg $CO_2$ Eq.)**

| End-Use Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Industrial | 100.2 | 112.0 | 115.1 | 120.9 | 124.9 | 136.7 | 136.0 |
| Residential | 46.4 | 47.6 | 47.5 | 34.6 | 30.9 | 33.1 | 34.6 |
| Commercial | 3.0 | 3.6 | 3.9 | 3.8 | 3.7 | 4.1 | 4.1 |
| Electricity Generation | + | + | + | + | + | + | + |
| **Total** | **149.6** | **163.3** | **166.6** | **159.3** | **159.6** | **173.9** | **174.8** |

Note: Totals may not sum due to independent rounding.

**Table 2-46: $CO_2$ Emissions from Wood Consumption by End-Use Sector (Gg)**

| End-Use Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Industrial | 100,204 | 112,038 | 115,145 | 120,908 | 124,933 | 136,740 | 135,964 |
| Residential | 46,424 | 47,622 | 47,542 | 34,598 | 30,933 | 33,070 | 34,626 |
| Commercial | 2,956 | 3,596 | 3,899 | 3,752 | 3,717 | 4,099 | 4,148 |
| Electricity Generation | 25 | 30 | 30 | 28 | 26 | 31 | 33 |
| **Total** | **149,609** | **163,286** | **166,617** | **159,286** | **159,610** | **173,940** | **174,770** |

Note: Totals may not sum due to independent rounding.

**Table 2-47: $CO_2$ Emissions from Ethanol Consumption**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 4.4 | 4,380 |
| 1995 | 8.1 | 8,099 |
| 1996 | 5.8 | 5,809 |
| 1997 | 7.4 | 7,356 |
| 1998 | 8.1 | 8,128 |
| 1999 | 8.5 | 8,451 |
| 2000 | 9.7 | 9,667 |

In 2000, the United States consumed an estimated 139 trillion Btus of ethanol. Emissions of $CO_2$ in 2000 due to ethanol fuel burning were estimated to be approximately 9.7 Tg $CO_2$ Eq. (8,451 Gg) (see Table 2-47).

Ethanol production dropped sharply in the middle of 1996 because of short corn supplies and high prices. Plant output began to increase toward the end of the growing season, reaching close to normal levels at the end of the year. However, total 1996 ethanol production fell far short of the 1995 level (EIA 1997). Since the low in 1996, production has continued to grow.

## Methodology

Woody biomass emissions were estimated by converting U.S. consumption data in energy units (17.2 million Btu per short ton) to megagrams (Mg) of dry matter using EIA assumptions. Once consumption data for each sector were converted to megagrams of dry matter, the carbon content of the dry fuel was estimated based on default values of 45 to 50 percent carbon in dry biomass. The amount of carbon released from combustion was estimated using 90 percent for the fraction oxidized (i.e., combustion efficiency). Ethanol consumption data in energy units were also multiplied by a carbon coefficient (18.96 mg C/Btu) to produce carbon emission estimates.

## Data Sources

Woody biomass consumption data were provided by EIA (2001) (see Table 2-48). Estimates of wood biomass consumption for fuel combustion do not include wood wastes, liquors, municipal solid waste, tires, etc. that are reported as biomass by EIA. The factor for converting energy units to mass was supplied by EIA (1994). Carbon content and combustion efficiency values were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

**Table 2-49: Ethanol Consumption**

| Year | Trillion Btu |
|---|---|
| 1990 | 63 |
| 1991 | 73 |
| 1992 | 83 |
| 1993 | 97 |
| 1994 | 109 |
| 1995 | 117 |
| 1996 | 84 |
| 1997 | 106 |
| 1998 | 117 |
| 1999 | 122 |
| 2000 | 139 |

**Table 2-48: Woody Biomass Consumption by Sector (Trillion Btu)**

| Year | Industrial | Residential | Commercial | Electric Generation |
|---|---|---|---|---|
| 1990 | 1,254 | 581 | 37 | NO |
| 1991 | 1,190 | 613 | 39 | NO |
| 1992 | 1,233 | 645 | 42 | NO |
| 1993 | 1,255 | 548 | 44 | NO |
| 1994 | 1,342 | 537 | 45 | NO |
| 1995 | 1,402 | 596 | 45 | NO |
| 1996 | 1,441 | 595 | 49 | NO |
| 1997 | 1,513 | 433 | 47 | NO |
| 1998 | 1,564 | 387 | 47 | NO |
| 1999 | 1,711 | 414 | 51 | NO |
| 2000 | 1,702 | 433 | 52 | NO |

NO (Not Occurring)
Emissions from ethanol were estimated using consumption data from EIA (2001) (see Table 2-49). The carbon coefficient used was provided by OTA (1991).

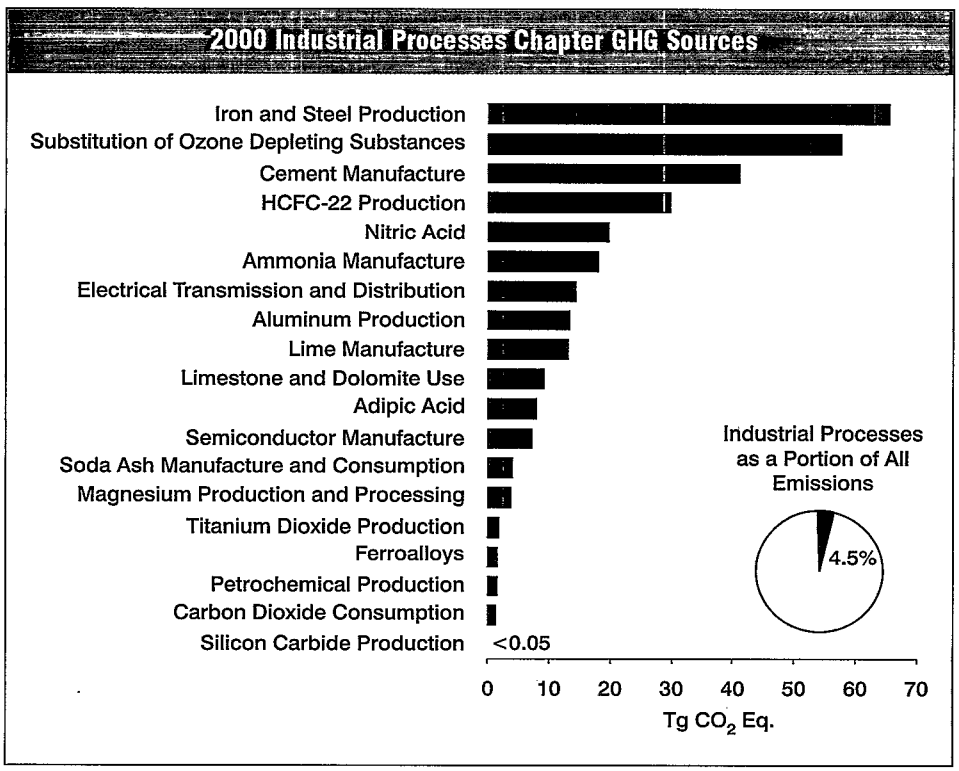
## Uncertainty

The fraction oxidized (i.e., combustion efficiency) factor used is believed to under estimate the efficiency of wood combustion processes in the United States. The IPCC emission factor has been used because better data are not yet available. Increasing the combustion efficiency would increase emission estimates. In addition, according to EIA (1994) commercial wood energy use is typically not reported because there are no accurate data sources to provide reliable estimates. 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.

# 3. Industrial Processes

Greenhouse gas emissions are produced as a by-product of various non-energy-related industrial activities. That is, these emissions are produced from an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically transformed from one state to another. This transformation can result in the release of greenhouse gases such as carbon dioxide ($CO_2$), methane ($CH_4$), or nitrous oxide ($N_2O$). The processes addressed in this chapter include iron and steel production, cement production, ammonia manufacture, lime manufacture, limestone and dolomite use (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash production and use, titanium dioxide production, ferroalloy production, $CO_2$ consumption, aluminum production, petrochemical production, silicon carbide production, nitric acid production, and adipic acid production (see Figure 3-1).

**Figure 3-1**




In addition to the three greenhouse gases listed above, there are also industrial sources of several classes 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. Usage of these gases, especially HFCs, 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 ODS substitutes, HFCs, PFCs, 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. Sulfur hexafluoride is the most potent greenhouse gas the IPCC has evaluated.

In 2000, industrial processes generated emissions of 312.8 Tg $CO_2$ Eq., or 4.5 percent of total U.S. greenhouse gas emissions. Carbon dioxide emissions from all industrial processes were 161.9 Tg $CO_2$ Eq. (161,940 Gg) in the same year. This amount accounted for only 2.8 percent of national $CO_2$ emissions. Methane emissions from petrochemical and silicon carbide production resulted in emissions of approximately 1.7 Tg $CO_2$ Eq. (79 Gg) in 2000, which was less than 1 percent of U.S. $CH_4$ emissions. Nitrous oxide emissions from adipic acid and nitric acid production were 27.9 Tg $CO_2$ Eq. (90 Gg) in 2000, or 6.6 percent of total U.S. $N_2O$ emissions. In the same year, combined emissions of HFCs, PFCs and $SF_6$ totaled 121.3 Tg $CO_2$ Eq. Overall, emissions from industrial processes increased by 6 percent from 1990 to 2000, which was the result of increases in emissions from several industrial processes—the largest being substitutes for ozone depleting substances—which was offset by decreases in emissions from adipic acid production, aluminum production, and production of HCFC-22.

Greenhouse gases are also emitted from a number of industrial processes not addressed in this chapter. For example, caprolactam—a chemical feedstock for the manufacture of nylon 6,6—and urea production are believed to be industrial sources of $N_2O$ emissions. However, emissions for these and other sources have not been estimated due to a lack of information on the emission processes, manufacturing data, or both. As more information becomes available, emission estimates for these processes will be calculated and included in future greenhouse gas emission inventories, although their contribution is expected to be small.[1]

The general method employed to estimate emissions for industrial processes, as recommended by the Intergovernmental Panel on Climate Change (IPCC), involves multiplying production data for each process by an emission factor per unit of production. 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 and, therefore, may not represent U.S. national averages. Additional sources of uncertainty specific to an individual source category are discussed in each section.

Table 3-1 summarizes emissions for the Industrial Processes chapter in units of teragrams of carbon dioxide equivalents (Tg $CO_2$ Eq.), while unweighted gas emissions in gigagrams (Gg) are provided in Table 3-2.

## Iron and Steel Production

In addition to being an energy intensive process, the production of iron and steel also generates process-related emissions of $CO_2$. Iron is produced by first reducing iron oxide (iron ore) with metallurgical coke in a blast furnace to produce pig iron (impure iron containing about 3 to 5 percent carbon by weight). Metallurgical coke is manufactured in a coke plant using coal as a raw material. Coke oven gas and coal tar are carbon by-products of the coke manufacturing process. The metallurgical coke is a raw material supplied to the blast furnace. Coke oven gas is generally burned as a fuel within the steel mill. Coal tar is used as a raw material in the manufacture of anodes used for primary aluminum production and for other electrolytic processes.

Carbon dioxide is produced as the metallurgical coke used in the blast furnace process is oxidized. Steel (containing less than 2 percent carbon by weight) 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 carbon from pig iron used to produce steel. Some carbon is also stored in the finished iron and steel products.

Emissions of $CO_2$ from iron and steel production in 2000 were 65.7 Tg $CO_2$ Eq. (65,709 Gg) (see Table 3-3). Emissions have fluctuated significantly from 1990 to 2000 due to changes in domestic economic conditions and changes in imports and exports. For the past several years, pig iron production has experienced a downward trend, however domestic production recovered somewhat in 2000. Pig iron production in 2000 was 4 percent higher than in 1999, but remains 6 percent below 1995 levels. Asian economic problems and the availability of low-priced imports limit growth in domestic production (USGS 2001).

[1] See AnnexV for a discussion of emission sources excluded.

**Table 3-1: Emissions from Industrial Processes (Tg $CO_2$ Eq.)**

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | **168.2** | **164.1** | **160.4** | **171.2** | **164.2** | **161.4** | **161.9** |
| Iron and Steel Production | 85.4 | 74.4 | 68.3 | 76.1 | 67.4 | 64.4 | 65.7 |
| Cement Manufacture | 33.3 | 36.8 | 37.1 | 38.3 | 39.2 | 40.0 | 41.1 |
| Ammonia Manufacture | 18.5 | 18.9 | 19.5 | 19.5 | 20.1 | 18.9 | 18.0 |
| Lime Manufacture | 11.2 | 12.8 | 13.5 | 13.7 | 13.9 | 13.5 | 13.3 |
| Limestone and Dolomite Use | 5.2 | 7.0 | 7.4 | 8.4 | 8.2 | 9.1 | 9.2 |
| Aluminum Production | 6.3 | 5.3 | 5.6 | 5.6 | 5.8 | 5.9 | 5.4 |
| Soda Ash Manufacture and Consumption | 4.1 | 4.3 | 4.2 | 4.4 | 4.3 | 4.2 | 4.2 |
| Ferroalloy Production | 2.0 | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 | 1.7 |
| Titanium Dioxide Production | 1.3 | 1.7 | 1.7 | 1.8 | 1.8 | 1.9 | 2.0 |
| Carbon Dioxide Consumption | 0.8 | 1.0 | 1.1 | 1.3 | 1.4 | 1.6 | 1.4 |
| **$CH_4$** | **1.2** | **1.5** | **1.6** | **1.6** | **1.7** | **1.7** | **1.7** |
| Petrochemical Production | 1.2 | 1.5 | 1.6 | 1.6 | 1.6 | 1.7 | 1.7 |
| Silicon Carbide Production | + | + | + | + | + | + | + |
| **$N_2O$** | **32.7** | **37.8** | **38.5** | **32.7** | **28.6** | **27.8** | **27.9** |
| Nitric Acid Production | 17.8 | 19.9 | 20.7 | 21.2 | 20.9 | 20.1 | 19.8 |
| Adipic Acid Production | 14.9 | 17.9 | 17.8 | 11.5 | 7.7 | 7.7 | 8.1 |
| **HFCs, PFCs, and $SF_6$** | **93.6** | **98.5** | **111.9** | **116.9** | **127.7** | **120.0** | **121.3** |
| Substitution of Ozone Depleting Substances | 0.9 | 21.8 | 30.6 | 38.0 | 44.9 | 51.3 | 57.8 |
| HCFC-22 Production | 35.0 | 27.0 | 31.1 | 30.0 | 40.2 | 30.4 | 29.8 |
| Electrical Transmission and Distribution | 31.2 | 26.5 | 26.8 | 24.5 | 20.1 | 15.5 | 14.4 |
| Aluminum Production | 18.1 | 11.8 | 12.5 | 11.0 | 9.0 | 8.9 | 7.9 |
| Semiconductor Manufacture | 2.9 | 5.9 | 5.4 | 6.5 | 7.3 | 7.7 | 7.4 |
| Magnesium Production and Processing | 5.5 | 5.5 | 5.5 | 6.9 | 6.2 | 6.1 | 4.0 |
| **Total** | **295.7** | **301.9** | **312.3** | **322.4** | **322.1** | **310.8** | **312.8** |

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

## Methodology

Since coke is consumed as a reducing agent during the manufacture of pig iron, the corresponding quantity of coal consumed during coking operations was identified. This quantity of coal is considered a non-energy use. Data were also collected on the amount of imported coke consumed in the blast furnace process. These data were converted to their energy equivalents. The carbon content of the combusted coal and imported coke was estimated by multiplying their energy consumption by material specific carbon-content coefficients. The carbon-content coefficients used are presented in Annex A.

Emissions from the re-use of scrap steel and imported pig iron in the steel production process were calculated by assuming that all the associated carbon-content of these materials are released on combustion. Steel has an associated carbon-content of approximately 0.4 percent, while pig iron is assumed to contain 4 percent carbon by weight.

Emissions from carbon anodes, used during the production of steel in electric arc furnaces (EAF), were also estimated. Emissions of $CO_2$ were calculated by multiplying the annual production of steel in electric arc furnaces by an emission factor (4.4 kg $CO_2$/ton $steel_{EAF}$). It was assumed that the carbon anodes 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 coking process and its carbon related emissions are already accounted for during the estimation of emissions from coal combustion, the emission factor was reduced by 20 percent to avoid double counting.

Similarly, an adjustment was made to account for the coal tar pitch component of carbon anodes consumed during the production of aluminum. Again, it was assumed that the carbon anodes have a composition of 80 percent petroleum coke and 20 percent coal tar. These coal tar emissions are accounted for in the aluminum production section of this

**Table 3-2: Emissions from Industrial Processes (Gg)**

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| $CO_2$ | **168,165** | **164,057** | **160,358** | **171,156** | **164,238** | **161,356** | **161,940** |
| Iron and Steel Production | 85,414 | 74,357 | 68,324 | 76,127 | 67,429 | 64,376 | 65,709 |
| Cement Manufacture | 33,278 | 36,847 | 37,079 | 38,323 | 39,218 | 39,991 | 41,067 |
| Ammonia Manufacture | 18,510 | 18,946 | 19,512 | 19,477 | 20,113 | 18,874 | 18,017 |
| Lime Manufacture | 11,238 | 12,804 | 13,495 | 13,685 | 13,914 | 13,466 | 13,316 |
| Limestone and Dolomite Use | 5,181 | 7,028 | 7,379 | 8,401 | 8,187 | 9,115 | 9,196 |
| Aluminum Production | 6,315 | 5,265 | 5,580 | 5,621 | 5,792 | 5,895 | 5,410 |
| Soda Ash Manufacture and Consumption | 4,142 | 4,305 | 4,239 | 4,355 | 4,325 | 4,217 | 4,181 |
| Ferroalloy Production | 1,980 | 1,866 | 1,954 | 2,038 | 2,027 | 1,996 | 1,719 |
| Titanium Dioxide Production | 1,308 | 1,670 | 1,657 | 1,836 | 1,819 | 1,853 | 1,963 |
| Carbon Dioxide Consumption | 800 | 968 | 1,140 | 1,294 | 1,413 | 1,572 | 1,361 |
| $CH_4$ | **57** | **73** | **76** | **78** | **79** | **80** | **79** |
| Petrochemical Production | 56 | 72 | 75 | 77 | 78 | 79 | 79 |
| Silicon Carbide Production | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| $N_2O$ | **106** | **122** | **124** | **106** | **92** | **90** | **90** |
| Nitric Acid Production | 58 | 64 | 67 | 68 | 67 | 65 | 64 |
| Adipic Acid Production | 48 | 58 | 57 | 37 | 25 | 25 | 26 |
| HFCs, PFCs, and $SF_6$ | **M** | **M** | **M** | **M** | **M** | **M** | **M** |
| Substitution of Ozone Depleting Substances | M | M | M | M | M | M | M |
| HCFC-22 Production[a] | 3 | 2 | 3 | 3 | 3 | 3 | 3 |
| Electrical Transmission and Distribution[b] | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Aluminum Production | M | M | M | M | M | M | M |
| Semiconductor Manufacture | M | M | M | M | M | M | M |
| Magnesium Production and Processing[b] | + | + | + | + | + | + | + |

+ Does not exceed 0.5 Gg
M (Mixture of gases)
[a] HFC-23 emitted
[b] $SF_6$ emitted
Note: Totals may not sum due to independent rounding.

chapter. To prevent double counting, 20 percent of the emissions reported in the aluminum section have been subtracted from the estimates for iron and steel production.

Carbon storage was accounted for by assuming that all domestically manufactured steel had a carbon content of 0.4 percent. Furthermore, any pig iron that was not consumed during steel production, but fabricated into finished iron products, was assumed to have a carbon content by weight of 4 percent.

**Table 3-3: $CO_2$ Emissions from Iron and Steel Production**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 85.4 | 85,414 |
| 1995 | 74.4 | 74,357 |
| 1996 | 68.3 | 68,324 |
| 1997 | 76.1 | 76,127 |
| 1998 | 67.4 | 67,429 |
| 1999 | 64.4 | 64,376 |
| 2000 | 65.7 | 65,709 |

## Data Sources

Data relating to the amount of coal consumed at coke plants, for the production of coke for domestic consumption in blast furnaces, as well as, the quantity of coke imported for iron production were taken from Energy Information Administration (EIA), *Quarterly Coal Report* October-December 2000 (EIA 2000); *U.S. Coal Domestic and International Issues* (EIA 2001); *Mineral Yearbook: Iron and Steel* (USGS 2000a, 1999, 1997, 1995a, 1993) and American Iron and Steel Institute (AISI), *Annual Statistical Report* (AISI 2000). Scrap steel and imported pig iron consumption data for 1990 through 2000 were obtained from *Annual Statistical Reports* (AISI 2000, 1995). Crude steel production, as well as pig iron use for purposes other than steel production, was also obtained from *Annual Statistical Reports* (AISI 2001, 1996). Carbon content percentages for pig iron and crude steel and the $CO_2$ emission factor for carbon anode emissions from steel production were obtained from *IPCC Good Practice Guidance and Uncertainty*

*Management* (IPCC 2000). Aluminum production data for 1990 through 2000 were obtained from *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1995b, 1998, 2000b, 2001). The $CO_2$ emission factor for carbon anode emissions from aluminum production was taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Estimates for the composition of carbon anodes used during steel and aluminum production were obtained from *Energy and Environmental Profile of the U.S. Aluminum Industry* (DOE 1997).

## Uncertainty

Estimating $CO_2$ emissions from coal and coke combustion is based on energy consumption data, average carbon contents, and the fraction of carbon oxidized produce a relatively accurate estimate of $CO_2$ emissions. However, there are uncertainties associated with each of these factors. For example, carbon 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 carbon anodes (80 percent petroleum coke and 20 percent coal tar). For example, within the aluminum industry, the coal tar pitch content of anodes can vary from 15 percent in prebaked anodes to 24 to 28 percent in Soderberg anode pastes (DOE 1997). An average value was assumed and applied to all carbon anodes utilized during aluminum and steel production. The assumption is also made that all coal tar used during anode production originates as a by-product of the domestic coking process. Similarly, it was assumed that all pig iron and crude steel have carbon contents of 4 percent and 0.4 percent, respectively. The carbon content of pig iron can vary between 3 and 5 percent, while crude steel can have a carbon content of up to 2 percent, although it is typically less than 1 percent (IPCC 2000).

There is uncertainty in the most accurate $CO_2$ emission factor for carbon anode consumption in aluminum production. Emissions vary depending on the specific technology used by each plant (Prebake or Soderberg). The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) provide $CO_2$ emission factors for each technology type. Using information gathered from the Voluntary Aluminum Industrial Partnership (VAIP) program, it was assumed that production was split 80 percent prebake and 20 percent Soderberg for the whole time series. Similarly, the carbon anode emission factor for steel production can vary between 3.7 and 5.5 kg $CO_2$/ton steel (IPCC 2000). For this analysis, the upper bound value was used.

# Cement Manufacture

Cement manufacture is an energy and raw material intensive process resulting in the generation of carbon dioxide ($CO_2$) from both the energy consumed in making the cement and the chemical process itself.[2] Cement production has accounted for about 2.4 percent of total global industrial and energy-related $CO_2$ emissions (IPCC 1996), and the United States is the world's third largest cement producer. Cement is manufactured in almost every U.S. state. Carbon dioxide emitted from the chemical process of cement production represents one of the largest sources of industrial $CO_2$ emissions in the United States.

During the cement production process, calcium carbonate ($CaCO_3$) is heated in a cement kiln at a temperature of about 1,300°C (2,400°F) to form lime (i.e., calcium oxide or CaO) and $CO_2$. This process is known as calcination or calcining. Next, the lime is combined with silica-containing materials to produce clinker (an intermediate product), with the earlier by-product $CO_2$ being released to the atmosphere. The clinker is then allowed to cool, mixed with a small amount of gypsum, and used to make Portland cement. The production of masonry cement from Portland cement requires additional lime and, thus, results in additional $CO_2$ emissions. However, this additional lime is already accounted for in the Lime Manufacture source category in this chapter; therefore, the additional emissions from making masonry cement from clinker are not counted in this source category's total. They are presented here for informational purposes only.

In 2000, U.S. clinker production—including Puerto Rico—totaled 79,417 thousand metric tons, and U.S. masonry cement production was estimated to be 4,275 thousand metric tons (USGS 2001). The resulting emissions

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

**Table 3-4: $CO_2$ Emissions from Cement Production***

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 33.3 | 33,278 |
| 1995 | 36.8 | 36,847 |
| 1996 | 37.1 | 37,079 |
| 1997 | 38.3 | 38,323 |
| 1998 | 39.2 | 39,218 |
| 1999 | 40.0 | 39,991 |
| 2000 | 41.1 | 41,066 |

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

of $CO_2$ from clinker production were estimated to be 41.1 Tg $CO_2$ Eq. (41,066 Gg) (see Table 3-4). Emissions from masonry production from clinker raw material were estimated to be 0.1 Tg $CO_2$ Eq. (96 Gg) in 2000, but again are accounted for under Lime Manufacture.

After falling in 1991 by 2 percent from 1990 levels, cement production emissions have grown every year since. Overall, from 1990 to 2000, emissions increased by 23 percent. In 2000, output by cement plants increased 3 percent over 1999, to 79,417 thousand metric tons. Cement is 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

Carbon dioxide emissions from cement manufacture are created by the chemical reaction of carbon-containing minerals (i.e., calcining limestone). While in the kiln, limestone is broken down into $CO_2$ and lime with the $CO_2$ released to the atmosphere. The quantity of the $CO_2$ 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 $CO_2$:

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

Carbon dioxide emissions were estimated by applying an emission factor, in tons of $CO_2$ released per ton of clinker produced, to the total amount of clinker produced. The emission factor used in this analysis is the product of the average lime fraction for clinker of 64.6 percent (IPCC 2000) and a constant reflecting the mass of $CO_2$ released per unit of lime. This calculation yields an emission factor of 0.507 tons of $CO_2$ per ton of clinker produced, which was determined as follows:

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 2 percent of the $CO_2$ emissions calculated from clinker production. Total cement production emissions were calculated by adding the emissions from clinker production to the emissions assigned to CKD (IPCC 2000).

Masonry cement requires additional lime over and above the lime used in clinker production. In particular, non-plasticizer additives such as lime, slag, and shale are added to the cement, increasing its weight by approximately 5 percent. Lime accounts for approximately 60 percent of this added weight. Thus, the additional lime is equivalent to roughly 2.86 percent of the starting amount of the product, since:

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

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

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

## Data Sources

The activity data for clinker and masonry cement production (see Table 3-5) were obtained from U.S. Geological Survey (USGS 1992, 1995a, 1995b, 1996, 1997, 1998, 1999, 2000, 2001). The data were compiled by USGS through questionnaires sent to domestic clinker and cement manufacturing plants.

**Table 3-5: Cement Production (Gg)**

| Year | Clinker | Masonry |
|---|---|---|
| 1990 | 64,355 | 3,209 |
| 1991 | 62,918 | 2,856 |
| 1992 | 63,415 | 3,093 |
| 1993 | 66,957 | 2,975 |
| 1994 | 69,786 | 3,283 |
| 1995 | 71,257 | 3,603 |
| 1996 | 71,706 | 3,469 |
| 1997 | 74,112 | 3,634 |
| 1998 | 75,842 | 3,989 |
| 1999 | 77,337 | 4,375 |
| 2000 | 79,417 | 4,275 |

## Uncertainty

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker, in the amount of lime added to masonry cement, and in the percentage of CKD recycled inside the clinker kiln. The lime content of clinker varies from 64 to 66 percent. CKD loss can range from 1.5 to 8 percent depending upon plant specifications. Additionally, some amount of $CO_2$ is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with $CO_2$ in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of surface area. Because the amount of $CO_2$ reabsorbed is thought to be minimal, it was not estimated.

# Ammonia Manufacture

Emissions of carbon dioxide ($CO_2$) occur during the production of synthetic ammonia. In the United States, roughly 98 percent of synthetic ammonia is produced by catalytic steam reforming of natural gas. The remainder is produced using naphtha (a petroleum fraction) as a feedstock or through the electrolysis of brine at chlorine plants (EPA 1997). The natural gas-based and naphtha-based processes produce $CO_2$ and hydrogen ($H_2$), the latter of which is used in the production of ammonia. The brine electrolysis process does not lead to $CO_2$ emissions.

There are five principal process steps in synthetic ammonia production from natural gas feedstock. The primary reforming step converts methane to $CO_2$, carbon monoxide (CO), and $H_2$ in the presence of a catalyst. Only 30 to 40 percent of the methane feedstock to the primary reformer is converted to CO and $CO_2$. The secondary reforming step converts the remaining methane feedstock to CO and $CO_2$. The CO in the process gas from the secondary reforming step (representing approximately 15 percent of the process gas) is converted to $CO_2$ in the presence of a catalyst, water, and air in the shift conversion step. Carbon dioxide is removed from the process gas by the shift conversion process, and the hydrogen gas is combined with the nitrogen 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 methane, including primary and secondary reforming and the shift conversion processes, is approximately as follows:

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

$$N_2 + 3\ H_2 \rightarrow 2\ NH_3$$

Emissions of $CO_2$ from ammonia production in 2000 were 18.0 Tg $CO_2$ Eq. (18,017 Gg). Carbon dioxide emissions from this source are summarized in Table 3-6.

## Methodology

Emissions of $CO_2$ were calculated by multiplying annual estimates of ammonia production by an emission factor (1.2 ton $CO_2$/ton $NH_3$). It was assumed that all ammonia was produced using conventional catalytic steam reformation and natural gas feedstock, although small amounts may have been produced using reforming of naphtha feedstock or electrolysis of chlorine brines. The actual amount produced using these alternative methods is not known, but assumed to be small, constituting less than

**Table 3-6: $CO_2$ Emissions from Ammonia Manufacture**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 18.5 | 18,510 |
| 1995 | 18.9 | 18,946 |
| 1996 | 19.5 | 19,512 |
| 1997 | 19.5 | 19,477 |
| 1998 | 20.1 | 20,113 |
| 1999 | 18.9 | 18,874 |
| 2000 | 18.0 | 18,017 |

**Table 3-7: Ammonia Manufacture**

| Year | Thousand Metric Tons |
|---|---|
| 1990 | 15,425 |
| 1991 | 15,576 |
| 1992 | 16,261 |
| 1993 | 15,599 |
| 1994 | 16,211 |
| 1995 | 15,788 |
| 1996 | 16,260 |
| 1997 | 16,231 |
| 1998 | 16,761 |
| 1999 | 15,728 |
| 2000 | 15,014 |

2 percent of all ammonia production. It was also assumed that 100 percent of the carbon in the natural gas feedstock to the ammonia synthesis process is ultimately converted to $CO_2$ and emitted to the atmosphere as process exhaust gas.

## Data Sources

The emission factor of 1.2 ton $CO_2$/ton $NH_3$ was taken from the European Fertilizer Manufacturers Association Best Available Techniques publication, *Production of Ammonia* (EFMA 1995). The EFMA reported an emission factor range of 1.15 to 1.30 ton $CO_2$/ton $NH_3$ with 1.2 ton $CO_2$/ton $NH_3$ as a typical value. The EFMA reference also indicates that more than 99 percent of the methane feedstock to the catalytic reforming process is ultimately converted to $CO_2$. Ammonia production data (see Table 3-7) were obtained from the Census Bureau of the U.S. Department of Commerce (Census Bureau 1998, 2000) as reported in *Chemical and Engineering News,* "Facts & Figures for the Chemical Industry."

## Uncertainty

It is uncertain how accurately the emission factor used represents an average across all ammonia plants. The EFMA reported an emission factor range of 1.15 to 1.30 ton $CO_2$/ton $NH_3$, with 1.2 ton $CO_2$/ton $NH_3$ reported as a typical value. The actual emission factor depends upon the amount of air used in the ammonia production process, with 1.15 ton $CO_2$/ton $NH_3$ being the approximate stoichiometric minimum that is achievable for the conventional reforming process. By using natural gas consumption data for each ammonia plant, more accurate estimates of $CO_2$ emissions from ammonia production could be calculated. However, these consumption data are often considered confidential. Also, natural gas is consumed at ammonia plants both as a feedstock to the reforming process and also for generating process heat and steam. Natural gas consumption data, if available, would need to be divided into feedstock use (non-energy) and process heat and steam (fuel) use in order to be used for the Inventory, as $CO_2$ emissions from fuel use and non-energy use are calculated separately in the Inventory.[3]

Natural gas feedstock consumption data for the U.S. ammonia industry as a whole is available from the Energy Information Administration (EIA) *Manufacturers Energy Consumption Survey* (MECS) for the years 1985, 1988, 1991, 1994 and 1998 (EIA 1994; EIA 1998). These feedstock consumption data collectively correspond to an effective average emission factor of 1.0 ton $CO_2$/ton $NH_3$, which appears to be below the stoichiometric minimum that is achievable for the conventional steam reforming process.

[3] It appears, for example, that the IPCC emission factor for ammonia production of 1.5 tonne $CO_2$ per tonne ammonia may include both $CO_2$ emissions from the natural gas feedstock to the process and some $CO_2$ emissions from the natural gas used to generate process heat and steam for the process. Table 2-5, Ammonia Production Emission Factors, in Volume 3 of the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual (IPCC, 1997) includes two emission factors, one reported for Norway and one reported for Canada. The footnotes to the table indicate that the factor for Norway does not include natural gas used as fuel but that it is unclear whether the factor for Canada includes natural gas used as fuel. However, the factors for Norway and Canada are nearly identical (1.5 and 1.6 tonnes $CO_2$ per tonne ammonia, respectively) and it is likely that if one value includes fuel use the other value also does. Further, for the conventional steam reforming process the EFMA reports an emission factor range for feedstock $CO_2$ of 1.15 to 1.30 tonnes per tonne (with a typical value of 1.2 tonne per tonne) and a emission factor for fuel $CO_2$ of 0.5 tonnes per tonne. This corresponds to a total $CO_2$ emission factor for the ammonia production process, including both feedstock $CO_2$ and process heat $CO_2$, of 1.7 tonne per tonne, which is closer to the emission factors reported in the IPCC 1996 Reference Guidelines than to the feedstock-only $CO_2$ emission factor of 1.2 tonne $CO_2$ per tonne ammonia reported by the EFMA.

The EIA data for natural gas consumption for the years 1994 and 1998 correspond more closely to the $CO_2$ emissions calculated using the EFMA emission factor than do data for previous years. The 1994 and 1998 data alone yield an effective emission factor of 1.1 ton $CO_2$/ton $NH_3$, corresponding to $CO_2$ emissions estimates that are approximately 1.5 Tg $CO_2$ Eq. below the estimates calculated using the EFMA emission factor of 1.2 ton $CO_2$/ ton $NH_3$. Natural gas feedstock consumption data are not available from EIA for other years, and data for 1991 and previous years may underestimate feedstock natural gas consumption, and therefore the emission factor was used to estimate $CO_2$ emissions from ammonia production, rather than EIA data.

All ammonia production in this analysis was assumed to be from the same process; conventional catalytic reforming of natural gas feedstock. However, actual emissions could differ because processes other than catalytic steam reformation and feedstocks other than natural gas may have been used for ammonia production.

## Lime Manufacture

Lime is an important manufactured product with many industrial, chemical, and environmental applications. Its major uses are in steel making, flue gas desulfurization (FGD) at coal-fired electric power plants, construction, pulp and paper manufacturing, and water purification. Lime has historically ranked fifth in total production of all chemicals in the United States. For U.S. operations, the term "lime" actually refers to a variety of chemical compounds. These include calcium oxide (CaO), or high-calcium quicklime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; dolomitic quicklime ([CaO•MgO]); and dolomitic hydrate ([$Ca(OH)_2$•MgO] or [$Ca(OH)_2$•$Mg(OH)_2$]).

Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide is generated during the calcination stage, when limestone—mostly calcium carbonate ($CaCO_3$)—is roasted at high temperatures in a kiln to produce CaO and $CO_2$. The $CO_2$ is driven off as a gas and is normally emitted to the atmosphere. Some of the $CO_2$ generated during the production process, however, is recovered at some facilities for use in sugar refining and precipitated calcium carbonate (PCC)[4] production. It is also important to note that, for certain applications, lime reabsorbs $CO_2$ during use (see Uncertainty, below).

Lime production in the United States—including Puerto Rico—was reported to be 19,541 thousand metric tons in 2000 (USGS 2001). This resulted in an estimated $CO_2$ emissions of 13.3 Tg $CO_2$ Eq. (13,316 Gg) (see Table 3-8 and Table 3-9).

**Table 3-8: $CO_2$ Emissions from Lime Manufacture**

| Year | Tg $CO_2$ Eq. |
|---|---|
| 1990 | 11.2 |
| 1995 | 12.8 |
| 1996 | 13.5 |
| 1997 | 13.7 |
| 1998 | 13.9 |
| 1999 | 13.5 |
| 2000 | 13.3 |

**Table 3-9: $CO_2$ Emissions from Lime Manufacture (Gg)**

| Year | Potential | Recovered* | Emissions |
|---|---|---|---|
| 1990 | 11,730 | (493) | 11,238 |
| 1995 | 13,701 | (896) | 12,804 |
| 1996 | 14,347 | (852) | 13,495 |
| 1997 | 14,649 | (964) | 13,685 |
| 1998 | 14,975 | (1,061) | 13,914 |
| 1999 | 14,655 | (1,188) | 13,466 |
| 2000 | 14,549 | (1,233) | 13,316 |

* For sugar refining and precipitated calcium carbonate production
Note: Totals may not sum due to independent rounding.

At the turn of the 20th Century, over 80 percent of lime consumed in the United States went for construction uses. The contemporary quicklime market is distributed across its four end-use categories as follows: metallurgical uses, 38 percent; environmental uses, 26 percent; chemical and industrial uses, 24 percent; and construction uses, 11 percent. Construction end-uses are still important to the hydrated lime market, accounting for 52 percent of consumption. However, hydrated lime constitutes only 8 percent of the total lime market (USGS 2001).

[4] Precipitated calcium carbonate is a specialty filler used in premium-quality coated and uncoated papers.

Lime production in 2000 declined less than 1 percent from 1999, the second consecutive drop in annual production. Overall, from 1990 to 2000, lime production increased by 23 percent. The increase in production is attributed in part to growth in demand for environmental applications, especially flue gas desulfurization (FGD) technologies. In 1993, the U.S. Environmental Protection Agency (EPA) completed regulations under the Clean Air Act capping sulfur dioxide ($SO_2$) emissions from electric utilities. Lime scrubbers' high efficiencies and increasing affordability have allowed the FGD end-use to expand from 10 percent of total lime consumption in 1990 to 16 percent in 2000 (USGS 1992, 2001).

## Methodology

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

For high-calcium lime:

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

For dolomitic lime:

$$(88.02\ g\ CO_2/mole) \div [(97.01\ g\ CaO{\bullet}MgO/mole) \div (0.95\ g\ CaO{\bullet}MgO/g\ lime)] = 0.86\ g\ CO_2/g\ lime$$

Production is adjusted to remove the mass of chemically combined water found in hydrated lime (see Table 3-11), using the midpoint of default ranges provided by the *IPCC Good Practice Guidance* (IPCC 2000). These factors set the chemically combined water content to 27 percent for high-calcium hydrated lime, and 24 percent for dolomitic hydrated lime.

Lime production in the United States was 19,541 thousand metric tons in 2000 (USGS 2001), resulting in potential $CO_2$ emissions of 14,549 Gg. Some of the $CO_2$ generated during the production process, however, was recovered for use in sugar refining and precipitated calcium carbonate (PCC) production. Combined lime manufacture by these producers was 2,067 thousand metric tons in 2000, generating 1.5 Tg of $CO_2$. It was assumed that approximately 80 percent of the $CO_2$ involved in sugar refining and PCC was recovered.

## Data Sources

The activity data for lime manufacture and lime consumption by sugar refining and precipitated calcium carbonate (PCC) for 1990 through 2000 (see Table 3-10) were obtained from USGS (1992, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001). The CaO and CaO•MgO contents of lime were obtained from the *IPCC Good Practice Guidance* (IPCC 2000). Since data for the individual lime types was not provided prior to 1997, total lime production for 1990 through 1996 was allocated according to the 1997 distribution. For lime consumption, it was assumed that 100 percent was high-calcium based on communication with the National Lime Association (Males 2001).

**Table 3-10: Lime Production and Lime Use for Sugar Refining and PCC (Thousand Metric Tons)**

| Year | High-Calcium Production[a] | Dolomite Production[a,b] | Use |
|---|---|---|---|
| 1990 | 12,947 | 2,895 | 826 |
| 1991 | 12,840 | 2,838 | 964 |
| 1992 | 13,307 | 2,925 | 1,023 |
| 1993 | 13,741 | 3,024 | 1,279 |
| 1994 | 14,274 | 3,116 | 1,374 |
| 1995 | 15,193 | 3,305 | 1,503 |
| 1996 | 15,856 | 3,434 | 1,429 |
| 1997 | 16,120 | 3,552 | 1,616 |
| 1998 | 16,750 | 3,423 | 1,779 |
| 1999 | 16,110 | 3,598 | 1,992 |
| 2000 | 16,350 | 3,191 | 2,067 |

[a] Includes hydrated limes.
[b] Includes dead-burned dolomite.

**Table 3-11: Hydrated Lime Production (Thousand Metric Tons)**

| Year | High-Calcium Hydrate | Dolomitic Hydrate |
|---|---|---|
| 1990 | 1,781 | 319 |
| 1991 | 1,841 | 329 |
| 1992 | 1,892 | 348 |
| 1993 | 1,908 | 342 |
| 1994 | 1,942 | 348 |
| 1995 | 2,027 | 363 |
| 1996 | 1,858 | 332 |
| 1997 | 1,820 | 352 |
| 1998 | 1,950 | 383 |
| 1999 | 2,010 | 298 |
| 2000 | 1,550 | 421 |

## Uncertainty

Uncertainties in the emission estimate 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). Carbon dioxide reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce precipitated calcium carbonate (PCC) reacts with $CO_2$; whereas most of the lime used in steelmaking 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.[5] As more information becomes available, this emission estimate will be adjusted accordingly.

In some cases, lime is generated from calcium carbonate by-products at paper mills and water treatment plants.[6] The lime generated by these processes is not included in the USGS data for commercial lime consumption. In the paper industry, mills that employ the sulfate process (i.e., Kraft) consume lime in order to causticize a waste sodium carbonate solution (i.e., black liquor). Most sulfate mills recover the waste calcium carbonate 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 biogenic in origin, and therefore would not be included in Inventory totals.

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.

# Limestone and Dolomite Use

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 to generate $CO_2$ 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 (FGD) systems for utility and industrial plants, as a raw material in glass manufacturing, or in magnesium production.

In 2000, approximately 16,314 thousand metric tons of limestone and 4,019 thousand metric tons of dolomite were used for these applications. Overall, both limestone and dolomite usage resulted in aggregate $CO_2$ emissions of 9.2 Tg $CO_2$ Eq. (9,196 Gg) (see Table 3-12 and Table 3-13).

Emissions in 2000 increased 1 percent from the previous year and 77 percent since 1990. In the future, increases in demand for crushed stone are anticipated. Demand for crushed stone from the transportation sector continues to drive growth in limestone and dolomite use. The Transportation Equity Act

[5] Representatives of the National Lime Association estimate that $CO_2$ reabsorption that occurs from the use of lime may offset as much as a third of the $CO_2$ emissions from calcination.

[6] 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 to the atmosphere.

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

**Table 3-12: $CO_2$ Emissions from Limestone & Dolomite Use (Tg $CO_2$ Eq.)**

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Flux Stone | 3.0 | 3.9 | 4.2 | 5.0 | 5.1 | 6.1 | 6.1 |
| Glass Making | 0.2 | 0.5 | 0.4 | 0.4 | 0.2 | 0.2 | 0.2 |
| FGD | 1.9 | 2.6 | 2.7 | 2.9 | 2.8 | 2.8 | 2.8 |
| Magnesium Production | 0.1 | + | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Total** | **5.2** | **7.0** | **7.4** | **8.4** | **8.2** | **9.1** | **9.2** |

Note: Totals may not sum due to independent rounding.

**Table 3-13: $CO_2$ Emissions from Limestone & Dolomite Use (Gg)**

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Flux Stone** | **3,005** | **3,903** | **4,249** | **5,042** | **5,142** | **6,065** | **6,144** |
| Limestone | 2,554 | 2,523 | 3,330 | 3,970 | 4,298 | 4,273 | 4,329 |
| Dolomite | 452 | 1,380 | 919 | 1,072 | 844 | 1,792 | 1,816 |
| **Glass Making** | **189** | **526** | **362** | **383** | **191** | **194** | **197** |
| Limestone | 189 | 421 | 251 | 266 | 65 | 67 | 67 |
| Dolomite | NA | 105 | 110 | 117 | 125 | 128 | 129 |
| **FGD** | **1,922** | **2,558** | **2,695** | **2,902** | **2,781** | **2,781** | **2,781** |
| **Magnesium Production** | **64** | **41** | **73** | **73** | **73** | **73** | **73** |
| **Total** | **5,182** | **7,028** | **7,379** | **8,401** | **8,187** | **9,115** | **9,196** |

NA (Not Available)
Note: Totals may not sum due to independent rounding.

for the 21st Century, which commits over $200 billion dollars to highway work through 2003, is expected to maintain the upward trend in consumption.

## Methodology

Carbon dioxide emissions were calculated by multiplying the amount of limestone consumed by an average carbon content for limestone, approximately 12.0 percent for limestone and 13.2 percent for dolomite (based on stoichiometry). Assuming that all of the carbon was oxidized and released to the atmosphere, the appropriate emission factor was multiplied by the annual level of consumption for flux stone, glass manufacturing, and FGD systems to determine emissions.

Carbon dioxide emitted during the thermic reduction of dolomite ($CaMg(CO_3)_2$) to magnesium metal vapor were estimated based on magnesium production capacity and the magnesium to carbon molar ratio. Operation at maximum operational capacity is assumed, this overestimation accounts for less than ideal (chemically) production. Stoichiometrically, two carbon molecules are emitted per magnesium molecule. One plant in the United States produces magnesium metal from the dolomitic process, the other production method used in the United States produces magnesium from magnesium chloride (electrolytic reduction). Capacity fluctuations are due to variable furnace availability.

## Data Sources

Consumption data for 1990 through 2000 of limestone and dolomite used as flux stone and in glass manufacturing (see Table 3-14) and production capacity of dolomitic magnesium metal (see Table 3-15) were obtained from the USGS (1993, 1995a, 1995b, 1996, 1997, 1998, 1999, 2000, 2001). Consumption data for limestone used in FGD were taken from unpublished survey data in the Energy Information Administration's Form EIA-767, "Steam Electric Plant Operation and Design Report," (EIA 1997, 1998, 1999). For 1990 and 1994, the USGS did not provide a breakdown of limestone and dolomite production by end-use and for 2000 the end-use breakdowns had not yet been finalized at the time of publication. Consumption figures for these years were estimated by assuming that limestone and dolomite accounted for the same percentage of total crushed stone consumption for a given year as the average

**Table 3-14: Limestone and Dolomite Consumption (Thousand Metric Tons)**

| Activity | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Flux Stone** | **6,737** | **6,052** | **5,185** | **4,263** | **5,487** | **8,586** | **9,468** | **11,239** | **11,512** | **13,415** | **13,590** |
| Limestone | 5,804 | 5,213 | 4,447 | 3,631 | 3,149 | 5,734 | 7,569 | 9,024 | 9,769 | 9,712 | 9,838 |
| Dolomite | 933 | 838 | 738 | 632 | 2,339 | 2,852 | 1,899 | 2,215 | 1,743 | 3,703 | 3,751 |
| **Glass Making** | **430** | **386** | **495** | **622** | **949** | **1,174** | **799** | **847** | **407** | **415** | **421** |
| Limestone | 430 | 386 | 495 | 622 | 949 | 958 | 571 | 605 | 148 | 151 | 153 |
| Dolomite | NA | NA | NA | NA | NA | 216 | 228 | 242 | 259 | 264 | 267 |
| **FGD** | **4,369** | **4,606** | **4,479** | **4,274** | **5,080** | **5,815** | **6,125** | **6,595** | **6,322** | **6,322** | **6,322** |

NA (Not Available)

**Table 3-15: Dolomitic Magnesium Metal Production Capacity (Metric Tons)**

| Year | Production Capacity |
|---|---|
| 1990 | 35,000 |
| 1991 | 35,000 |
| 1992 | 14,909 |
| 1993 | 12,964 |
| 1994 | 21,111 |
| 1995 | 22,222 |
| 1996 | 40,000 |
| 1997 | 40,000 |
| 1998 | 40,000 |
| 1999 | 40,000 |
| 2000 | 40,000 |
| 2001 | 29,167 |

of the percentages for the years before and after.[8] Furthermore, following 1996, limestone used in glass manufacture has only been reported for 1998. For 1996 and 1997, limestone used in glass manufacture was estimated based on the percent of total crushed stone for 1995 and 1998. For 1999 and 2000, limestone used in glass manufacture was estimated based on the percent of total crushed stone for 1998.

It should be noted that 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 as flux stone and for glass manufacture. 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.[9]

## Uncertainty

Uncertainties in this estimate are due in part, to variations in the chemical composition of limestone. In addition to calcite, limestone may contain smaller amounts of magnesia, silica, and sulfur. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process, the kind of ore processed, and the final use of the slag. Similarly, the quality of the limestone used for glass manufacturing will depend on the type of glass being manufactured.

Uncertainties also exist in the activity data. Much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses. Also, some of the limestone reported as "limestone" is believed to actually be dolomite, which has a higher carbon content than limestone. Lastly, the uncertainty of the estimates for limestone used in glass making are especially high. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey respondees. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. However, since glass making accounts for no more than 10 percent of limestone consumption, its contribution to the overall emissions estimate is low.

[8] Exception: 1990 and 2000 consumption were estimated using the percentages for only 1991 and 1999, respectively.

[9] This approach was recommended by USGS.

## Soda Ash Manufacture and Consumption

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 the largest soda ash-producing country in the world. 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 Wyoming has net emissions of $CO_2$. This difference is a result of the production processes employed in each State.[10] During the production process used in Wyoming, natural sources of sodium carbonate are heated and transformed into a crude soda ash that requires further refining. Carbon dioxide ($CO_2$) 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 2000, $CO_2$ emissions from the manufacture of soda ash from trona were approximately 1.5 Tg $CO_2$ Eq. (1,529 Gg). Soda ash consumption in the United States also generated 2.7 Tg $CO_2$ Eq. (2,652 Gg) in 2000. Total emissions from this source in 2000 were then 4.2 Tg $CO_2$ Eq. (4,181 Gg) (see Table 3-16 and Table 3-17). Emissions have fluctuated since 1990. These fluctuations were strongly related to the behavior of the export market and the U.S. economy. Emissions in 2000 decreased by 1 percent from the previous year, and have increased 1 percent since 1990.

The United States has the world's largest deposits of trona and represents about one-third of total world soda ash output. The distribution of soda ash by end-use in 2000 was glass making, 50 percent; chemical production, 27 percent; soap and detergent manufacturing, 11 percent; distributors, 6 percent; flue gas desulfurization, and pulp and paper production, 2 percent each; and water treatment and miscellaneous, 1 percent each (USGS 2001).

**Table 3-16: $CO_2$ Emissions from Soda Ash Manufacture and Consumption**

| Year | Tg $CO_2$ Eq. |
|---|---|
| 1990 | 4.1 |
| 1995 | 4.3 |
| 1996 | 4.2 |
| 1997 | 4.4 |
| 1998 | 4.3 |
| 1999 | 4.2 |
| 2000 | 4.2 |

**Table 3-17: $CO_2$ Emissions from Soda Ash Manufacture and Consumption (Gg)**

| Year | Manufacture | Consumption | Total |
|---|---|---|---|
| 1990 | 1,432 | 2,710 | 4,142 |
| 1995 | 1,607 | 2,698 | 4,305 |
| 1996 | 1,588 | 2,652 | 4,239 |
| 1997 | 1,666 | 2,689 | 4,355 |
| 1998 | 1,607 | 2,718 | 4,325 |
| 1999 | 1,549 | 2,668 | 4,217 |
| 2000 | 1,529 | 2,652 | 4,181 |

Note: Totals may not sum due to independent rounding.

Soda ash production and consumption decreased by 1 percent from 1999 values. Exports were a driving force behind U.S. soda ash production and the Asian economic crisis beginning in late 1997 has been cited as a major cause for the drop in world soda ash demand. However, growing demand in Asia and South America is expected to lead to moderate growth (between 0.5 and 1 percent) in U.S. soda ash production.

Construction is currently underway on a major soda ash plant that will use a new feedstock—nahcolite, a natural sodium bicarbonate found in deposits in Colorado's Piceance Creek Basin. The new facility will have an annual capacity of 900,000 tons of soda ash and is slated to open in January 2001 (USGS 2000). Part of this production

[10] 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.

process involves the stripping of $CO_2$. At this point, however, it is unknown whether any $CO_2$ will be released to the atmosphere or captured and used for conversion back to sodium bicarbonate.

## Methodology

During the production process, trona ore is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as by-products of the calcination process. Carbon dioxide emissions from the calcination of trona can be estimated based on the following chemical reaction:

$$2(Na_3H(CO_3)_2 \times 2H_2O) \rightarrow 3Na_2CO_3 + 5H_2O + CO_2$$

[trona] [soda ash]

Based on this formula, approximately 10.27 metric tons of trona are required to generate one metric ton of $CO_2$. Thus, the 15.7 million metric tons of trona mined in 2000 for soda ash production (USGS 2001) resulted in $CO_2$ emissions of approximately 1.5 Tg $CO_2$ Eq. (1,529 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 carbon is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of carbon (or 0.415 metric tons of $CO_2$) are released for every metric ton of soda ash consumed.

## Data Sources

The activity data for trona production and soda ash consumption (see Table 3-18) were taken from USGS (1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001). Soda ash manufacture and consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry. All six of the soda ash manufacturing operations in the United States completed surveys to provide data to the USGS.

## Uncertainty

Emissions from soda ash manufacture are considered to be relatively certain. Both the emissions factor and activity data are reliable. However, 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, uncertainty exists as to the accuracy of the emission factors.

**Table 3-18: Soda Ash Manufacture and Consumption (Thousand Metric Tons)**

| Year | Manufacture* | Consumption |
|---|---|---|
| 1990 | 14,734 | 6,527 |
| 1991 | 14,674 | 6,278 |
| 1992 | 14,900 | 6,360 |
| 1993 | 14,500 | 6,350 |
| 1994 | 14,600 | 6,240 |
| 1995 | 16,500 | 6,510 |
| 1996 | 16,300 | 6,470 |
| 1997 | 17,100 | 6,670 |
| 1998 | 16,500 | 6,550 |
| 1999 | 15,900 | 6,430 |
| 2000 | 15,700 | 6,390 |

* Soda ash manufactured from trona ore only.

# Ferroalloy Production

Carbon dioxide is emitted from the production of several ferroalloys. Ferroalloys are composites of iron and other elements often including 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. As a result, government information disclosure rules prevent the publication of production data for them. 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. The CO is eventually oxidized, becoming $CO_2$. A representative reaction equation for the production of 50 percent ferrosilicon is given below:

Emissions of $CO_2$ from ferroalloy production in 2000 were 1.7 Tg $CO_2$ Eq. (1,719 Gg) (see Table 3-19).

**Table 3-19: $CO_2$ Emissions from Ferroalloy Production**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 2.0 | 1,980 |
| 1995 | 1.9 | 1,866 |
| 1996 | 2.0 | 1,954 |
| 1997 | 2.0 | 2,038 |
| 1998 | 2.0 | 2,027 |
| 1999 | 2.0 | 1,996 |
| 2000 | 1.7 | 1,719 |

## Methodology

Emissions of $CO_2$ from ferroalloy production were calculated by multiplying annual ferroalloy production by material-specific emission factors. Emission factors taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) 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 ferrosilicon 50 percent (2.35 tons $CO_2$/ton of alloy produced) was applied. Additionally, for ferrosilicon alloys containing 56 to 95 percent silicon, an emission factor for ferrosilicon 75 percent (3.9 tons $CO_2$ per ton alloy produced) was applied. The emission factor for silicon metal was assumed to be 4.3 tons $CO_2$/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/UNEP/OECD/IEA 1997) although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite carbon inputs. The amount of petroleum coke consumed in ferroalloy production was calculated assuming that the petroleum coke used is 90 percent carbon and 10 percent inert material.

## Data Sources

Emission factors for ferroalloy production were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Ferroalloy production data for 1990 through 1999 (see Table 3-20) were obtained from the U.S. Geological Survey's (USGS) *Minerals Yearbook: Silicon Annual Report* (USGS 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000). Data for 2000 were obtained from USGS (2001) *Mineral Industry Surveys – Silicon in December 2000*. Until 1999, the USGS reported production of ferrosilicon 25 to 55 percent 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 3-20). The composition data for petroleum coke was obtained from Onder and Bagdoyan (1993).

## Uncertainty

Although some ferroalloys may be produced using wood or other biomass as a carbon 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 carbon is of biogenic origin.[11] Emissions from ferroalloys produced with coking coal or graphite inputs would be counted in national trends, but may generate differing amounts of $CO_2$ per unit of ferroalloy produced compared to the use of petroleum coke. The most accurate method for these estimates would be basing calculations on the amount of reducing agent used in the process, rather than the amount of ferroalloys produced. These data were not available, however.

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.

# Titanium Dioxide Production

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 $TiO_2$ 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

[11] Emissions and sinks of biogenic carbon are accounted for in the Land-Use Change and Forestry chapter.

**Table 3-20: 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 | 72,444 |
| 1995 | 181,000 | 128,000 | 163,000 | 99,500 |
| 1996 | 182,000 | 132,000 | 175,000 | 110,000 |
| 1997 | 175,000 | 147,000 | 187,000 | 106,000 |
| 1998 | 162,000 | 147,000 | 195,000 | 99,800 |
| 1999 | 252,000 | 145,000 | 195,000 | NA |
| 2000 | 229,000 | 100,000 | 184,000 | NA |

NA (Not Available)

sulfate process. Carbon dioxide is emitted from the chloride process, which 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 carbon as a raw material and does not emit $CO_2$. In 2000, approximately 93 percent of the titanium dioxide production capacity was chloride process and the remainder was sulfate process.

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 carbon 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 $CO_2$. More than 90 percent of U.S. $TiO_2$ was produced through chloride process, and a special grade of petroleum coke is manufactured specifically for this purpose. Emissions of $CO_2$ from titanium dioxide production have grown from 1.3 Tg $CO_2$ Eq. (1,308 Gg) in 1990 to 2.0 Tg $CO_2$ Eq. (1,963 Gg) in 2000, due to growth in titanium dioxide production (see Table 3-21).

**Table 3-21: $CO_2$ Emissions from Titanium Dioxide**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 1.3 | 1,308 |
| 1995 | 1.7 | 1,670 |
| 1996 | 1.7 | 1,657 |
| 1997 | 1.8 | 1,836 |
| 1998 | 1.8 | 1,819 |
| 1999 | 1.9 | 1,853 |
| 2000 | 2.0 | 1,963 |

## Methodology

Emissions of $CO_2$ from titanium dioxide production were calculated by multiplying annual titanium dioxide production by chlorine process-specific emission factors.

Data were obtained for the total amount of titanium dioxide produced each year, and it was assumed that 93 percent of the total production in 2000 was produced using the chloride process. 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 titanium dioxide produced using the chloride process was produced using petroleum coke, although some titanium dioxide may have been produced with graphite or other carbon inputs. The amount of petroleum coke consumed annually in titanium dioxide production was calculated based on the assumption that petroleum coke used in the process is 90 percent carbon and 10 percent inert materials.

## Data Sources

The emission factor for the titanium dioxide chloride process was taken from the report *Everything You've Always Wanted to Know about Petroleum Coke* (Onder and Bagdoyan 1993). Titanium dioxide production data for 1990 through 1999 (see Table 3-22) were obtained from the U.S. Geological Survey's (USGS) *Minerals Yearbook: Titanium Annual Report* (USGS 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000). Data for 2000 were obtained from USGS (2001) *Mineral Industry Surveys – Titanium in December 2000.* Data for the percentage of the total titanium dioxide production capacity that is chloride process for 1994 through 1999 were also taken from the USGS *Minerals Yearbook*. Percentage chloride process data were not available for 1990 through 1993, and data from the 1994

**Table 3-22: Titanium Dioxide Production**

| Year | Metric Tons |
|---|---|
| 1990 | 979,000 |
| 1991 | 992,000 |
| 1992 | 1,140,000 |
| 1993 | 1,160,000 |
| 1994 | 1,250,000 |
| 1995 | 1,250,000 |
| 1996 | 1,230,000 |
| 1997 | 1,340,000 |
| 1998 | 1,330,000 |
| 1999 | 1,350,000 |
| 2000 | 1,440,000 |

USGS *Minerals Yearbook* were used for these years. The chloride process percentage for 2000 was estimated from data published in the *Chemical Market Report* (2000). The composition data for petroleum coke were obtained from Onder and Bagdoyan (1993).

## Uncertainty

Although some titanium dioxide may be produced using graphite or other carbon inputs, information and data regarding these practices were not available. Titanium dioxide produced using graphite inputs may generate differing amounts of $CO_2$ per unit of titanium dioxide produced compared to the use of petroleum coke. The most accurate method for these estimates would be basing calculations on the amount of reducing agent used in the process, rather than the amount of titanium dioxide produced. These data were not available, however.

Also, annual titanium production is not reported by USGS by the type of production process used (chloride or sulfate). Only the percentage of total production capacity is reported. It was assumed that titanium dioxide 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. 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 titanium dioxide production, literature data were used for petroleum coke composition. Certain grades of petroleum coke are manufactured specifically for use in the titanium dioxide chloride process, however this composition information was not available.

# Carbon Dioxide Consumption

Carbon dioxide ($CO_2$) is used for a variety of applications, including food processing, chemical production, carbonated beverages, and enhanced oil recovery (EOR). Carbon dioxide used for EOR is injected into the ground to increase reservoir pressure, and is therefore considered sequestered.[12] For the most part, however, $CO_2$ used in non-EOR applications will eventually be released to the atmosphere.

Carbon dioxide is produced from a small number of natural wells, as a by-product from the production of chemicals (e.g., ammonia), or separated from crude oil and natural gas. Depending on the raw materials that are used, the by-product $CO_2$ generated during these production processes may already be accounted for in the $CO_2$ emission estimates from fossil fuel consumption (either during combustion or from non-fuel uses). For example, ammonia is primarily manufactured using natural gas as a feedstock. Carbon dioxide emissions from this process are accounted for in the Energy chapter under Fossil Fuel Combustion and, therefore, are not included here.

In 2000, $CO_2$ emissions from this source not accounted for elsewhere were 1.4 Tg $CO_2$ Eq. (1,361 Gg) (see Table 3-23). This amount represents a decrease of 13 percent from the previous year and is 70 percent higher than emissions in 1990.

## Methodology

Carbon dioxide emission estimates were based on $CO_2$ consumption with the assumption that the end-use applications, except enhanced oil recovery, eventually release 100 percent of the $CO_2$ into the

[12] It is unclear to what extent the $CO_2$ used for EOR will be re-released. For example, the $CO_2$ used for EOR may show up at the wellhead after a few years of injection (Hangebrauk et al. 1992). This $CO_2$, however, is typically recovered and re-injected into the well. More research is required to determine the amount of $CO_2$ that in fact escapes from EOR operations. For the purposes of this analysis, it is assumed that all of the $CO_2$ remains sequestered.

**Table 3-23: $CO_2$ Emissions from Carbon Dioxide Consumption**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 0.8 | 800 |
| 1995 | 1.0 | 968 |
| 1996 | 1.1 | 1,140 |
| 1997 | 1.3 | 1,294 |
| 1998 | 1.4 | 1,413 |
| 1999 | 1.6 | 1,572 |
| 2000 | 1.4 | 1,361 |

atmosphere. Carbon dioxide consumption for uses other than enhanced oil recovery was about 6,807 thousand metric tons in 2000. The Freedonia Group estimates that, in the United States, there is an 80 percent to 20 percent split between $CO_2$ produced as a by-product and $CO_2$ produced from natural wells. Thus, emissions are equal to 20 percent of $CO_2$ consumption. The remaining 80 percent was assumed to already be accounted for in the $CO_2$ emission estimates from other categories (the most important being Fossil Fuel Combustion).

## Data Sources

Carbon dioxide consumption data (see Table 3-24) were obtained from *Industrial Gases to 2004*, published by the Freedonia Group Inc. (1994, 1996, 1999a, 1999b, 2000). The 2000 report contains actual data for 1999 only. Data for 1996 were obtained by personal communication with Paul Ita of the Freedonia Group Inc. (Ita 1997). Data for 1997 and 2000 production were calculated from annualized growth rates for 1994 through 1996 and 1997 through 1999 respectively. The 1997 and 2000 values for enhanced oil recovery were set equal to the 1998 and 1999 values, respectively. The percent of carbon dioxide produced from natural wells was obtained from Freedonia Group Inc. (1991).

**Table 3-24: Carbon Dioxide Consumption**

| Year | Thousand Metric Tons |
|---|---|
| 1990 | 4,000 |
| 1991 | 4,200 |
| 1992 | 4,410 |
| 1993 | 4,559 |
| 1994 | 4,488 |
| 1995 | 4,842 |
| 1996 | 5,702 |
| 1997 | 6,468 |
| 1998 | 7,067 |
| 1999 | 6,512 |
| 2000 | 6,807 |

## Uncertainty

Uncertainty exists in the assumed allocation of carbon dioxide produced from fossil fuel by-products (80 percent) and carbon dioxide produced from wells (20 percent). In addition, it is possible that $CO_2$ recovery exists in particular end-use sectors. Contact with several organizations did not provide any information regarding recovery. More research is required to determine the quantity, if any, that may be recovered.

# Petrochemical Production

Small amounts of methane ($CH_4$) are released during the production of some petrochemicals. Petrochemicals are chemicals isolated or derived from petroleum or natural gas. Emissions are presented here from the production of five chemicals: carbon black, ethylene, ethylene dichloride, styrene, and methanol.

Carbon black is an intensely black powder made by the incomplete combustion of an aromatic petroleum feedstock. Most carbon black produced in the United States is added to rubber to impart strength and abrasion resistance, and the tire industry is by far the largest consumer. Ethylene is consumed in the production processes of the plastics industry including polymers such as high, low, and linear low density polyethylene (HDPE, LDPE, LLDPE), polyvinyl chloride (PVC), ethylene dichloride, ethylene oxide, and ethylbenzene. Ethylene dichloride is one of the first manufactured chlorinated hydrocarbons with reported production as early as 1795. In addition to being an important intermediate in the synthesis of chlorinated hydrocarbons, ethylene dichloride is used as an industrial solvent and as a fuel additive. Styrene is a common precursor for many plastics, rubber, and resins. It can be found in many construction products, such as foam insulation, vinyl flooring, and epoxy adhesives. 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. The United States produces close to one quarter of the world's supply of methanol.

Aggregate emissions of $CH_4$ from petrochemical production in 2000 were 1.7 Tg $CO_2$ Eq. (79 Gg) (see Table 3-25).

**Table 3-25: $CH_4$ Emissions from Petrochemical Production**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 1.2 | 56 |
| 1995 | 1.5 | 72 |
| 1996 | 1.6 | 75 |
| 1997 | 1.6 | 77 |
| 1998 | 1.6 | 78 |
| 1999 | 1.7 | 79 |
| 2000 | 1.7 | 79 |

## Methodology

Emissions of $CH_4$ were calculated by multiplying annual estimates of chemical production by an emission factor. The following factors were used: 11 kg $CH_4$/metric ton carbon black, 1 kg $CH_4$/metric ton ethylene, 0.4 kg $CH_4$/metric ton ethylene dichloride,[13] 4 kg $CH_4$/metric ton styrene, and 2 kg $CH_4$/metric ton methanol. These emission factors were based upon measured material balances. Although the production of other chemicals may also result in methane emissions, there were not sufficient data to estimate their emissions.

## Data Sources

Emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Annual production data for 1990 through 1998 (see Table 3-26) were obtained from the Chemical Manufacturer's Association *Statistical Handbook* (CMA 1999). Production for 1999 and 2000 was projected by the American Chemistry Council (2001).

## Uncertainty

The emission factors used here were based on a limited number of studies. Using plant-specific factors instead of average factors could increase the accuracy of the emissions estimates, however, such data were not available. There may also be other significant sources of methane arising from petrochemical production activities that have not been included in these estimates.

# Silicon Carbide Production

Methane is emitted from the production of silicon carbide, a material used as an industrial abrasive. To make silicon carbide (SiC), quartz ($SiO_2$) is reacted with carbon in the form of petroleum coke. Methane is produced during this reaction from volatile compounds in the petroleum coke. Although $CO_2$ is also emitted from this production process, the requisite data were unavailable for these calculations. Regardless, they are already accounted for under $CO_2$ from Fossil Fuel Combustion in the Energy chapter. Emissions of $CH_4$ from silicon carbide production in 2000 (see Table 3-27) were 1 Gg $CH_4$ (0.01 Tg $CO_2$ Eq.).

**Table 3-27: $CH_4$ Emissions from Silicon Carbide Production**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | + | 1 |
| 1995 | + | 1 |
| 1996 | + | 1 |
| 1997 | + | 1 |
| 1998 | + | 1 |
| 1999 | + | 1 |
| 2000 | + | 1 |

+ Does not exceed 0.05 Tg $CO_2$ Eq.

**Table 3-26: Production of Selected Petrochemicals (Thousand Metric Tons)**

| Chemical | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Carbon Black | 1,306 | 1,225 | 1,365 | 1,452 | 1,492 | 1,524 | 1,560 | 1,588 | 1,610 | 1,642 | 1,674 |
| Ethylene | 16,542 | 18,124 | 18,563 | 18,709 | 20,201 | 21,199 | 22,197 | 23,088 | 23,474 | 25,119 | 24,971 |
| Ethylene Dichloride | 6,282 | 6,221 | 6,872 | 8,141 | 8,482 | 7,829 | 9,303 | 10,324 | 11,080 | 10,309 | 9,866 |
| Styrene | 3,637 | 3,681 | 4,082 | 4,565 | 5,112 | 5,167 | 5,387 | 5,171 | 5,183 | 5,410 | 5,421 |
| Methanol | 3,785 | 3,948 | 3,666 | 4,782 | 4,904 | 4,991 | 5,280 | 5,743 | 5,861 | 5,303 | 5,221 |

[13] The emission factor obtained from IPCC/UNEP/OECD/IEA (1997), page 2.23 is assumed to have a misprint; the chemical identified should be dichloroethylene ($C_2H_2Cl_2$) instead of ethylene dichloride ($C_2H_4Cl_2$).

## Methodology

Emissions of $CH_4$ were calculated by multiplying annual silicon carbide production by an emission factor (11.6 kg $CH_4$/ metric ton silicon carbide). This emission factor was derived empirically from measurements taken at Norwegian silicon carbide plants (IPCC/UNEP/OECD/IEA 1997).

## Data Sources

The emission factor was taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Production data for 1990 through 2000 (see Table 3-28) were obtained from the *Minerals Yearbook: Volume I-Metals and Minerals, Manufactured Abrasives* (USGS 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001).

**Table 3-28: Production of Silicon Carbide**

| Year | Metric Tons |
|---|---|
| 1990 | 105,000 |
| 1991 | 78,900 |
| 1992 | 84,300 |
| 1993 | 74,900 |
| 1994 | 84,700 |
| 1995 | 75,400 |
| 1996 | 73,600 |
| 1997 | 68,200 |
| 1998 | 69,800 |
| 1999 | 65,000 |
| 2000 | 45,000 |

## Uncertainty

The emission factor used here was based on one study of Norwegian plants. The applicability of this factor to average U.S. practices at silicon carbide plants is uncertain. A better 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. These data were not available, however.

# Adipic Acid Production

Adipic acid production has been identified as an anthropogenic source of nitrous oxide ($N_2O$) emissions. Worldwide, there are few adipic acid plants. The United States is the major producer with three companies in four locations accounting for approximately forty percent of world production. Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, coatings, plastics, urethane foams, elastomers, and synthetic lubricants. Commercially, it is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Approximately 80 percent of all adipic acid produced in the United States is used in the production of nylon 6,6. Food grade adipic acid is also used to provide some foods with a "tangy" flavor.

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. Nitrous oxide is generated as a by-product of the nitric acid oxidation stage and is emitted in the waste gas stream. Process emissions from the production of adipic acid will vary with the types of technologies and level of emissions 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.[14] Only one small plant, representing approximately two percent of production, does not control for $N_2O$.

Nitrous oxide emissions from this source were estimated to be 8.11 Tg $CO_2$ Eq. (26.2 Gg) in 2000 (see Table 3-29).

[14] During 1997, the $N_2O$ emission controls installed by the third plant operated for approximately a quarter of the year.

**Table 3-29: $N_2O$ Emissions from Adipic Acid Production**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 14.9 | 48 |
| 1995 | 17.9 | 58 |
| 1996 | 17.8 | 57 |
| 1997 | 11.5 | 37 |
| 1998 | 7.7 | 25 |
| 1999 | 7.7 | 25 |
| 2000 | 8.1 | 26 |

**Table 3-30: Adipic Acid Production**

| Year | Thousand Metric Tons |
|---|---|
| 1990 | 735 |
| 1991 | 771 |
| 1992 | 708 |
| 1993 | 765 |
| 1994 | 815 |
| 1995 | 816 |
| 1996 | 835 |
| 1997 | 860 |
| 1998 | 866 |
| 1999 | 1,100 |
| 2000 | 1,128 |

National adipic acid production has increased about 50 percent over the period of 1990 through 2000, to approximately 1.1 million metric tons. This increase was primarily due to a 120,000 metric ton expansion in production capacity and rising demand for engineering plastics. At the same time, emissions have been significantly reduced due to the widespread installation of pollution control measures.

## Methodology

For two plants, emission estimates were based on information obtained directly from the plant engineer. For the other two plants, $N_2O$ emissions were calculated by multiplying adipic acid production by the ratio of $N_2O$ emitted per unit of adipic acid produced and adjusting for the actual percentage of $N_2O$ released as a result of plant-specific emission controls. Because emissions of $N_2O$ in the United States are not regulated, emissions have not been well characterized. However, on the basis of experiments (Thiemens and Trogler 1991), the overall reaction stoichiometry for $N_2O$ production in the preparation of adipic acid was estimated at approximately 0.3 kg of $N_2O$ per kilogram of product. Emissions are estimated using the following equation:

$N_2O$ emissions = [production of adipic acid] × [0.3 kg $N_2O$ / kg adipic acid] × [ 1 – ($N_2O$ destruction factor × abatement system utility factor) ]

The "$N_2O$ destruction factor" represents the amount of $N_2O$ expressed as a percentage of $N_2O$ emissions that are destroyed by the currently installed abatement technology. The "abatement system utility factor" represents the percent of time that the abatement equipment operates. Overall, in the United States, two of the plants employ catalytic destruction, one plant employs thermal destruction, and the smallest plant uses no $N_2O$ abatement equipment. The $N_2O$ abatement system destruction factor is assumed to be 95 percent for catalytic abatement and 98 percent for thermal abatement (Reimer et al. 1999, Reimer 1999).

## Data Sources

National adipic acid production data for 1990 through 1995 (see Table 3-30) were obtained from *Chemical and Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992, 1993, 1994, 1995, 1996). For 1996 and 1997 data were projected from the 1995 manufactured total based upon suggestions from industry contacts. For 1998, production data were obtained from *Chemical Week,* Product focus: adipic acid/adiponitrile (CW 1999). Production data for 1999 are based on an estimate provided by the adipic acid industry (Reimer 2000). The production data for the smallest plant in 2000 was obtained from *Chemical Week* (Westervelt 2000). The emission factor was taken from Thiemens and Trogler (1991). Adipic acid plant capacities for 1998, 1999, and 2000 were updated using *Chemical Week,* Product focus: adipic acid/adiponitrile (CW 1999, 2001). Plant capacities for previous years were obtained from *Chemical Market Reporter* (1998). The national production and plant capacities were utilized for two of the four plants. Information for the other two plants was taken directly from the plant engineer (Childs 2000).

## Uncertainty

Because $N_2O$ emissions are controlled in some adipic acid production facilities, the amount of $N_2O$ that is actually released will depend on the level of controls in place at a specific production plant. Thus, in order to calculate emissions, it is necessary to have production data on a plant-specific basis. In most cases, however, these data are confidential. As a result, plant-specific production figures were estimated by allocating total adipic acid production using existing plant capacities. This creates a degree of uncertainty in the adipic acid production data used to derive the emission estimates as it is necessary to assume that all plants operate at equivalent utilization levels. For two of the plants, estimates were calculated based on information obtained directly from the plant.

The emission factor was based on experiments (Thiemens and Trogler 1991) that attempt to replicate the industrial process and, thereby, measure the reaction stoichiometry for $N_2O$ production in the preparation of adipic acid. However, the extent to which the lab results are representative of actual industrial emission rates is not known.

# Nitric Acid Production

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 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 affective 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. Currently, it is estimated that approximately 20 percent of nitric acid plants use NSCR (Choe, et al. 1993). The remaining 80 percent use SCR or extended absorption, neither of which is known to reduce $N_2O$ emissions.

**Table 3-31: $N_2O$ Emissions from Nitric Acid Production**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 17.8 | 58 |
| 1995 | 19.9 | 64 |
| 1996 | 20.7 | 67 |
| 1997 | 21.2 | 68 |
| 1998 | 20.9 | 67 |
| 1999 | 20.1 | 65 |
| 2000 | 19.8 | 64 |

Nitrous oxide emissions from this source were estimated at 19.8 Tg $CO_2$ Eq. (64 Gg) in 2000 (see Table 3-31). Emissions from nitric acid production have increased 11 percent since 1990.

## Methodology

Nitrous oxide emissions were calculated by multiplying nitric acid production by the amount of $N_2O$ emitted per unit of nitric acid produced. The emissions factor was determined as a weighted average of 2 kg for plants using non-selective catalytic reduction (NSCR) systems and 9.5 kg for plants not equipped with NSCR (Reimer et al. 1992). An estimated 20 percent of $HNO_3$ plants in the United States were equipped with NSCR (Choe, et al. 1993). In the process of destroying $NO_x$, NSCR systems also destroy 80 to 90 percent of the $N_2O$. Hence, the emission factor is equal to $(9.5 \times 0.80) + (2 \times 0.20) = 8$ kg $N_2O$ / metric ton $HNO_3$.

## Data Sources

Nitric acid production data for 1990 through 2000 (see Table 3-32) were obtained from *Chemical and Engineering News*, "Facts and Figures" (C&EN 2001). The emission factor range was taken from Reimer et al. (1992).

**Table 3-32: Nitric Acid Production**

| Year | Thousand Metric Tons |
|---|---|
| 1990 | 7,196 |
| 1991 | 7,191 |
| 1992 | 7,381 |
| 1993 | 7,488 |
| 1994 | 7,905 |
| 1995 | 8,020 |
| 1996 | 8,351 |
| 1997 | 8,557 |
| 1998 | 8,423 |
| 1999 | 8,115 |
| 2000 | 7,981 |

## Uncertainty

In general, the nitric acid industry is not well categorized. A significant degree of uncertainty exists in nitric acid production figures because nitric acid plants are often part of larger production facilities, such as fertilizer or explosives manufacturing. As a result, only a small volume of nitric acid is sold on the market making production quantities difficult to track. Emission factors are also difficult to determine because of the large number of plants using many different technologies. Based on expert judgment, it is estimated that the $N_2O$ destruction factor for NSCR nitric acid facilities is associated with an uncertainty of approximately ± 10 percent.

## Substitution of Ozone Depleting Substances

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used primarily 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.[15] 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, unlike ODSs, 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 3-33 and Table 3-34.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—a component of the refrigerant blend R-500 used in chillers—and HFC-134a in refrigeration end-uses. Beginning in 1992, HFC-134a was used in growing amounts as a refrigerant in motor vehicle air conditioners and in refrigerant blends such as R-404A.[16]

**Table 3-33: Emissions of HFCs and PFCs from ODS Substitution (Tg $CO_2$ Eq.)**

| Gas | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| HFC-23 | + | 0.1 | 0.2 | 0.2 | 0.3 | 0.4 | 0.5 |
| HFC-32 | + | + | + | + | + | + | 0.1 |
| HFC-125 | + | 1.3 | 1.9 | 2.5 | 3.1 | 3.6 | 4.4 |
| HFC-134a | 0.7 | 15.9 | 21.1 | 26.2 | 30.0 | 33.9 | 37.6 |
| HFC-143a | + | 0.4 | 0.8 | 1.3 | 1.9 | 2.6 | 3.4 |
| HFC-236fa | + | + | + | 0.1 | 0.8 | 1.3 | 1.9 |
| $CF_4$ | + | + | + | + | + | + | + |
| Others* | 0.2 | 4.1 | 6.7 | 7.7 | 8.8 | 9.4 | 10.0 |
| **Total** | **0.9** | **21.8** | **30.6** | **38.0** | **44.9** | **51.3** | **57.8** |

+ Does not exceed 0.05 Tg $CO_2$ Eq.
* Others include HFC-152a, HFC-227ea, 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.

[15] [42 U.S.C § 7671, CAA § 601]

[16] R-404 contains HFC-125, HFC-143a, and HFC-134a.

**Table 3-34: Emissions of HFCs and PFCs from ODS Substitution (Mg)**

| Gas | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| HFC-23 | + | 8 | 14 | 20 | 28 | 36 | 45 |
| HFC-32 | + | + | 3 | 7 | 11 | 17 | 94 |
| HFC-125 | + | 478 | 675 | 889 | 1,116 | 1,289 | 1,559 |
| HFC-134a | 564 | 12,232 | 16,211 | 20,166 | 23,089 | 26,095 | 28,906 |
| HFC-143a | + | 111 | 209 | 334 | 488 | 676 | 903 |
| HFC-236fa | + | + | + | 15 | 120 | 213 | 296 |
| $CF_4$ | + | + | + | + | + | 1 | 1 |
| Others* | M | M | M | M | M | M | M |

M (Mixture of Gases)
+ Does not exceed 0.5 Mg
* Others include HFC-152a, HFC-227ea, HFC-4310mee and PFC/PFPEs, which are a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

In 1993, the use of HFCs in foam production and as an aerosol propellant began, and in 1994 these compounds also found applications as solvents and sterilants. In 1995, ODS substitutes for halons entered widespread use in the United States as halon production was phased-out.

The use and subsequent emissions of HFCs and PFCs as ODS substitutes has been increasing from small amounts in 1990 to 57.8 Tg $CO_2$ Eq. in 2000. 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 in 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.

## Methodology and Data Sources

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 40 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 J.

## Uncertainty

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates must be made using analytical tools such as the Vintaging Model or the methods outlined in IPCC/UNEP/OECD/IEA (1997). Though the model is more comprehensive than the IPCC default methodology, significant uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

**Table 3-35: $CO_2$ Emissions from Aluminum Production**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 6.3 | 6,315 |
| 1995 | 5.3 | 5,265 |
| 1996 | 5.6 | 5,580 |
| 1997 | 5.6 | 5,621 |
| 1998 | 5.8 | 5,792 |
| 1999 | 5.9 | 5,895 |
| 2000 | 5.4 | 5,410 |

**Table 3-36: PFC Emissions from Aluminum Production (Tg $CO_2$ Eq.)**

| Year | $CF_4$ | $C_2F_6$ | Total |
|---|---|---|---|
| 1990 | 15.8 | 2.3 | 18.1 |
| 1995 | 10.5 | 1.3 | 11.8 |
| 1996 | 11.1 | 1.4 | 12.5 |
| 1997 | 9.8 | 1.2 | 11.0 |
| 1998 | 8.1 | 0.9 | 9.0 |
| 1999 | 8.0 | 0.9 | 8.9 |
| 2000 | 7.1 | 0.8 | 7.9 |

Note: Totals may not sum due to independent rounding.

## Aluminum Production

Aluminum is a light-weight, malleable, and corrosion resistant metal that is used in many manufactured products including aircraft, automobiles, bicycles, and kitchen utensils. In 2000, the United States was the largest producer of primary aluminum, with 15 percent of the world total (USGS 2001). 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 several greenhouse gases including carbon dioxide ($CO_2$) and two perfluorocarbons (PFCs): perfluoromethane ($CF_4$) and perfluoroethane ($C_2F_6$).

Carbon dioxide is emitted during the aluminum smelting process when alumina (aluminum oxide, $Al_2O_3$) is reduced to aluminum using the Hall-Heroult reduction process. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite ($Na_3AlF_6$). The reduction cells contain a carbon lining that serves as the cathode. Carbon is also contained in the anode, which can be a carbon mass of paste, coke briquettes, or prebaked carbon blocks from petroleum coke. During reduction, some of this carbon is oxidized and released to the atmosphere as $CO_2$.

Process emissions of $CO_2$ from aluminum production were estimated at 5.4 Tg $CO_2$ Eq. (5,410 Gg) in 2000 (see Table 3-35). The carbon anodes consumed during aluminum production consist of petroleum coke and, to a minor extent, coal tar pitch. The petroleum coke portion of the total $CO_2$ process emissions from aluminum production is considered to be a non-energy use of petroleum coke, and is accounted for in the Industrial Processes chapter and not with Fossil Fuel Combustion emissions in the Energy chapter. Similarly, the coal tar pitch portion of these $CO_2$ process emissions is subtracted from the Iron and Steel section—where it would otherwise be counted—to avoid double-counting.

In addition to $CO_2$ emissions, the aluminum production industry is also the largest source of PFC emissions in the United States. During the smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, 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. The more frequent and long-lasting the anode effects, the greater the emissions.

Primary aluminum production-related emissions of PFCs are estimated to have declined 56 percent since 1990. Since 1990, emissions of $CF_4$ and $C_2F_6$ have declined 55 and 64 percent, respectively, to 7.1 Tg $CO_2$ Eq. of $CF_4$ (1.10 Gg $CF_4$) and 0.8 Tg $CO_2$ Eq. of $C_2F_6$ (0.1 Gg $C_2F_6$) in 2000, as shown in Table 3-36 and Table 3-37. This decline was due to both reductions in domestic aluminum production and actions taken by aluminum smelting companies to reduce the frequency and duration of anode effects.

**Table 3-37: PFC Emissions from Aluminum Production (Gg)**

| Year | $CF_4$ | $C_2F_6$ |
|---|---|---|
| 1990 | 2.4 | 0.2 |
| 1995 | 1.6 | 0.1 |
| 1996 | 1.7 | 0.1 |
| 1997 | 1.5 | 0.1 |
| 1998 | 1.2 | 0.1 |
| 1999 | 1.2 | 0.1 |
| 2000 | 1.1 | 0.1 |

U.S. primary aluminum production for 2000—totaling 3,468 thousand metric tons—decreased slightly from 1999.[17] This decrease is attributed to the curtailment of production at several U.S. smelters, due to high electric power costs in various regions of the country. The transportation industry remained the largest domestic consumer of aluminum, accounting for about 37 percent (USGS 2001).

## Methodology

Carbon dioxide is generated during alumina reduction to aluminum metal following the reaction below:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

The $CO_2$ emission factor employed was estimated from the production of primary aluminum metal and the carbon consumed by the process. Emissions vary depending on the specific technology used by each plant (e.g., Prebake or Soderberg). The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) provide $CO_2$ emission factors for each technology type. During alumina reduction in a prebake anode cell process, approximately 1.5 metric tons of $CO_2$ are emitted for each metric ton of aluminum produced (IPCC/UNEP/OECD/IEA 1997). Similarly, during alumina reduction in a Soderberg cell process, approximately 1.8 metric tons of $CO_2$ are emitted per metric ton of aluminum produced (IPCC/UNEP/OECD/IEA 1997). Based on information gathered by EPA's Voluntary Aluminum Industrial Partnership (VAIP) program, it was assumed that production was split 80 percent prebake and 20 percent Soderberg for the whole time series.

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:

PFC ($CF_4$ or $C_2F_6$) kg/metric ton Al = S × Anode Effect Minutes/Cell-Day

where,

S = Slope coefficient

Anode Effect Minutes/Cell-Day = Anode Effect Frequency × Anode Effect Duration

The slope coefficient was established for each smelter based on field measurements, where available, or default coefficients by technology-type, based on field measurements. Once established, the slope coefficient was used along with smelter anode effect data, collected by aluminum companies and reported to the VAIP, to estimate emissions factors over time. Where smelter-specific anode effect data were not available, industry averages were used. Emissions factors were multiplied by annual production to estimate annual emissions at the smelter level. Emissions were then aggregated across smelters to estimate national emissions. The methodology used to estimate emissions is consistent with the methodologies recommended by the *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000).

## Data Sources

Primary aluminum production data for 2000 (see Table 3-38) were obtained by using information from VAIP program submittals and from USGS, *Mineral Industry Surveys: Aluminum Annual Report* (USGS 2001). The 2000 data from the USGS were adjusted based on the VAIP submittals. Primary aluminum production data for 1990 through 1999 (see Table 3-38) were obtained from USGS, *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1995, 1998, 2000). The USGS requested data from the 12 domestic producers, all of whom responded. The $CO_2$ emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Emission estimates of PFCs

[17] Comparing a subset of smelter specific production data from EPA's Voluntary Aluminum Industrial Partnership (VAIP) program and the USGS *Mineral Industry Surveys: Aluminum Annual Report* (USGS 2001), it was observed that the VAIP program data was approximately 200 thousand metric tons less than the USGS production total. The data from VAIP were believed to provide a more accurate estimate of U.S. aluminum production and therefore were used to calculate emissions.

**Table 3-38: Production of Primary Aluminum**

| Year | Thousand Metric Tons |
|---|---|
| 1990 | 4,048 |
| 1991 | 4,121 |
| 1992 | 4,042 |
| 1993 | 3,695 |
| 1994 | 3,299 |
| 1995 | 3,375 |
| 1996 | 3,577 |
| 1997 | 3,603 |
| 1998 | 3,713 |
| 1999 | 3,779 |
| 2000 | 3,468 |

were provided by aluminum smelters participating in the VAIP program. Where smelter-specific slope coefficients were not available, technology-specific coefficients were drawn from the IPCC's *Good Practice Guidance* (IPCC 2000). Information on the average frequency and duration of anode effects was taken from the International Aluminum Institute's anode effect survey (IAI 2000).

## Uncertainty

Carbon dioxide emissions vary depending on the specific technology used by each plant. A more accurate method would be to calculate $CO_2$ emissions based upon the amount of carbon—in the form of petroleum coke or tar pitch—consumed by the process; however, this type of information was not available.

For PFC emission estimates, the uncertainty in the aluminum production data is relatively low (roughly ± 1 to 2 percent) compared to the uncertainty in the emissions factors (roughly ± 10 to 50 percent). Uncertainty in the emissions factors arises from the lack of comprehensive data for both the slope coefficients and anode effect data. Currently, insufficient measurement data exist to quantify a relationship between PFC emissions and anode effect minutes for all smelters. Future inventories will incorporate additional data reported by aluminum smelters and ongoing research into PFC emissions from aluminum production.

Occasionally, sulfur hexafluoride ($SF_6$) is also used by the aluminum industry as a cover gas or a fluxing and degassing agent in experimental and specialized casting operations. In its application as a cover gas, $SF_6$ is mixed with nitrogen or carbon dioxide and injected above the surface of molten aluminum; as a fluxing and degassing agent, $SF_6$ is mixed with argon, nitrogen, and/or chlorine and blown through molten aluminum. These practices are not employed extensively by primary aluminum producers and are believed to be isolated to secondary casting firms. The aluminum industry in the United States and Canada was estimated to use 230 Mg of $SF_6$ per year (Maiss and Brenninkmeijer 1998); however, this estimate is highly uncertain.

Historically, $SF_6$ from aluminum activities has been omitted from estimates of global $SF_6$ emissions, with the caveat that any emissions would be insignificant (Ko et al. 1993, Victor and MacDonald 1998). Emissions are believed to be insignificant, given that 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).

Emissions of $SF_6$ from aluminum fluxing and degassing have not been estimated. Uncertainties exist as to the quantity of $SF_6$ used by the aluminum industry and its rate of destruction in its uses as a degassing agent or cover gas.

[18] 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]

**Table 3-39: HFC-23 Emissions from HCFC-22 Production**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 35.0 | 3.0 |
| 1995 | 27.0 | 2.3 |
| 1996 | 31.1 | 2.7 |
| 1997 | 30.0 | 2.6 |
| 1998 | 40.2 | 3.4 |
| 1999 | 30.4 | 2.6 |
| 2000 | 29.8 | 2.6 |

**Table 3-40: HCFC-22 Production**

| Year | Gg |
|---|---|
| 1990 | 138.9 |
| 1991 | 142.7 |
| 1992 | 149.6 |
| 1993 | 132.4 |
| 1994 | 146.8 |
| 1995 | 154.7 |
| 1996 | 166.1 |
| 1997 | 164.5 |
| 1998 | 182.8 |
| 1999 | 165.5 |
| 2000 | 186.9 |

# HCFC-22 Production

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. Since 1990, production and use of HCFC-22 has increased significantly as it has replaced chlorofluorocarbons (CFCs) in many applications. 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. [18] 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, or may be captured for use in a limited number of applications.

Emissions of HFC-23 in 2000 were estimated to be 29.8 Tg $CO_2$ Eq. (2.6 Gg). This quantity represents a 15 percent decrease from emissions in 1990 (see Table 3-39). Although HCFC-22 production has increased by 35 percent since 1990, the intensity of HFC-23 emissions (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) has declined by 37 percent, lowering emissions.

In the future, production of HCFC-22 in the United States is expected to decline as non-feedstock HCFC production is phased-out. Feedstock production is anticipated to continue growing, mainly for manufacturing fluorinated polymers.

## Methodology

The methodology employed for estimating emissions was based upon measurements of critical feed components at individual HCFC-22 production plants. Individual producers also measured HFC-23 concentrations in their output stream by gas chromatography. Using measurements of feed components and HFC-23 concentrations in output streams, the amount of HFC-23 generated was estimated. HFC-23 concentrations were determined at the point the gas leaves the chemical reactor; therefore, estimates also include fugitive emissions.

## Data Sources

Emission estimates were provided by the EPA's Global Programs Division in cooperation with the U.S. manufacturers of HCFC-22. Annual estimates of U.S. HCFC-22 production are presented in Table 3-40.

## 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. It is believed that the emissions reported are roughly within 10 percent of the true value. This methodology accounted for the declining intensity of HFC-23 emissions over time. The use of a constant emission factor would not have allowed for such accounting. More simplistic emission estimates generally assume that HFC-23 emissions are between 2 and 4 percent of HCFC-22 production on a mass ratio basis.

# Semiconductor Manufacture

The semiconductor industry uses multiple long-lived fluorinated gases in plasma etching and chemical vapor deposition (CVD) processes. The gases most commonly employed are trifluoromethane (HFC-23), 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.

Plasma etching is performed to provide pathways for conducting material to connect individual circuit components in silicon wafers, using HFCs, PFCs, $SF_6$ and other gases in plasma form. The etching process uses plasma-generated fluorine atoms that react at the semiconductor surface according to prescribed patterns to selectively remove substrate material. A single semiconductor wafer may require as many as 100 distinct process steps that use these gases. Chemical vapor deposition chambers, used for depositing materials that will act as insulators and wires, are cleaned periodically using PFCs 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. However, due to the low destruction efficiency (i.e., high dissociation energy) of PFCs, a portion of the gas flowing into the chamber flows unreacted through the chamber and, unless emission abatement technologies are used, this portion is emitted into the atmosphere. In addition to emissions of unreacted gases, these compounds can also be transformed in the plasma processes into a different HFC or PFC compound, which is then exhausted into the atmosphere. For example, when either $CHF_3$ or $C_2F_6$ is used in cleaning or etching, $CF_4$ is generated and emitted as a process by-product.

For 2000, in part, total weighted emissions of all fluorinated greenhouse gases by the U.S. semiconductor industry were estimated to be 7.6 Tg $CO_2$ Eq. Combined emissions of all fluorinated greenhouse gases are presented in Table 3-41 and Table 3-42 below. The rapid growth of this industry and the increasing complexity of semiconductor products which use more PFCs in the production process have led to an increase in emissions of over 160 percent since 1990. However, the growth rate in emissions has slowed since 1997, and emissions declined between 1999 and 2000. This decline is due to the initial implementation of PFC emission reduction methods, such as process optimization.

## Methodology

Emissions from semiconductor manufacturing were estimated using two sets of data. For 1990 through 1994, emission estimates were based on the historical consumption of silicon (i.e., square centimeters), the estimated average number of interconnecting layers in the chips produced, and an estimated per-layer emission factor. (The number of layers per chip, and hence the PFC emissions per square centimeter of silicon, increases as the line-width of the chip decreases.) The average number of layers per chip was based on industry estimates of silicon consumption by line-width and of the number of layers per line-width. The per-layer emission factor was based on the total annual emissions reported by participants in EPA's PFC Emission Reduction Partnership for the Semiconductor Industry in 1995 and later years. For the three years for which gas sales data were available (1992 to 1994), the estimates derived using this method are within 10 percent of the estimates derived using gas sales data and average values for emission factors and global warming potentials (GWPs).

For 1995 through 2000, total U.S. emissions were extrapolated from the total annual emissions reported by the participants in the PFC Emission Reduction Partnership for the Semiconductor Industry. The emissions from the participants were multiplied by the ratio of the total layer-

**Table 3-41: PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacture (Tg $CO_2$ Eq.)**

| Year | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| $CF_4$ | 0.7 | 1.5 | 1.4 | 1.7 | 1.8 | 1.9 | 1.9 |
| $C_2F_6$ | 1.5 | 3.2 | 2.9 | 3.5 | 3.9 | 4.2 | 4.0 |
| $C_3F_8$ | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.2 |
| HFC-23 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.2 |
| $SF_6$ | 0.4 | 0.8 | 0.8 | 1.0 | 1.0 | 1.1 | 1.1 |
| $NF_3$* | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 |
| **Total** | **2.9** | **6.1** | **5.6** | **6.7** | **7.4** | **7.9** | **7.6** |

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 3-42: PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacture (Mg)**

| Year | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| $CF_4$ | 111 | 229 | 211 | 254 | 282 | 300 | 286 |
| $C_2F_6$ | 167 | 345 | 318 | 383 | 424 | 452 | 431 |
| $C_3F_8$ | 14 | 28 | 26 | 31 | 35 | 37 | 35 |
| HFC-23 | 8 | 17 | 16 | 19 | 21 | 22 | 21 |
| $SF_6$ | 17 | 35 | 32 | 39 | 43 | 46 | 44 |
| $NF_3$ | 9 | 19 | 17 | 21 | 23 | 24 | 23 |

weighted capacity of all of the semiconductor plants in the United States and the total layer-weighted capacity of the plants operated by the participants. The layer-weighted capacity of a plant (or group of plants) consists of the silicon capacity of that plant multiplied by the number of layers used in the chips produced by that plant. This method assumes that participants and non-participants have similar capacity utilizations and per-layer emission factors.

From 1995 through 1999, the per-layer emission factor calculated for participants remained fairly constant and was assumed to be applicable to the non-participants. In 2000, the per-layer emission factor of participants declined significantly, presumably reflecting efforts to reduce PFC emissions. However, non-participants were assumed to emit PFCs at the historic per-layer rate during the year 2000. The 2000 U.S. emissions estimate was adjusted accordingly.

Chemical-specific emission estimates were based data submitted for the year by participants, which were the first reports to provide emissions by chemical. It was assumed that emissions from non-participants and emissions from previous years were distributed among the chemicals in the same proportions as in these 2000 participant reports. This assumption is supported by chemical sales information from previous years and chemical-specific emission factors.

Participants estimate their emissions using a range of methods. For 2000, all participants used a method at least as accurate as the IPCC's method 2c, recommended in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). The partners with relatively high emissions typically use the more accurate IPCC 2b or 2a methods, multiplying estimates of their PFC consumption by process-specific emission factors that they have either measured or obtained from tool suppliers.

## Data Sources

Aggregate emissions estimates from the semiconductor manufacturers participating in the EPA's PFC Emission Reduction Partnership were used to develop these estimates. Estimates of the capacities and characteristics of plants operated by participants and non-participants were derived from the Semiconductor Equipment and Materials International (SEMI) *World Fab Watch* (formerly *International Fabs on Disk*) database (1996 to 2001). Estimates of silicon consumed by line-width from 1990 through 1994 were derived from information from VLSI Research (2000), and the number of layers per line-width was obtained from International SEMATECH's *International Technology Roadmap: 2000 Update.*

**Table 3-43: $SF_6$ Emissions from Electrical Transmission and Distribution**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 31.2 | 1.3 |
| 1995 | 26.5 | 1.1 |
| 1996 | 26.8 | 1.1 |
| 1997 | 24.5 | 1.0 |
| 1998 | 20.1 | 0.8 |
| 1999 | 15.5 | 0.7 |
| 2000 | 14.4 | 0.6 |

## Uncertainty

Emission estimates for this source category have improved, but are still relatively uncertain. Emissions vary depending upon the total amount of gas used and the tool and process employed. Much of this information is tracked by semiconductor manufacturers participating in the EPA's PFC Emission Reduction Partnership; however, there is some uncertainty associated with the data collected. In addition, not all semiconductor manufacturers track this information. Total U.S. emissions were extrapolated from the information submitted by the participants, introducing additional uncertainty.

# Electrical Transmission and Distribution

The largest use for sulfur hexafluoride ($SF_6$), both domestically and internationally, is as an electrical insulator in equipment that transmits and distributes electricity (RAND 2000). 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 installation, servicing, and disposal. In the past, some electric utilities vented $SF_6$ to the atmosphere during servicing and disposal; however, increased awareness and the relatively high cost of the gas have reduced this practice.

Emissions of $SF_6$ from electrical transmission and distribution systems were estimated to be 14.4 Tg $CO_2$ Eq. (0.6 Gg) in 2000. This quantity represents a 54 percent decrease below the estimate for 1990 (see Table 3-43). This decrease, which is reflected in the atmospheric record, is believed to be a response to increases in the price of $SF_6$ and to growing awareness of the environmental impact of $SF_6$ emissions.

## Methodology

The 2000 estimate of $SF_6$ emissions from electrical equipment, 14.4 Tg $CO_2$ Eq., is comprised of (1) estimated emissions of approximately 14.3 Tg $CO_2$ Eq. from U.S. electric power systems, and (2) estimated emissions of approximately 0.2 Tg $CO_2$ Eq. from U.S. electrical equipment manufacturers (original equipment manufacturers, or OEMs). The 2000 estimate of emissions from electric power systems is based on the reported 2000 emissions (5.1 Tg $CO_2$) of participating utilities in EPA's $SF_6$ Emissions Reduction Partnership for Electric Power Systems, which began in 1999. These emissions were scaled up to the national level using the results of a regression analysis that indicated that utilities' emissions are strongly correlated with their transmission miles. The 2000 emissions estimate for OEMs of 0.2 Tg $CO_2$ is based on statistics compiled by the National Electrical Manufacturers Association and a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE) in May 2001 (P. O'Connell, et al., Study Committee 23), which indicates that OEMs have a release rate of approximately 3 percent of the amount of $SF_6$ installed in new equipment. Emissions for 1999 were estimated similarly.

Because most participating utilities reported emissions only for 1999 and 2000, and only one reported emissions for more than three years, it was necessary to model "backcast" electric power system $SF_6$ emissions for the years 1990 through 1998. It was assumed that $SF_6$ purchases were strongly related to emissions. To estimate 1990 through 1998 emissions, aggregate world sales of $SF_6$ (RAND 2000) for each year from 1990 through 1999 were divided by the world sales from 1999. The result was a time series that gave each year's sales as a multiple of 1999 sales. Each year's normalized sales were then multiplied by the estimated U.S. emissions of $SF_6$ from electrical equipment in 1999, which

was estimated to be 15.5 Tg of $CO_2$ Eq., to estimate U.S. emissions of $SF_6$ from electrical equipment in that year. This yielded a time series that was related to statistics for both $SF_6$ emissions and $SF_6$ sales.

## Data Sources

Emission estimates were provided by EPA's Global Programs Division in cooperation with companies that participate in the $SF_6$ Emissions Reduction Partnership for Electric Power Systems and with producers of $SF_6$.

## Uncertainty

There is uncertainty involved in extrapolating emissions reported by participants to total U.S. emissions, and in extrapolating to estimate past emissions. The regression equations used to extrapolate U.S. emissions from participant reports have a variance (at the 95 percent confidence level) of +/- 2 Tg $CO_2$ for 1999 and +/- 2.5 Tg $CO_2$ for 2000. In addition, emission rates for utilities that were not participants, which accounted for approximately 75 percent of U.S. transmission miles, may differ from those that were participants. Global sales of $SF_6$ appear to closely reflect global emissions; global sales declined by 24 percent between 1995 and 1998, while atmospheric measurements indicate that world emissions of $SF_6$ declined by 27 percent during the same period. However, U.S. emission patterns may differ from global emission patterns.

# Magnesium Production and Processing

The magnesium metal production and casting industry uses sulfur hexafluoride ($SF_6$) as a covergas to prevent the violent oxidation of molten magnesium in the presence of air. A dilute gaseous mixture of $SF_6$ with dry air and/or carbon dioxide is blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A minute portion of the $SF_6$ reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and magnesium fluoride. It is assumed that the amount of $SF_6$ reacting in magnesium production and processing is negligible and thus all $SF_6$ used is emitted into the atmosphere. Sulfur hexafluoride has been used in this application around the world for the last twenty years. It has largely replaced salt fluxes and sulfur dioxide ($SO_2$), which are more toxic and corrosive than $SF_6$.

**Table 3-44: $SF_6$ Emissions from Magnesium Production and Processing**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 5.5 | 0.2 |
| 1995 | 5.5 | 0.2 |
| 1996 | 5.5 | 0.2 |
| 1997 | 6.9 | 0.3 |
| 1998 | 6.2 | 0.3 |
| 1999 | 6.1 | 0.3 |
| 2000 | 4.0 | 0.2 |

The magnesium industry emitted 4.0 Tg $CO_2$ Eq. (0.17 Gg) of $SF_6$ in 2000 (see Table 3-44). There are no significant plans for expansion of primary magnesium production in the United States, but demand for magnesium metal by U.S. casting companies has grown as auto manufacturers design more lightweight magnesium parts into vehicle models. Foreign magnesium producers are expected to meet the growing U.S. demand for primary magnesium.

## Methodology

U.S. magnesium metal production (primary and secondary) and consumption data from 1993 to 1999 were available from the U.S. Geological Survey (USGS).[19] Emissions were estimated by multiplying average industry emission factors (kg $SF_6$/tonne Mg produced or processed) by the amount of metal produced or consumed in the six major processes that require $SF_6$ melt protection; 1) primary production, 2) secondary production, 3) die casting, 4) gravity casting, 5) wrought products and, 6) anodes. The emission factors were derived from participants in EPA's SF6 Emission Reduction Partnership for the Magnesium Industry, technical publications (Gjestland and Magers 1996), and expert judgement. Participants represent 100 percent of U.S. primary production and approximately 60 percent of magnesium casting in the United States.

[19] http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/index.html#mis

## Box 3-1: 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. Because all chemicals consumed will eventually be emitted into the atmosphere, in the long term the cumulative emission estimates using the two approaches should be equivalent unless the chemical is captured and destroyed. 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, it is assumed that there is no delay between consumption and emission and that no destruction of the chemical takes place. In this case, actual emissions equal potential emissions.
- *Emissions that are not easily defined*. In some processes, such as PFC emissions from semiconductor manufacture, the gases used in the process may be destroyed or transformed into other compounds, which may also be greenhouse gases. It is therefore not logical to estimate potential emissions based on consumption of the original chemical.

Table 3-45 presents potential emission estimates for HFCs and PFCs from the substitution of ozone depleting substances and $SF_6$ emissions from semiconductor manufacturer, magnesium production and processing, and electrical transmission and distribution.[20] Potential emissions associated with the substitution for ozone depleting substances were calculated through a combination of the EPA's Vintaging Model and information provided by U.S. chemical manufacturers. For $SF_6$ from semiconductor manufacture, estimates were assumed to equal emissions divided by a 0.53 percent emission factor. The U.S. utility purchases of $SF_6$ for electrical equipment were backcasted based on world sales of $SF_6$ to utilities, this was added to the SF6 Purchased by U.S. orignal equipment manufacturers (OEMs).

**Table 3-45: 2000 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 | 203.4 | 57.8 |
| Aluminum Production | - | 7.9 |
| HCFC-22 Production | - | 29.8 |
| Semiconductor Manufacture* | 2.0 | 7.4 |
| Magnesium Production and Processing | 4.0 | 4.0 |
| Electrical Transmission and Distribution | 23.2 | 14.4 |

- Not applicable.
*Potential emissions only include $SF_6$, while actual emissions include $SF_6$ and PFCs.

[20] See Annex V for a discussion of sources of $SF_6$ emissions excluded from the actual emissions estimates in this report.

**Table 3-46: $NO_x$, CO, and NMVOC Emissions from Industrial Processes (Gg)**

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$NO_x$** | **921** | **842** | **976** | **991** | **924** | **946** | **1184** |
| Chemical & Allied Product Manufacturing | 152 | 144 | 113 | 115 | 117 | 119 | 122 |
| Metals Processing | 88 | 89 | 75 | 80 | 80 | 80 | 83 |
| Storage and Transport | 3 | 5 | 14 | 15 | 15 | 15 | 15 |
| Other Industrial Processes | 343 | 362 | 397 | 417 | 424 | 422 | 442 |
| Miscellaneous* | 335 | 242 | 376 | 364 | 288 | 311 | 523 |
| **CO** | **9,502** | **5,291** | **7,171** | **8,776** | **5,557** | **10,763** | **19,469** |
| Chemical & Allied Product Manufacturing | 1,074 | 1,109 | 955 | 972 | 981 | 981 | 1,009 |
| Metals Processing | 2,395 | 2,159 | 1,455 | 1,550 | 1,544 | 1,518 | 1,574 |
| Storage and Transport | 69 | 22 | 64 | 64 | 65 | 65 | 67 |
| Other Industrial Processes | 487 | 566 | 509 | 528 | 535 | 543 | 562 |
| Miscellaneous* | 5,479 | 1,435 | 4,188 | 5,662 | 2,431 | 7,656 | 16,257 |
| **NMVOCs** | **3,110** | **3,622** | **3,110** | **3,578** | **3,145** | **3,883** | **4,232** |
| Chemical & Allied Product Manufacturing | 575 | 599 | 351 | 352 | 357 | 359 | 369 |
| Metals Processing | 111 | 113 | 66 | 71 | 71 | 69 | 72 |
| Storage and Transport | 1,356 | 1,499 | 1,169 | 1,204 | 1,204 | 1,129 | 1,111 |
| Other Industrial Processes | 364 | 409 | 383 | 397 | 402 | 420 | 435 |
| Miscellaneous* | 705 | 185 | 375 | 759 | 308 | 1,065 | 2,244 |

* Miscellaneous includes the following categories: catastrophic/accidental release, other combustion, health services, TSDFs (Transport, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act), cooling towers, and fugitive dust. It does not include agricultural fires or slash/prescribed burning, which are accounted for under the Agricultural Residue Burning source.
Note: Totals may not sum due to independent rounding.

## Data Sources

Emission estimates were provided by EPA's Climate Protection Division in cooperation with the U.S. EPA $SF_6$ Emission Reduction Partnership for the Magnesium Industry and the USGS.

## Uncertainty

There are a number of uncertainties in these estimates, including the assumption that $SF_6$ neither reacts nor decomposes during use. It is possible that the melt surface reactions and high temperatures associated with molten magnesium would cause some gas degradation. As is the case for other sources of $SF_6$ emissions, total $SF_6$ consumption data for magnesium production and processing in United States were not available. Sulfur hexafluoride may also be used as a covergas for the casting of molten aluminum with a high magnesium content; however, it is unknown to what extent this technique is used in the United States.

# Industrial Sources of Ambient Air Pollutants

In addition to the main greenhouse gases addressed above, many industrial processes generate emissions of ambient air pollutants. Total emissions of nitrogen oxides ($NO_x$), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs) from non-energy industrial processes from 1990 to 2000 are reported in Table 3-46.

## Methodology and Data Sources

The emission estimates for this source were taken directly from the EPA (2001). 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.

# 4. Solvent Use

The use of solvents and other chemical products can result in emissions of various ozone precursors (i.e., ambient air pollutants).[1] Nonmethane volatile organic compounds (NMVOCs), commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum based solvents. Surface coatings accounted for just under a majority of NMVOC emissions from solvent use—43 percent in 2000—while "non-industrial"[2] uses accounted for about 36 percent and degreasing applications for 8 percent. Overall, solvent use accounted for approximately 24 percent of total U.S. emissions of NMVOCs in 2000, and decreased 16 percent since 1990.

Although NMVOCs are not considered direct greenhouse gases, their role as precursors to the formation of ozone—which is a greenhouse gas—results in their inclusion in a greenhouse gas inventory. Emissions from solvent use have been reported separately by the United States to be consistent with the inventory reporting guidelines recommended by the IPCC. These guidelines identify solvent use as one of the major source categories for which countries should report emissions. 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.). Because some of these industrial applications also employ thermal incineration as a control technology, combustion by-products (CO and $NO_x$) are also reported with this source category.

Total emissions of nitrogen oxides ($NO_x$), nonmethane volatile organic compounds (NMVOCs), and carbon monoxide (CO) from 1990 to 2000 are reported in Table 4-1.

## 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 emission factors to the type 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.

[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.

[2] "Non-industrial" uses include cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

**Table 4-1: Emissions of $NO_x$, CO, and NMVOC from Solvent Use (Gg)**

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$NO_x$** | **1** | **3** | **3** | **3** | **3** | **3** | **3** |
| Degreasing | + | + | + | + | + | + | + |
| Graphic Arts | + | 1 | 1 | 1 | 1 | 1 | 1 |
| Dry Cleaning | + | + | + | + | + | + | + |
| Surface Coating | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| Other Industrial Processes[a] | + | + | + | + | + | + | + |
| Non-Industrial Processes[b] | + | + | + | + | + | + | + |
| **CO** | **4** | **5** | **1** | **1** | **1** | **1** | **1** |
| Degreasing | + | + | + | + | + | + | + |
| Graphic Arts | + | + | + | + | + | + | + |
| Dry Cleaning | + | 1 | + | + | + | + | + |
| Surface Coating | + | 1 | 1 | 1 | 1 | 1 | 1 |
| Other Industrial Processes[a] | 4 | 3 | + | + | + | + | + |
| Non-Industrial Processes[b] | + | + | + | + | + | + | + |
| **NMVOCs** | **5,225** | **5,618** | **4,973** | **5,108** | **4,679** | **4,390** | **4,388** |
| Degreasing | 675 | 716 | 546 | 566 | 337 | 337 | 347 |
| Graphic Arts | 249 | 307 | 260 | 266 | 272 | 268 | 276 |
| Dry Cleaning | 195 | 209 | 140 | 148 | 151 | 152 | 153 |
| Surface Coating | 2,289 | 2,432 | 2,153 | 2,228 | 1,989 | 1,940 | 1,893 |
| Other Industrial Processes[a] | 94 | 96 | 106 | 110 | 111 | 113 | 118 |
| Non-Industrial Processes[b] | 1,724 | 1,858 | 1,768 | 1,790 | 1,818 | 1,581 | 1,601 |

[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.

## Data Sources

The emission estimates for this source were taken directly from the EPA (2001). 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 data bases.

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.

# 5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of non-carbon dioxide emissions from the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and agricultural residue burning (see Figure 5-1). Carbon dioxide ($CO_2$) emissions and removals from agriculture-related land-use activities, such as conversion of grassland to cultivated land, are discussed in the Land-Use Change and Forestry chapter.

In 2000, agricultural activities were responsible for emissions of 485.1 Tg $CO_2$ Eq., or 6.9 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. Methane emissions from enteric fermentation and manure management represent about 20 percent and 6 percent of total $CH_4$ emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of methane. Rice cultivation and agricultural crop residue burning were minor sources of methane. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. $N_2O$ emissions, accounting for 70 percent. Manure management and agricultural residue burning were also small sources of $N_2O$ emissions.

**Figure 5-1**

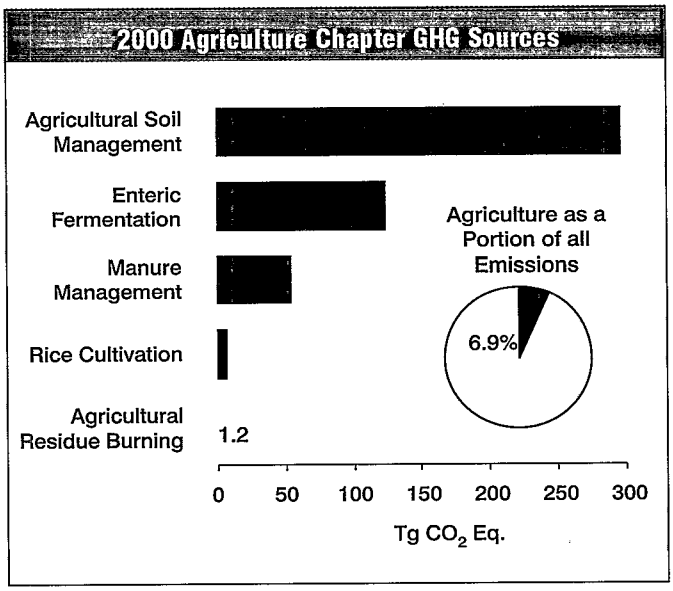



Table 5-1 and Table 5-2 present emission estimates for the Agriculture chapter. Between 1990 and 2000, $CH_4$ emissions from agricultural activities increased by 2.9 percent while $N_2O$ emissions increased by 11.3 percent. In addition to $CH_4$ and $N_2O$, agricultural residue burning was also a minor source of the ambient air pollutants carbon monoxide (CO) and nitrogen oxides ($NO_x$).

**Table 5-1: Emissions from Agriculture (Tg $CO_2$ Eq.)**

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| $CH_4$ | **164.9** | **176.2** | **171.5** | **170.9** | **171.6** | **171.1** | **169.6** |
| Enteric Fermentation | 127.9 | 133.2 | 129.6 | 126.8 | 124.9 | 124.5 | 123.9 |
| Manure Management | 29.2 | 34.8 | 34.2 | 35.8 | 38.0 | 37.6 | 37.5 |
| Rice Cultivation | 7.1 | 7.6 | 7.0 | 7.5 | 7.9 | 8.3 | 7.5 |
| Agricultural Residue Burning | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 |
| $N_2O$ | **283.5** | **300.2** | **309.8** | **315.0** | **316.0** | **313.9** | **315.5** |
| Agricultural Soil Management | 267.1 | 283.4 | 292.6 | 297.5 | 298.4 | 296.3 | 297.6 |
| Manure Management | 16.0 | 16.4 | 16.8 | 17.1 | 17.1 | 17.1 | 17.5 |
| Agricultural Residue Burning | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.4 | 0.5 |
| **Total** | **448.4** | **476.4** | **481.3** | **485.9** | **487.6** | **485.0** | **485.1** |

Note: Totals may not sum due to independent rounding.

**Table 5-2: Emissions from Agriculture (Gg)**

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| $CH_4$ | **7,851** | **8,392** | **8,166** | **8,136** | **8,172** | **8,149** | **8,076** |
| Enteric Fermentation | 6,089 | 6,342 | 6,171 | 6,037 | 5,948 | 5,929 | 5,898 |
| Manure Management | 1,390 | 1,657 | 1,628 | 1,707 | 1,811 | 1,788 | 1,784 |
| Rice Cultivation | 339 | 363 | 332 | 356 | 376 | 395 | 357 |
| Agricultural Residue Burning | 33 | 31 | 36 | 36 | 37 | 36 | 37 |
| $N_2O$ | **914** | **968** | **999** | **1,016** | **1,019** | **1,012** | **1,018** |
| Agricultural Soil Management | 862 | 914 | 944 | 960 | 963 | 956 | 960 |
| Manure Management | 52 | 53 | 54 | 55 | 55 | 55 | 57 |
| Agricultural Residue Burning | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Note: Totals may not sum due to independent rounding.

## Enteric Fermentation

Methane ($CH_4$) 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 methane as a by-product, which can be exhaled or eructated by the animal. The amount of methane produced and excreted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Among domesticated animal types, ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of methane 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 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 methane emissions among all animal types.

Non-ruminant domesticated animals (e.g., swine, horses, mules, and goats) also produce methane emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less methane on a per-animal basis than ruminants because the capacity of the large intestine to produce methane is lower.

In addition to the type of digestive system, an animal's feed intake also affects methane emissions. In general, a higher feed intake leads to higher methane emissions. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types.

**Table 5-3: $CH_4$ Emissions from Enteric Fermentation (Tg $CO_2$ Eq.)**

| Livestock Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Beef Cattle | 93.3 | 100.1 | 98.1 | 95.4 | 93.5 | 93.0 | 91.7 |
| Dairy Cattle | 28.7 | 27.5 | 26.1 | 26.0 | 25.9 | 26.2 | 26.9 |
| Horses | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Sheep | 1.9 | 1.5 | 1.4 | 1.3 | 1.3 | 1.2 | 1.2 |
| Swine | 1.7 | 1.9 | 1.8 | 1.8 | 2.0 | 1.9 | 1.9 |
| Goats | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| **Total** | **127.9** | **133.2** | **129.6** | **126.8** | **124.9** | **124.5** | **123.9** |

Note: Totals may not sum due to independent rounding.

**Table 5-4: $CH_4$ Emissions from Enteric Fermentation (Gg)**

| Livestock Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Beef Cattle | 4,444 | 4,768 | 4,673 | 4,541 | 4,453 | 4,429 | 4,365 |
| Dairy Cattle | 1,369 | 1,308 | 1,241 | 1,240 | 1,234 | 1,246 | 1,283 |
| Horses | 93 | 94 | 94 | 94 | 95 | 96 | 96 |
| Sheep | 91 | 72 | 68 | 64 | 63 | 58 | 56 |
| Swine | 81 | 88 | 84 | 88 | 93 | 90 | 88 |
| Goats | 13 | 11 | 10 | 10 | 10 | 10 | 10 |
| **Total** | **6,089** | **6,342** | **6,171** | **6,037** | **5,948** | **5,929** | **5,898** |

Note: Totals may not sum due to independent rounding.

Methane emission estimates from enteric fermentation are provided in Table 5-3 and Table 5-4. Total livestock methane emissions in 2000 were 123.9 Tg $CO_2$ Eq. (5,898 Gg), decreasing slightly since 1999. Beef cattle remain the largest contributor of methane emissions from enteric fermentation, accounting for 74 percent in 2000. Emissions from dairy cattle in 2000 accounted for 22 percent, and the remaining 4 percent was from horses, sheep, swine, and goats.

## 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 methane emissions from livestock in the United States. Cattle production systems in the United States are better characterized in comparison with other livestock management systems. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimating emissions for cattle. Emission estimates for other domesticated animals 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 methane produced by individual ruminant animals, particularly cattle. A detailed model that incorporates this information and other analyses of livestock population, feeding practices and production characteristics was used to estimate emissions from cattle populations.

National cattle population statistics were disaggregated into the following cattle sub-populations:

**Dairy Cattle**

- Calves
- Heifer Replacements
- Cows

**Beef Cattle**

- Calves
- Heifer Replacements
- Heifer and Steer Stockers
- Animals in Feedlots
- Cows
- Bulls

Calf birth estimates, end of year population statistics, detailed feedlot placement information, and slaughter weight data were used in the model to initiate and track cohorts of individual animal types having distinct emissions profiles. The key variables tracked for each of the cattle population categories are described in Annex K. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain.

Diet characteristics were estimated by State and region for U.S. dairy, beef, and feedlot cattle. These estimates were used to calculate Digestible Energy (DE) values and methane conversion rates ($Y_m$) for each population category. The IPCC recommends $Y_m$ values of 3.5 to 4.5 percent for feedlot cattle and 5.5 to 6.5 percent for all other cattle. 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 contact with state agricultural extension specialists, a review of published forage quality studies, expert opinion, and modeling of animal physiology. See Annex K for more details on the method used to characterize cattle diets in the United States.

In order to estimate methane emissions from cattle, the population was divided into region, age, sub-type (e.g., calves, heifer replacements, cows, etc.), and production (i.e., pregnant, lactating, etc.) groupings to more fully capture any differences in methane emissions from these animal types. Cattle diet characteristics developed under Step 2 were used to develop regional emission factors for each sub-category. Tier 2 equations from IPCC (2000) were used to produce methane emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, heifer feedlot animals, and steer and heifer feedlot step-up diet animals. To estimate emissions from cattle, population data were multiplied by the emission factor for each cattle type. More details can be found in Annex K.

Emission estimates for other animal types were based upon average emission factors representative of entire populations of each animal type. Methane emissions from these animals accounted for a minor portion of total methane emissions from livestock in the United States from 1990 through 2000. 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.

See Annex K for more detailed information on the methodology and data used to calculate methane emissions from enteric fermentation.

## Data Sources

Annual cattle population data were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (1995a-d, 1996b, 1997, 1998a, 1999a-c,f-g, 2000a,c,d,f, 2001a,c,d,g). DE and $Y_m$ values were used to calculate emissions from cattle populations. DE and $Y_m$ for dairy and beef cows, and for beef stockers, 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. Weight data were estimated from Feedstuffs (1998), Western Dairyman (1998), and expert opinion. Annual livestock population data for other livestock types, except horses, as well as feedlot placement information were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1998b-c, 1999d,e,h, 2000b,e, 2001b,e,f). Horse data were obtained from the Food and Agriculture Organization (FAO) statistical database (FAO 2000, 2001). Methane emissions from sheep, goats, swine, and horses were estimated by using emission factors utilized in Crutzen et al. (1986). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. The methodology is the same as that recommended by IPCC (IPCC/UNEP/OECD/IEA 1997, IPCC 2000).

## Uncertainty

The basic uncertainties associated with estimating emissions from enteric fermentation are the range of emission factors possible for the different animal types and the number of animals with a particular emissions profile that exist during the year. Although determining an emission factor for all possible cattle sub-groupings and diet characterizations in the United States is not possible, the

enteric fermentation model that was used estimates the likely emission factors for the major animal types and diets. The model generates estimates for dairy and beef cows, dairy and beef replacements, beef stockers, and feedlot animals. The analysis departs from the recommended IPCC (2000) DE and $Y_m$ values to account for diets for these different animal types regionally. Based on expert opinion and peer reviewer recommendations, it is believed that the values supporting the development of emission factors for the animal types studied are appropriate for the situation in the United States.

In addition to the uncertainty associated with developing emission factors for different cattle population categories based on estimated energy requirements and diet characterizations, there is uncertainty in the estimation of animal populations by animal type. The model estimates the movement of animal cohorts through the various monthly age and weight classes by animal type. Several inputs affect the precision of this approach, including estimates of births by month, weight gain of animals by age class, and placement of animals into feedlots based on placement statistics and slaughter weight data. However, it is believed that the model sufficiently characterizes the U.S. cattle population and captures the potential differences related to the emission factors used for different animal types.

In order to ensure the quality of the emission estimates from enteric fermentation, the IPCC Tier 1 and Tier 2 QA/QC procedures were implemented. Tier 1 procedures included quality checks on data gathering, input, and documentation, as well as checks on the actual emission calculations. Additionally, Tier 2 procedures included quality checks on emission factors, activity data, and emissions.

## Manure Management

The management of livestock manure can produce anthropogenic methane ($CH_4$) and nitrous oxide ($N_2O$) emissions. Methane is produced by the anaerobic decomposition of manure. Nitrous oxide is produced as part of the nitrogen cycle through the nitrification and denitrification of the organic nitrogen in livestock manure and urine.

When livestock or poultry manure are stored or treated in systems that promote anaerobic conditions (e.g., as a liquid 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 pits) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no $CH_4$. A number of other factors related to how the manure is handled also affect the amount of $CH_4$ produced: 1) ambient temperature and moisture affect the amount of $CH_4$ produced because they influence the growth of the bacteria responsible for methane formation; 2) methane production generally increases with rising temperature and residency time; and 3) for non-liquid based manure systems, moist conditions (which are a function of rainfall and humidity) favor $CH_4$ production. Although the majority of manure is handled as a solid, producing little $CH_4$, the general trend in manure management, particularly for large dairy and swine producers, is one of increasing use of liquid systems. In addition, use of daily spread systems at smaller dairies is decreasing, due to new regulations limiting the application of manure nutrients, which has resulted in an increase of manure managed and stored on site at these smaller dairies.

The composition of the manure also affects the amount of methane produced. Manure composition varies by animal type, including the animal's digestive system and diet. In general, the greater the energy content of the feed, the greater the potential for $CH_4$ emissions. For example, feedlot cattle fed a high energy grain diet generate manure with a high $CH_4$-producing capacity (represented by $B_o$). Range cattle fed a low energy diet of forage material produce manure with about 50 percent of the $CH_4$-producing potential of feedlot cattle manure. In addition, there is a trend in the dairy industry indicating that dairy cows are producing more milk per year. These high-production milk cows tend to produce more volatile solids in their manure as milk production increases, which increases the probability of $CH_4$ production.

A very small portion of the total nitrogen excreted is expected to convert to nitrous oxide in the waste management system. The production of nitrous oxide from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For

$N_2O$ emissions to occur, the manure must first be handled aerobically where ammonia or organic nitrogen is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to nitrogen gas ($N_2$), with intermediate production of nitrous oxide ($N_2O$) 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. For example, manure at cattle drylots is deposited on soil, oxidized to nitrite and nitrate, and has the potential to encounter saturated conditions following rain events.

Certain $N_2O$ emissions are accounted for and discussed under Agricultural Soil Management. These are emissions from livestock manure and urine deposited on pasture, range, or paddock lands, as well as emissions from manure and urine that is spread onto fields either directly as "daily spread" or after it is removed from manure management systems (e.g., lagoon, pit, etc.).

Table 5-5 and Table 5-6 provide estimates of $CH_4$ and $N_2O$ emissions from manure management by animal category. Estimates for methane emissions in 2000 were 37.5 Tg $CO_2$ Eq. (1,783 Gg), 28 percent higher than in 1990. The majority of this increase was from swine and dairy cow manure and is attributed to shifts by the swine and dairy industries towards larger facilities. Larger swine and dairy farms tend to use flush or scrape liquid systems to manage and store manure. Thus the shift towards larger facilities is translated into an increasing use of liquid manure management systems. This shift was accounted for by incorporating state-specific weighted methane conversion factor (MCF) values calculated from the 1992 and 1997 farm-size distribution reported in the *Census of Agriculture* (USDA 1999e). In 2000, swine $CH_4$ emissions decreased from 1999 due to a decrease in those animal populations.

As stated previously, smaller dairies are moving away from daily spread systems. Therefore, more manure is managed and stored on site, contributing to additional $CH_4$ emissions over the time series. The $CH_4$ estimates also account for changes in volatile solids production from dairy cows correlated to their generally increasing milk production. A description of the methodology is provided in Annex L.

Total $N_2O$ emissions from manure management systems in 2000 were estimated to be 17.5 Tg $CO_2$ Eq. (56.5 Gg). The 9 percent increase in $N_2O$ emissions from 1990 to 2000 can be partially attributed to a shift in the poultry industry away from the use of liquid manure management systems, in favor of litter-based systems and high rise houses. In addition, there was an overall increase in the population of poultry and swine from 1990 to 2000, although swine populations declined slightly in 1993, 1995, 1996, 1999, and 2000 from previous years and poultry populations decreased in 1995.

The population of beef cattle in feedlots, which tend to store and manage manure on site, also increased, resulting in increased $N_2O$ emissions from this animal category. Although dairy cow populations decreased overall, the population of dairies managing and storing manure on site—as opposed to using pasture, range, or paddock or daily spread systems—increased. Therefore, the increase in dairies using on-site storage to manage their manure results in increased $N_2O$ emissions. As stated previously, $N_2O$ emissions from livestock manure deposited on pasture, range, or paddock land and manure immediately applied to land in daily spread systems are accounted for under Agricultural Soil Management.

## Methodology

The methodologies presented in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000) form the basis of the $CH_4$ and $N_2O$ emissions estimates for each animal type. The calculation of emissions requires the following information:

- Animal population data (by animal type and state)
- Amount of nitrogen produced (amount per 1000 pound animal times average weight times number of head)
- Amount of volatile solids produced (amount per 1000 pound animal times average weight times number of head)
- Methane producing potential of the volatile solids (by animal type)
- Extent to which the methane producing potential is realized for each type of manure management system (by State and manure management system)

**Table 5-5: $CH_4$ and $N_2O$ Emissions from Manure Management (Tg $CO_2$ Eq.)**

| Gas/Animal Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CH_4$** | **29.2** | **34.8** | **34.2** | **35.9** | **38.0** | **37.6** | **37.5** |
| Dairy Cattle | 9.6 | 12.0 | 12.1 | 12.7 | 13.1 | 13.3 | 13.7 |
| Beef Cattle | 3.2 | 3.5 | 3.5 | 3.4 | 3.4 | 3.4 | 3.4 |
| Swine | 13.0 | 16.0 | 15.3 | 16.4 | 18.1 | 17.6 | 17.1 |
| Sheep | 0.1 | 0.1 | + | + | + | + | + |
| Goats | + | + | + | + | + | + | + |
| Poultry | 2.7 | 2.6 | 2.6 | 2.7 | 2.7 | 2.6 | 2.6 |
| Horses | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| **$N_2O$** | **16.0** | **16.4** | **16.8** | **17.1** | **17.1** | **17.2** | **17.5** |
| Dairy Cattle | 4.2 | 4.0 | 3.9 | 3.9 | 3.8 | 3.8 | 3.8 |
| Beef Cattle | 4.9 | 5.3 | 5.1 | 5.4 | 5.5 | 5.5 | 5.9 |
| Swine | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 |
| Sheep | + | + | + | + | + | + | + |
| Goats | + | + | + | + | + | + | + |
| Poultry | 6.3 | 6.5 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 |
| Horses | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| **Total** | **45.2** | **51.2** | **51.0** | **53.0** | **55.1** | **54.8** | **55.0** |

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

**Table 5-6: $CH_4$ and $N_2O$ Emissions from Manure Management (Gg)**

| Gas/Animal Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CH_4$** | **1,390** | **1,657** | **1,628** | **1,707** | **1,811** | **1,788** | **1,783** |
| Dairy Cattle | 457 | 571 | 577 | 604 | 624 | 634 | 653 |
| Beef Cattle | 151 | 166 | 165 | 163 | 161 | 160 | 161 |
| Swine | 621 | 763 | 729 | 782 | 864 | 839 | 814 |
| Sheep | 3 | 2 | 2 | 2 | 2 | 2 | 2 |
| Goats | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Poultry | 128 | 124 | 125 | 127 | 130 | 124 | 124 |
| Horses | 29 | 29 | 29 | 29 | 29 | 30 | 30 |
| **$N_2O$** | **52** | **53** | **54** | **55** | **55** | **55** | **57** |
| Dairy Cattle | 14 | 13 | 13 | 12 | 12 | 12 | 12 |
| Beef Cattle | 16 | 17 | 17 | 17 | 18 | 18 | 19 |
| Swine | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Sheep | + | + | + | + | + | + | + |
| Goats | + | + | + | + | + | + | + |
| Poultry | 21 | 21 | 23 | 23 | 23 | 23 | 23 |
| Horses | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

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

- Portion of manure managed in each manure management system (by State and animal type)
- Portion of manure deposited on pasture, range, or paddock or used in daily spread systems

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, 1998d, 2000h) and EPA (ERG 2000a, EPA 2001a, 2001b). For beef cattle and poultry, manure management system usage data was not tied to farm size (ERG 2000a, USDA 2000i). For other animal types, manure management system usage was based on previous EPA estimates (EPA 1992).

Next, MCFs and $N_2O$ emission factors were determined for all manure management systems. MCFs for dry systems and $N_2O$ emission factors for all systems were set equal to

default IPCC factors (IPCC 2000). 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 (see Annex L for detailed information on MCF derivations for liquid systems). The MCF calculations model the average monthly ambient temperature, a minimum system temperature, the carryover of volatile solids in the system from month to month due to long storage times exhibited by anaerobic lagoon systems, and a factor to account for management and design practices that result in the loss of volatile solids from lagoon systems.

For each animal group—except sheep, goats, and horses—the base emission factors were then weighted to incorporate the distribution of management systems used within each state and thereby to create an overall state-specific weighted emission factor. To calculate this weighted factor, the percent of manure for each animal group managed in a particular system in a state was multiplied by the emission factor for that system and state, and then summed for all manure management systems in the state.

Methane emissions were estimated by calculating the volatile solids (VS) production for all livestock. For each animal group except dairy cows, 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. For dairy cows, the national average VS constant was replaced with a mathematical relationship between milk production and VS (USDA 1996a), which was then multiplied by State-specific average annual milk production (USDA 2001g). The resulting VS for each animal group was then multiplied by the maximum methane producing capacity of the waste ($B_o$), and the State-specific methane conversion factors.

Nitrous oxide emissions were estimated by determining total Kjeldahl nitrogen (TKN)[1] production for all livestock wastes using livestock population data and nitrogen excretion rates. For each animal group, TKN production was calculated using a national average nitrogen excretion 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. State-specific weighted $N_2O$ emission factors specific to the type of manure management system were then applied to total nitrogen production to estimate $N_2O$ emissions.

See Annex L for more detailed information on the methodology and data used to calculate methane and nitrous oxide emissions from manure management.

## Data Sources

Animal population data for all livestock types, except horses and goats, were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a-g, 2001a-f). Horse population data were obtained from the FAOSTAT database (FAO 2001). Goat population data were obtained from the Census of Agriculture (USDA 1999d). Information regarding poultry turnover (i.e., slaughter) rate was obtained from State Natural Resource Conservation Service (NRCS) personnel (Lange 2000). Dairy cow and swine population data by farm size for each state, used for the weighted MCF and emission factor calculations, were obtained from the *Census of Agriculture*, which is conducted every five years (USDA 1999e).

Manure management system usage data for dairy and swine operations were obtained from USDA's Centers for Epidemiology and Animal Health (USDA 1996b, 1998d, 2000h) for small operations and from preliminary estimates for EPA's Office of Water regulatory effort for large operations (ERG 2000a; EPA 2001a, 2001b). Data for layers were obtained from a voluntary United Egg Producers' survey (UEP 1999), previous EPA estimates (EPA 1992), and USDA's Animal Plant Health Inspection Service (USDA 2000i). Data for beef feedlots were also obtained from EPA's Office of Water (ERG 2000a; EPA 2001a, 2001b). Manure management system usage data for other livestock were taken from previous EPA estimates (EPA 1992). Data regarding the use of daily spread and pasture, range, or paddock systems for dairy cattle were obtained from personal communications with personnel from several organizations, and data provided by those personnel (Poe

[1] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

et al. 1999). These organizations include State NRCS offices, State extension services, State universities, USDA National Agriculture Statistics Service (NASS), and other experts (Deal 2000, Johnson 2000, Miller 2000, Stettler 2000, Sweeten 2000, and Wright 2000). Additional information regarding the percent of beef steer and heifers on feedlots was obtained from contacts with the national USDA office (Milton 2000).

Methane conversion factors for liquid systems were calculated based on average ambient temperatures of the counties in which animal populations were located. The average county and state temperature data were obtained from the National Climate Data Center (NOAA 2001), and the county population data were based on 1992 and 1997 Census data (USDA 1999e). County population data for 1990 and 1991 were assumed to be the same as 1992; county population data for 1998 through 2000 were assumed to be the same as 1997; and county population data for 1993 through 1996 were extrapolated based on 1992 and 1997 data.

The maximum methane producing capacity of the volatile solids, 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.

Volatile solids and nitrogen excretion rate data from the USDA *Agricultural Waste Management Field Handbook* (USDA 1996a) were used for all livestock except sheep, goats, and horses. Data from the American Society of Agricultural Engineers (ASAE 1999) were used for these animal types. In addition, annual NASS data for average milk production per cow per State (USDA 2001g) were used to calculate state-specific volatile solids production rates for dairy cows for each year of the inventory. Nitrous oxide emission factors and MCFs for dry systems were taken from *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000).

## Uncertainty

The primary factors contributing to the uncertainty in emission estimates are a lack of information on the usage of various manure management systems in each regional location and the exact methane generating characteristics of each type of manure management system. Because of significant shifts in the swine and dairy sectors toward larger farms, it is believed that increasing amounts of manure are being managed in liquid manure management systems. The existing estimates reflect these shifts in the weighted MCFs based on the 1992 and 1997 farm-size data. However, the assumption of a direct relationship between farm size and liquid system usage may not apply in all cases and may vary based on geographic location. In addition, the $CH_4$ generating characteristics of each manure management system type are based on relatively few laboratory and field measurements, and may not match the diversity of conditions under which manure is managed nationally.

*Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000) published a default range of MCFs for anaerobic lagoon systems of 0 to 100 percent, which reflects the wide range in performance that may be achieved with these systems. There exist relatively few data points on which to determine country-specific MCFs for these systems. In the United States, many livestock waste treatment systems classified as anaerobic lagoons are actually holding ponds that are substantially organically overloaded and therefore not producing methane at the same rate as a properly designed lagoon. In addition, these systems may not be well operated, contributing to higher loading rates when sludge is allowed to enter the treatment portion of the lagoon or the lagoon volume is pumped too low to allow treatment to occur. Rather than setting the MCF for all anaerobic lagoon systems in the United States based on data available from optimized lagoon systems, an MCF methodology was developed that more closely matches observed system performance and accounts for the affect of temperature on system performance.

However, there is uncertainty related to the new methodology. The MCF methodology used in the inventory includes a factor to account for management and design practices that result in the loss of volatile solids from the management system. This factor is currently estimated based on data from anaerobic lagoons in temperate climates, and from only three systems. However, this methodology is intended to account for systems across a range of management practices. Future work in gathering measurement data from animal waste lagoon systems across the country will contribute to the verification and refinement of this methodology. It will also be evaluated whether lagoon

temperatures differ substantially from ambient temperatures and whether the lower bound estimate of temperature established for lagoons and other liquid systems should be revised for use with this methodology.

The IPCC provides a suggested MCF for poultry waste management operations of 1.5 percent. Additional study is needed in this area to determine if poultry high-rise houses promote sufficient aerobic conditions to warrant a lower MCF.

The default $N_2O$ emission factors published in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000) were derived using limited information. The IPCC factors are global averages; U.S.-specific emission factors may be significantly different. Manure and urine in anaerobic lagoons and liquid/slurry management systems produce methane at different rates, and would in all likelihood produce nitrous oxide at different rates, although a single $N_2O$ emission factors was used for both system types. In addition, there are little data available to determine the extent to which nitrification-denitrification occurs in animal waste management systems. Ammonia concentrations that are present in poultry and swine systems suggest that $N_2O$ emissions from these systems may be lower than predicted by the IPCC default factors. At this time, there are insufficient data available to develop U.S.-specific $N_2O$ emission factors; however, this is an area of on-going research, and warrants further study as more data become available.

Although an effort was made to introduce the variability in volatile solids production due to differences in diet for dairy cows, additional work is needed to establish the relationship between milk production and volatile solids production. In addition, the corresponding dairy methane emissions may be underestimated because milk production was unable to be correlated to specific manure management systems in each state. A methodology to assess variability in swine volatile solids production would be useful in future inventory estimates.

Uncertainty also exists with the maximum $CH_4$ producing potential of volatile solids excreted by different animal groups (i.e., $B_o$). The $B_o$ values used in the $CH_4$ calculations are published values for U.S. animal waste. However, there are several studies that provide a range of $B_o$ values for certain animals, including dairy and swine. The $B_o$ values chosen for dairy assign separate values for dairy cows and dairy heifers to better represent the feeding regimens of these animal groups. For example, dairy heifers do not receive an abundance of high energy feed and consequently, dairy heifer manure will not produce as much methane as manure from a milking cow. However, the data available for $B_o$ values are sparse, and do not necessarily reflect the rapid changes that have occurred in this industry with respect to feed regimens. Current research is being conducted to evaluate the usefulness of incorporating animal excretion data developed for the enteric fermentation emissions inventory into the manure management inventory calculations.

## Rice Cultivation

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 the oxygen present in the soil and floodwater, causing anaerobic conditions in the soil to develop. Once the environment becomes anaerobic, methane is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. As much as 60 to 90 percent of the methane produced is oxidized by aerobic methanotrophic bacteria in the soil (Holzapfel-Pschorn et al. 1985, Sass et al. 1990). Some of the $CH_4$ is also leached away as dissolved methane 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 methane 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 more shallow 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 methane 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, and seeding and weeding practices). The factors that determine the amount of organic material that is available to decompose (i.e., organic fertilizer use, soil type, rice variety,[2] and cultivation practices) are the most important variables influencing the amount of $CH_4$ emitted over an entire growing season because 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 seven states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, and Texas. Soil types, rice varieties, and cultivation practices for rice vary from state to state, and even from farm to farm. However, most rice farmers utilize organic fertilizers in the form of rice residue from the previous 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. 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 for the stubble to decay aerobically), the amount of organic material that is available for decomposition is considerably higher than with the first (i.e., primary) crop. Methane emissions from ratoon crops have been found to be considerably higher than those from the primary crop.

Rice cultivation is a small source of $CH_4$ in the United States (Table 5-7 and Table 5-8). In 2000, $CH_4$ emissions from rice cultivation were 7.5 Tg $CO_2$ Eq. (357 Gg). Although annual emissions fluctuated considerably between the years 1990 and 2000, there was an overall increase of 5 percent over the ten year period due to an overall increase in harvested area. However, between 1990 and 1999 there was a 17 percent increase in emissions, which highlights the annual variability in the estimates. In 2000, the harvest area was the largest since 1996, as seen in Table 5-9.

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. Price is the primary factor affecting rice area in Arkansas, as farmers will plant more of what is most lucrative amongst soybeans, rice, and cotton. Government support programs have also been influential in so much as they affect the price received for a rice crop (Slaton 2001b, Mayhew 1997). California rice area is primarily influenced by price and government programs, but is also affected by water availability (Mutters 2001). In Florida, the State having the smallest harvested rice area, rice acreage is largely a function of the price of rice relative to sugarcane and corn. Most rice in Florida is rotated with sugarcane, but sometimes it is more profitable for farmers to follow their sugarcane crop with sweet corn or more sugarcane instead of rice (Schueneman 1997, 2001b). In Louisiana, rice area is influenced by government support programs, the price of rice relative to cotton, soybeans, and corn, and in some years, weather (Saichuk 1997, Linscombe 2001b). For example, a drought in 2000 caused extensive saltwater

[2] 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.

## Table 5-7: $CH_4$ Emissions from Rice Cultivation (Tg $CO_2$ Eq.)

| State | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Arkansas | 2.1 | 2.4 | 2.1 | 2.5 | 2.7 | 2.9 | 2.5 |
| California | 0.7 | 0.8 | 0.9 | 0.9 | 0.8 | 0.9 | 1.0 |
| Florida | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Louisiana | 2.1 | 2.2 | 2.0 | 2.2 | 2.3 | 2.3 | 2.1 |
| Mississippi | 0.4 | 0.5 | 0.4 | 0.4 | 0.5 | 0.6 | 0.4 |
| Missouri | 0.1 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 |
| Texas | 1.6 | 1.4 | 1.3 | 1.1 | 1.3 | 1.1 | 1.1 |
| **Total** | **7.1** | **7.6** | **7.0** | **7.5** | **7.9** | **8.3** | **7.5** |

Note: Totals may not sum due to independent rounding.

## Table 5-8: $CH_4$ Emissions from Rice Cultivation (Gg)

| Site | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Arkansas | 102 | 114 | 99 | 118 | 126 | 138 | 120 |
| California | 34 | 40 | 42 | 44 | 39 | 43 | 47 |
| Florida | 3 | 6 | 5 | 5 | 5 | 5 | 4 |
| Louisiana | 98 | 102 | 96 | 105 | 111 | 111 | 101 |
| Mississippi | 21 | 24 | 18 | 20 | 23 | 27 | 19 |
| Missouri | 7 | 10 | 8 | 10 | 12 | 16 | 15 |
| Texas | 75 | 67 | 63 | 55 | 60 | 55 | 52 |
| **Total** | **339** | **363** | **332** | **356** | **376** | **395** | **357** |

Note: Totals may not sum due to independent rounding.

## Table 5-9: Rice Areas Harvested (Hectares)

| State/Crop | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Arkansas | | | | | | | |
| Primary | 485,633 | 542,291 | 473,493 | 562,525 | 600,971 | 657,628 | 570,619 |
| Ratoon* | NO | NO | NO | NO | 202 | 202 | NO |
| California | 159,854 | 188,183 | 202,347 | 208,822 | 185,350 | 204,371 | 221,773 |
| Florida | | | | | | | |
| Primary | 4,978 | 9,713 | 8,903 | 7,689 | 8,094 | 7,229 | 7,801 |
| Ratoon | 2,489 | 4,856 | 4,452 | 3,845 | 4,047 | 4,673 | 3,193 |
| Louisiana | | | | | | | |
| Primary | 220,558 | 230,676 | 215,702 | 235,937 | 250,911 | 249,292 | 194,253 |
| Ratoon | 66,168 | 69,203 | 64,711 | 70,781 | 75,273 | 74,788 | 77,701 |
| Mississippi | 101,174 | 116,552 | 84,176 | 96,317 | 108,458 | 130,716 | 88,223 |
| Missouri | 32,376 | 45,326 | 38,446 | 47,349 | 57,871 | 74,464 | 70,417 |
| Texas | | | | | | | |
| Primary | 142,857 | 128,693 | 120,599 | 104,816 | 114,529 | 104,816 | 86,605 |
| Ratoon | 57,143 | 51,477 | 48,240 | 41,926 | 45,811 | 41,926 | 43,302 |
| **Total** | **1,273,229** | **1,386,969** | **1,261,068** | **1,380,008** | **1,451,518** | **1,550,106** | **1,363,888** |

Note: Totals may not sum due to independent rounding.
* Arkansas ratooning occurred only in 1998 and 1999.
NO (Not Occurring)

intrusion along the Gulf Coast, making over 32,000 hectares unplantable. In Mississippi, rice is usually rotated with soybeans, but if soybean prices increase relative to rice prices, then some of the acreage that would have been planted in rice, is instead planted in soybeans (Street 1997, 2001). In Missouri, rice acreage is affected by weather (e.g., rain during the planting season may prevent the planting of rice), the price differential between rice and soybeans or cotton, and government support programs (Stevens 1997, Guethle 2001). In Texas, rice area is affected mainly by the price of rice, government support programs, and water availability (Klosterboer 1997, 2001b).

## Methodology

The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) recommends utilizing annual harvested rice areas and area-based seasonally integrated emission factors (i.e., amount of $CH_4$ emitted over a growing season per unit harvested area) to estimate annual $CH_4$ emissions from rice cultivation. This methodology is followed but a United States specific emission factor is used in the calculations. In addition, because daily average emissions have been found to be much higher for ratooned crops than for primary crops, emissions from ratooned and primary areas are estimated separately. This is consistent with IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000).

## Data Sources

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 5-9. Data for 1990 through 2000 for all states except Florida 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), *Crop Production 1999 Summary* (USDA 2000), and *Crop Production 2000 Summary* (USDA 2001). Harvested rice areas in Florida, which are not reported by USDA, were obtained from Tom Schueneman (1999b, 1999c, 2000, 2001a), a Florida agricultural extension agent. Acreages for the ratoon crops were derived from conversations with the agricultural extension agents in each state. In Arkansas, ratooning occurred only in 1998 and 1999, when the ratooned area was less than 1 percent of the primary area (Slaton 1999, 2000, 2001a). 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), and around 41 percent of the primary area in 2000 (Schueneman 2001a). In Louisiana, the percentage of the primary area that was ratooned was constant at 30 percent over the 1990 to 1999 period, but increased to approximately 40 percent in 2000 (Linscombe 1999a, 2001a and Bollich 2000). In Texas, the percentage of the primary area that was ratooned was constant at 40 percent over the entire 1990 to 1999 period, but increased to 50 percent in 2000 due to an early primary crop (Klosterboer 1999, 2000, 2001a).

To determine what seasonal $CH_4$ emission factors should be used for the primary and ratoon crops, $CH_4$ flux information from rice field measurements in the United States was collected. Experiments which involved 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 in which floodwaters were drained mid-season, were excluded from the analysis. The remaining experimental results[3] 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 synthetic and organic fertilizer added (Bossio et al. 1999, Cicerone et al. 1992, Sass et al. 1991a and 1991b) were averaged to derive an emission factor for the primary crop, and the experimental results from ratoon crops with synthetic fertilizer added (Lindau and Bollich 1993, Lindau et al. 1995) were averaged to derive an emission factor for the ratoon crop. The resultant emission factor for the primary crop is 210 kg $CH_4$/hectare-season, and the resultant emission factor for the ratoon crop is 780 kg $CH_4$/hectare-season.

[3] In some of these remaining experiments, measurements from individual plots were excluded from the analysis because of the reasons just mentioned. 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 since this emission rate is unusually high compared to other flux measurements in the United States, as well as in Europe and Asia (IPCC/UNEP/OECD/IEA 1997).

## 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 variability is due to differences in cultivation practices, particularly the type, amount, and mode of fertilizer application; differences in cultivar type; and differences in soil and climatic conditions. Some of this variability is accounted for by separating primary from ratooned areas. However, even within a cropping season, measured emissions vary significantly. Of the experiments that were used to derive the emission factors used 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. Based on these emission ranges, total $CH_4$ emissions from rice cultivation in 2000 were estimated to range from 1.8 to 16 Tg $CO_2$ Eq. (87 to 779 Gg).

A second source of uncertainty is the ratooned area data, which are not compiled regularly. However, this is a relatively minor source of uncertainty, as these areas account for less than 10 percent of the total area. Expert judgment was used to estimate these areas.

The last source of uncertainty is in the practice of flooding outside of the normal rice season. According to agriculture extension agents, all of the rice-growing States practice this on some part of their rice acreage. Estimates of these areas range from 5 to 33 percent of the rice acreage. Fields are flooded for a variety of reasons: to provide habitat for waterfowl, to provide ponds for crawfish production, and to aid in rice straw decomposition. To date, methane flux measurements have not been undertaken in these flooded areas, so this activity is not included in the emission estimates presented here.

# Agricultural Soil Management

Nitrous oxide ($N_2O$) is produced naturally in soils through the microbial processes of nitrification and denitrification.[4] A number of agricultural activities add nitrogen to soils, thereby increasing the amount of nitrogen available for nitrification and denitrification, and ultimately the amount of $N_2O$ emitted. These activities may add nitrogen to soils either directly or indirectly (Figure 5-2). Direct additions occur through various soil management practices and from the deposition of manure on soils by animals on pasture, range, and paddock (i.e., by animals whose manure is not managed). Soil management practices that add nitrogen to soils include fertilizer use, application of managed livestock manure, disposal of sewage sludge, production of nitrogen-fixing crops, retention of crop residues, and cultivation of histosols (i.e., soils with a high organic matter content, otherwise known as organic soils).[5] Indirect additions of nitrogen to soils occur through two mechanisms: 1) volatilization and subsequent atmospheric deposition of applied nitrogen;[6] and 2) surface runoff and leaching of applied nitrogen into groundwater and surface water. Other agricultural soil management practices, such as irrigation, drainage, tillage practices, and fallowing of land, can affect fluxes of $N_2O$, as well as other greenhouse gases, to and from soils. However, because there are significant uncertainties associated with these other fluxes, they have not been estimated.

Agricultural soil management is the largest source of $N_2O$ in the United States.[7] Estimated emissions from this source in 2000 were 297.4 Tg $CO_2$ Eq. (959 Gg $N_2O$) (see Table 5-10 and Table 5-11). Although annual agricultural soil management emissions fluctuated between 1990 and 2000, there was a general increase in emissions over the

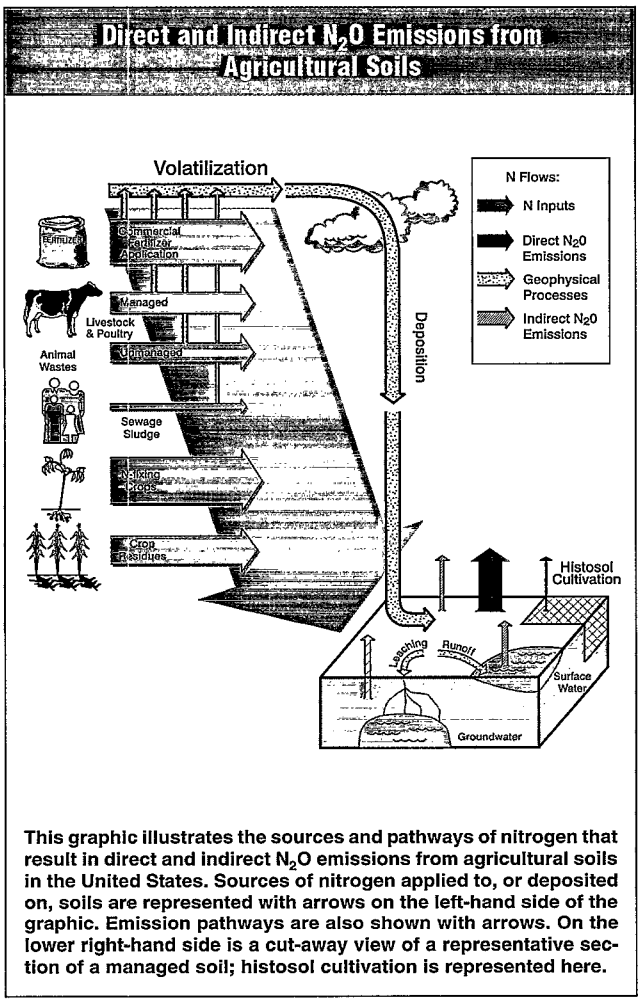
[4] Nitrification and denitrification are two processes within the nitrogen cycle that are brought about by certain microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium ($NH_4$) to nitrate ($NO_3$), and denitrification is the anaerobic microbial reduction of nitrate to dinitrogen 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).

[5] Cultivation of histosols does not, *per se*, "add" nitrogen to soils. Instead, the process of cultivation enhances mineralization of old, nitrogen-rich organic matter that is present in histosols, thereby enhancing $N_2O$ emissions from histosols.

[6] These processes entail volatilization of applied nitrogen as ammonia ($NH_3$) and oxides of nitrogen ($NO_x$), transformations of these gases within the atmosphere (or upon deposition), and deposition of the nitrogen primarily in the form of particulate ammonium ($NH_4$), nitric acid ($HNO_3$), and oxides of nitrogen.

[7] Note that the emission estimates for this source category include applications of nitrogen to *all* soils, but the term "Agricultural Soil Management" is kept for consistency with the reporting structure of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Figure 5-2




**This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect $N_2O$ emissions from agricultural 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.**

eleven-year period (see Annex M for a complete time series of emission estimates). This general increase in emissions was due primarily to an increase in synthetic fertilizer use, manure production, and crop production over this period. The year-to-year fluctuations are largely a reflection of annual variations in synthetic fertilizer consumption and crop production. Over the eleven-year period, total emissions of $N_2O$ from agricultural soil management increased by approximately 11 percent.

Estimated direct and indirect $N_2O$ emissions, by subsource, are provided in Table 5-12, Table 5-13, and Table 5-14.

## Methodology

The methodology used to estimate emissions from agricultural soil management is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), as amended by the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). The *Revised 1996 IPCC Guidelines* divide this $N_2O$ source category into three components: (1) direct emissions from managed soils due to applied nitrogen and cultivation of histosols; (2) direct emissions from soils due to the deposition of manure by livestock on pasture, range, and paddock; and (3) indirect emissions from soils induced by applied nitrogen.

**Table 5-10: $N_2O$ Emissions from Agricultural Soil Management (Tg $CO_2$ Eq.)**

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Direct** | **193.5** | **204.8** | **212.1** | **217.2** | **218.4** | **216.5** | **217.5** |
| Managed Soils | 153.0 | 161.1 | 168.6 | 175.0 | 177.1 | 175.5 | 177.1 |
| Pasture, Range, & Paddock Livestock | 40.4 | 43.6 | 43.6 | 42.2 | 41.4 | 41.0 | 40.5 |
| **Indirect** | **73.6** | **78.6** | **80.3** | **80.0** | **79.8** | **79.8** | **79.8** |
| **Total** | **267.1** | **283.4** | **292.4** | **297.2** | **298.3** | **296.3** | **297.4** |

Note: Totals may not sum due to independent rounding.

**Table 5-11: $N_2O$ Emissions from Agricultural Soil Management (Gg)**

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Direct** | **624** | **661** | **684** | **701** | **705** | **698** | **702** |
| Managed Soils | 494 | 520 | 544 | 564 | 571 | 566 | 571 |
| Pasture, Range, & Paddock Livestock | 130 | 141 | 140 | 136 | 133 | 132 | 131 |
| **Indirect** | **237** | **254** | **259** | **258** | **257** | **257** | **257** |
| **Total** | **862** | **914** | **943** | **959** | **962** | **956** | **959** |

Note: Totals may not sum due to independent rounding.

## Table 5-12: Direct $N_2O$ Emissions from Managed Soils (Tg $CO_2$ Eq.)

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Commercial Fertilizers* | 55.4 | 59.2 | 61.2 | 61.3 | 61.4 | 61.6 | 61.7 |
| Livestock Manure | 12.7 | 13.2 | 13.2 | 13.4 | 13.6 | 13.8 | 13.8 |
| Sewage Sludge | 0.4 | 0.6 | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 |
| N Fixation | 58.5 | 61.8 | 63.9 | 68.2 | 69.2 | 68.2 | 69.0 |
| Crop Residue | 23.2 | 23.4 | 26.8 | 28.7 | 29.3 | 28.3 | 29.1 |
| Histosol Cultivation | 2.8 | 2.8 | 2.8 | 2.9 | 2.9 | 2.9 | 2.9 |
| **Total** | **153.0** | **161.1** | **168.6** | **175.0** | **177.1** | **175.5** | **177.1** |

Note: Totals may not sum due to independent rounding.
* Excludes sewage sludge and livestock manure used as commercial fertilizers.

## Table 5-13: Direct $N_2O$ Emissions from Pasture, Range, and Paddock Livestock Manure (Tg $CO_2$ Eq.)

| Animal Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Beef Cattle | 35.2 | 38.9 | 39.0 | 37.8 | 37.0 | 36.7 | 36.2 |
| Dairy Cows | 1.7 | 1.5 | 1.4 | 1.3 | 1.3 | 1.2 | 1.2 |
| Swine | 0.5 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| Sheep | 0.4 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Goats | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Poultry | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Horses | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| **Total** | **40.4** | **43.6** | **43.6** | **42.2** | **41.4** | **41.0** | **40.5** |

Note: Totals may not sum due to independent rounding.

## Table 5-14: Indirect $N_2O$ Emissions (Tg $CO_2$ Eq.)

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Volatilization & Atm. Deposition** | **11.6** | **12.4** | **12.6** | **12.6** | **12.5** | **12.5** | **12.5** |
| Commercial Fertilizers* | 4.9 | 5.3 | 5.4 | 5.5 | 5.5 | 5.5 | 5.5 |
| Livestock Manure | 6.6 | 7.0 | 7.1 | 7.0 | 6.9 | 6.9 | 6.9 |
| Sewage Sludge | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Surface Leaching & Runoff** | **62.0** | **66.2** | **67.6** | **67.4** | **67.3** | **67.3** | **67.3** |
| Commercial Fertilizers* | 36.9 | 39.5 | 40.8 | 40.9 | 40.9 | 41.1 | 41.1 |
| Livestock Manure | 24.7 | 26.3 | 26.4 | 26.1 | 25.8 | 25.7 | 25.7 |
| Sewage Sludge | 0.3 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| **Total** | **73.6** | **78.6** | **80.3** | **80.0** | **79.8** | **79.8** | **79.8** |

Note: Totals may not sum due to independent rounding.
* Excludes sewage sludge and livestock manure used as commercial fertilizers.

Annex M provides more detailed information on the methodologies and data used to calculate $N_2O$ emissions from each of these three components.

### Direct $N_2O$ Emissions from Managed Soils

Direct $N_2O$ emissions from managed soils are composed of two parts, which are estimated separately and then summed. These two parts are 1) emissions due to nitrogen applications, and 2) emissions from histosol cultivation.

Estimates of direct $N_2O$ emissions from nitrogen applications were based on the total amount of nitrogen that is applied to soils annually through the following practices: (a) the application of synthetic and organic commercial fertilizers, (b) the application of livestock manure through both daily spread operations and through the eventual application of manure that had been stored in manure management systems, (c) the application of sewage sludge, (d) the production of nitrogen-fixing crops, and (e) the retention of crop residues (i.e., leaving residues in the field after harvest). For each of these practices, the annual amounts of nitrogen applied were estimated as follows:

a) Synthetic and organic commercial fertilizer nitrogen applications were derived from annual fertilizer consumption data and the nitrogen content of the fertilizers.

b) Livestock manure nitrogen applications were based on the assumption that all livestock manure is applied to soils except for two components: 1) a small portion of poultry manure that is used as a livestock feed supplement, and 2) the manure from pasture, range, and paddock livestock. The manure nitrogen data were derived from animal population and weight statistics, information on manure management system usage, annual nitrogen excretion rates for each animal type, and information on the fraction of poultry litter that is used as a livestock feed supplement.

c) Sewage sludge nitrogen applications were derived from estimates of annual U.S. sludge production, the nitrogen content of the sludge, and periodic surveys of sludge disposal methods.

d) The amounts of nitrogen made available to soils through the cultivation of nitrogen-fixing crops were based on estimates of the amount of nitrogen in aboveground plant biomass, which were derived from annual crop production statistics, mass ratios of aboveground residue to crop product, dry matter fractions, and nitrogen contents of the plant biomass.

e) Crop residue nitrogen retention data were derived from information about which residues are typically left on the field, the fractions of residues left on the field, annual crop production statistics, mass ratios of aboveground residue to crop product, and dry matter fractions and nitrogen contents of the residues.

After the annual amounts of nitrogen applied were estimated for each practice, each amount of nitrogen was reduced by the fraction that is assumed to volatilize according to the *Revised 1996 IPCC Guidelines* and the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. The net amounts left on the soil from each practice were then summed to yield total unvolatilized applied nitrogen, which was multiplied by the IPCC default emission factor for nitrogen applications.

Estimates of annual $N_2O$ emissions from histosol cultivation were based on estimates of the total U.S. acreage of histosols cultivated annually for each of two climatic zones: 1) temperate, and 2) sub-tropical. 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.[8]

Total annual emissions from nitrogen applications, and annual emissions from histosol cultivation, were then summed to estimate total direct emissions from managed soils.

### Direct $N_2O$ Emissions from Pasture, Range, and Paddock Livestock Manure

Estimates of $N_2O$ emissions from this component are based on the amount of nitrogen in the manure that is deposited annually on soils by livestock in pasture, range, and paddock. Estimates of annual manure nitrogen from

[8] Note that the IPCC default emission factors for histosols have been revised in the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000). These revised default emission factors (IPCC 2000) were used in these calculations.

these livestock were derived from animal population and weight statistics; information on the fraction of the total population of each animal type that is on pasture, range, or paddock; and annual nitrogen excretion rates for each animal type. The annual amounts of manure nitrogen from each animal type were summed over all animal types to yield total pasture, range, and paddock manure nitrogen, which was then multiplied by the IPCC default emission factor for pasture, range, and paddock nitrogen to estimate $N_2O$ emissions.

### Indirect $N_2O$ Emissions from Soils

Indirect emissions of $N_2O$ are composed of two parts, which are estimated separately and then summed. These two parts are 1) emissions resulting from volatilization and subsequent deposition of the nitrogen in applied fertilizers, applied sewage sludge, and all livestock manure,[9] and 2) leaching and runoff of nitrogen in applied fertilizers, applied sewage sludge, and applied plus deposited livestock manure. The activity data (i.e., nitrogen in applied fertilizers, applied sewage sludge, all livestock manure, and applied plus deposited livestock manure) were estimated in the same way as for the direct emission estimates.

To estimate the annual amount of applied nitrogen that volatilizes, the annual amounts of applied synthetic fertilizer nitrogen, applied sewage sludge nitrogen, and all livestock manure nitrogen, were each multiplied by the appropriate IPCC default volatilization fraction. The three amounts of volatilized nitrogen were then summed, and the sum was multiplied by the IPCC default emission factor for volatilized/deposited nitrogen.

To estimate the annual amount of nitrogen that leaches or runs off, the annual amounts of applied synthetic fertilizer nitrogen, applied sewage sludge nitrogen, and applied plus deposited livestock manure nitrogen were each multiplied by the IPCC default leached/runoff fraction. The three amounts of leached/runoff nitrogen were then summed, and the sum was multiplied by the IPCC default emission factor for leached/runoff nitrogen.

Total annual indirect emissions from volatilization, and annual indirect emissions from leaching and runoff, were then summed to estimate total indirect emissions of $N_2O$ from managed soils.

## Data Sources

The activity data used in these calculations were obtained from numerous sources. Annual synthetic and organic fertilizer consumption data for the United States were obtained from annual publications on commercial fertilizer statistics (TVA 1991, 1992a, 1993, 1994; AAPFCO 1995, 1996, 1997, 1998, 1999, 2000b). Fertilizer nitrogen contents were taken from these same publications and AAPFCO (2000a). Livestock population data were obtained from USDA publications (USDA 1994b,c; 1995a,b; 1998a,c; 1999a-e; 2000a-g; 2001b-g), the FAOSTAT database (FAO 2001), and Lange (2000). Manure management information was obtained from Poe et al. (1999), Safley et al. (1992), and personal communications with agricultural experts (Anderson 2000, Deal 2000, Johnson 2000, Miller 2000, Milton 2000, Stettler 2000, Sweeten 2000, Wright 2000). Livestock weight data were obtained from Safley (2000), USDA (1996, 1998d), and ASAE (1999); daily rates of nitrogen excretion from ASAE (1999) and USDA (1996); and information about the fraction of poultry litter used as a feed supplement from Carpenter (1992). Data collected by the EPA were used to derive annual estimates of land application of sewage sludge (EPA 1993, 1999). The nitrogen content of sewage sludge was taken from Metcalf and Eddy, Inc. (1991). Annual production statistics for nitrogen-fixing crops were obtained from USDA reports (USDA 1994a, 1998b, 2000i, 2001a), a book on forage crops (Taylor and Smith 1995, Pederson 1995, Beuselinck and Grant 1995, Hoveland and Evers 1995), and personal communications with forage experts (Cropper 2000, Gerrish 2000, Hoveland 2000, Evers 2000, and Pederson 2000). Mass ratios of aboveground residue to crop product, dry matter fractions, and nitrogen contents for nitrogen-fixing crops were obtained from Strehler and Stützle (1987), Barnard and Kristoferson (1985), Karkosh (2000), Ketzis (1999), and IPCC/UNEP/OECD/IEA (1997).

[9] Total livestock manure nitrogen is used in the calculation of indirect $N_2O$ emissions from volatilization because all manure nitrogen, regardless of how the manure is managed or used, is assumed to be subject to volatilization.

Annual production statistics for crops whose residues are left on the field, except for rice in Florida, were obtained from USDA reports (USDA 1994a, 1998b, 2000i, 2001a). Production statistics for rice in Florida are not recorded by USDA, so these were derived from Smith (2001) and Schueneman (1999, 2001). Aboveground residue to crop mass ratios, residue dry matter fractions, and residue nitrogen contents were obtained from Strehler and Stützle (1987), Turn et al. (1997), Ketzis (1999), and Barnard and Kristoferson (1985). Estimates of the fractions of residues left on the field were based on information provided by Karkosh (2000), and on information about rice residue burning (see the Agricultural Residue Burning section). The annual areas of cultivated histosols were estimated from 1982, 1992, and 1997 statistics in USDA's *1997 National Resources Inventory* (USDA 2000h, as extracted by Eve 2001, and revised by Ogle 2002).

All emission factors, volatilization fractions, and the leaching/runoff fraction were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), as amended by the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000).

## Uncertainty

The amount of $N_2O$ emitted from managed soils depends not only on N inputs, but also on a large number of variables, including organic carbon availability, $O_2$ partial pressure, soil moisture content, pH, soil temperature, and soil amendment management practices. However, the effect of the combined interaction of these other variables on $N_2O$ flux is complex and highly uncertain. Therefore, the IPCC default methodology, which is used here, is based only on N inputs and does not utilize these other variables. As noted in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), this is a generalized approach that treats all soils, except cultivated histosols, as being under the same conditions. The estimated ranges around the IPCC default emission factors provide an indication of the uncertainty in the emission estimates due to this simplified methodology. Most of the emission factor ranges are about an order of magnitude, or larger. Developing an emission estimation methodology that explicitly utilizes these other variables will require more scientific research and much more detailed databases, and will likely involve the use of process models.

Uncertainties also exist in the activity data used to derive emission estimates. In particular, the fertilizer statistics include only those organic fertilizers that enter the commercial market, so non-commercial fertilizers (other than the estimated manure and crop residues) have not been captured. The livestock excretion values, while based on detailed population and weight statistics, were derived using simplifying assumptions concerning the types of management systems employed. Statistics on sewage sludge applied to soils were not available on an annual basis; annual production and application estimates were based on figures and projections that were calculated from surveys that yielded uncertainty levels as high as 14 percent (Bastian 1999). Annual data were obtained by interpolating and extrapolating at constant rates from these uncertain figures, though change between the years was unlikely to be constant (Bastian 2001). The production statistics for the nitrogen-fixing crops that are forage legumes are highly uncertain because statistics are not compiled for any of these crops except alfalfa, and the alfalfa statistics include alfalfa mixtures. Conversion factors for the nitrogen-fixing crops were based on a limited number of studies, and may not be representative of all conditions in the United States. Data on crop residues left on the field are not available, so expert judgment was used to estimate the amount of residues left on soils. And finally, the estimates of cultivated histosol areas are uncertain because they are from a natural resource inventory that was not explicitly designed as a soil survey, and this natural resource inventory contains data for only three years (1982, 1992, and 1997). Annual histosol areas were estimated by linear interpolation and extrapolation.

# Agricultural Residue Burning

Large quantities of agricultural crop residues are produced by farming activities. There are a variety of ways to dispose of these residues. For example, agricultural residues can be left on or plowed back into the field, composted and then applied to soils, landfilled, or burned

in the field. Alternatively, they can be collected and used as a fuel or sold in supplemental feed markets. Field burning of crop residues is not considered a net source of carbon dioxide ($CO_2$) 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 methane ($CH_4$), nitrous oxide ($N_2O$), carbon monoxide (CO), and nitrogen oxides ($NO_x$), which are released during combustion.

Field burning is not a common method of agricultural residue disposal in the United States; therefore, emissions from this source are minor. The primary crop types whose residues are typically burned in the United States are wheat, rice, sugarcane, corn, barley, soybeans, and peanuts. Of these residues, less than 5 percent is burned each year, except for rice.[10] Annual emissions from this source over the period 1990 through 2000 averaged approximately 0.7 Tg $CO_2$ Eq. (35 Gg) of $CH_4$, 0.4 Tg $CO_2$ Eq. (1 Gg) of $N_2O$, 725 Gg of CO, and 31 Gg of $NO_x$ (see Table 5-15 and Table 5-16).

## Methodology

The methodology for estimating greenhouse gas emissions from field burning of agricultural residues is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). In order to estimate the amounts of carbon and nitrogen released during burning, the following equations were used:[11]

Carbon Released = (Annual Crop Production) × (Residue/Crop Product Ratio) × (Fraction of Residues Burned *in situ*) × (Dry Matter Content of the Residue) × (Burning Efficiency) × (Carbon Content of the Residue) × (Combustion Efficiency)[12]

Nitrogen Released = (Annual Crop Production) × (Residue/Crop Product Ratio) × (Fraction of Residues Burned *in situ*) × (Dry Matter Content of the Residue) × (Burning Efficiency) × (Nitrogen Content of the Residue) × (Combustion Efficiency)

**Table 5-15: Emissions from Agricultural Residue Burning (Tg $CO_2$ Eq.)**

| Gas/Crop Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CH_4$** | **0.7** | **0.7** | **0.7** | **0.8** | **0.8** | **0.8** | **0.8** |
| Wheat | 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 |
| Sugarcane | + | + | + | + | + | + | + |
| Corn | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 |
| Barley | + | + | + | + | + | + | + |
| Soybeans | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Peanuts | + | + | + | + | + | + | + |
| **$N_2O$** | **0.4** | **0.4** | **0.4** | **0.4** | **0.5** | **0.4** | **0.5** |
| Wheat | + | + | + | + | + | + | + |
| Rice | + | + | + | + | + | + | + |
| Sugarcane | + | + | + | + | + | + | + |
| Corn | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Barley | + | + | + | + | + | + | + |
| Soybeans | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 |
| Peanuts | + | + | + | + | + | + | + |
| **Total** | **1.1** | **1.0** | **1.2** | **1.2** | **1.2** | **1.2** | **1.2** |

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

[10] The fraction of rice straw burned each year is significantly higher than that for other crops (see "Data Sources" discussion below).

[11] Note: As is explained below, the fraction of residues burned varies among states for rice, so these equations were applied at the state level for rice. These equations were applied at the national level for all other crop types.

[12] Burning Efficiency is defined as the fraction of dry biomass exposed to burning that actually burns. Combustion Efficiency is defined as the fraction of carbon in the fire that is oxidized completely to $CO_2$. In the methodology recommended by the IPCC, the "burning efficiency" is assumed to be contained in the "fraction of residues burned" factor. However, the number used here to estimate the "fraction of residues burned" does not account for the fraction of exposed residue that does not burn. Therefore, a "burning efficiency factor" was added to the calculations.

**Table 5-16: Emissions from Agricultural Residue Burning (Gg)***

| Gas/Crop Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CH_4$** | **33** | **31** | **36** | **36** | **37** | **36** | **37** |
| Wheat | 7 | 5 | 5 | 6 | 6 | 5 | 5 |
| Rice | 4 | 4 | 4 | 3 | 3 | 3 | 3 |
| Sugarcane | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Corn | 13 | 13 | 16 | 16 | 17 | 16 | 17 |
| Barley | 1 | 1 | 1 | 1 | 1 | + | 1 |
| Soybeans | 7 | 8 | 9 | 10 | 10 | 10 | 10 |
| Peanuts | + | + | + | + | + | + | + |
| **$N_2O$** | **1** | **1** | **1** | **1** | **1** | **1** | **1** |
| Wheat | + | + | + | + | + | + | + |
| Rice | + | + | + | + | + | + | + |
| Sugarcane | + | + | + | + | + | + | + |
| Corn | + | + | + | + | + | + | + |
| Barley | + | + | + | + | + | + | + |
| Soybeans | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Peanuts | + | + | + | + | + | + | + |
| **CO** | **685** | **656** | **747** | **761** | **781** | **760** | **786** |
| Wheat | 137 | 109 | 114 | 124 | 128 | 115 | 111 |
| Rice | 81 | 80 | 85 | 66 | 58 | 69 | 69 |
| Sugarcane | 18 | 20 | 19 | 21 | 22 | 23 | 24 |
| Corn | 282 | 263 | 328 | 328 | 347 | 336 | 355 |
| Barley | 16 | 13 | 15 | 13 | 13 | 10 | 12 |
| Soybeans | 148 | 167 | 183 | 207 | 211 | 204 | 213 |
| Peanuts | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **$NO_x$** | **28** | **29** | **32** | **34** | **35** | **34** | **35** |
| Wheat | 4 | 3 | 3 | 3 | 3 | 3 | 3 |
| Rice | 3 | 3 | 3 | 2 | 2 | 2 | 2 |
| Sugarcane | + | + | + | + | + | + | + |
| Corn | 7 | 6 | 8 | 8 | 8 | 8 | 9 |
| Barley | 1 | + | + | + | + | + | + |
| Soybeans | 14 | 16 | 17 | 20 | 20 | 19 | 20 |
| Peanuts | + | + | + | + | + | + | + |

* Full molecular weight basis.
+ Does not exceed 0.5 Gg
Note: Totals may not sum due to independent rounding.

Emissions of $CH_4$ and CO were calculated by multiplying the amount of carbon released by the appropriate IPCC default emission ratio (i.e., $CH_4$-C/C or CO-C/C). Similarly, $N_2O$ and $NO_x$ emissions were calculated by multiplying the amount of nitrogen released by the appropriate IPCC default emission ratio (i.e., $N_2O$-N/N or $NO_x$-N/N).

## Data Sources

The crop residues that are burned in the United States were determined from various state level greenhouse gas emission inventories (ILENR 1993, Oregon Department of Energy 1995, Wisconsin Department of Natural Resources 1993) and publications on agricultural burning in the United States (Jenkins et al. 1992, Turn et al. 1997, EPA 1992).

Crop production data for all crops except rice in Florida were taken from the USDA's *Field Crops, Final Estimates 1987-1992, 1992-1997* (USDA 1994, 1998), *Crop Production 1999 Summary* (USDA 2000), and *Crop Production 2000 Summary* (USDA 2001). Crop production data for Florida, which are not collected by USDA, were estimated by applying average primary and ratoon crop yields for Florida (Smith 2001) to Florida acreages (Schueneman 1999b, 2001). The production data for the crop types whose residues are burned are presented in Table 5-17.

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

**Table 5-17: Agricultural Crop Production (Thousand Metric Tons of Product)**

| Crop | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Wheat | 74,292 | 59,404 | 61,980 | 67,534 | 69,327 | 62,569 | 60,512 |
| Rice | 7,105 | 7,935 | 7,828 | 8,339 | 8,570 | 9,381 | 8,708 |
| Sugarcane | 25,525 | 27,922 | 26,729 | 28,766 | 30,896 | 32,023 | 32,973 |
| Corn* | 201,534 | 187,970 | 234,518 | 233,864 | 247,882 | 239,549 | 253,208 |
| Barley | 9,192 | 7,824 | 8,544 | 7,835 | 7,667 | 6,103 | 6,921 |
| Soybeans | 52,416 | 59,174 | 64,780 | 73,176 | 74,598 | 72,223 | 75,338 |
| Peanuts | 1,635 | 1,570 | 1,661 | 1,605 | 1,798 | 1,737 | 1,491 |

*Corn for grain (i.e., excludes corn for silage).

**Table 5-18: Percentage of Rice Area Burned by State**

| State | Percent Burned 1990-1998 | Percent Burned 1999 | Percent Burned 2000 |
|---|---|---|---|
| Arkansas | 10 | 10 | 10 |
| California | variable[a] | 27 | 27 |
| Florida[b] | 0 | 0 | 0 |
| Louisiana | 6 | 0 | 5 |
| Mississippi | 10 | 40 | 40 |
| Missouri | 5 | 5 | 8 |
| Texas | 1 | 2 | 0 |

[a] Values provided in Table 5-19.
[b] Burning of crop residues is illegal in Florida.

**Table 5-19: Percentage of Rice Area Burned in California**

| Year | California |
|---|---|
| 1990 | 75 |
| 1995 | 59 |
| 1996 | 63 |
| 1997 | 34 |
| 1998 | 33 |
| 1999 | 27 |
| 2000 | 27 |

Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996). Estimates of the percentage of rice acreage on which residue burning took place were obtained on a state-by-state basis from agricultural extension agents in each of the seven rice-producing states (Bollich 2000; Guethle 1999, 2000, 2001; Fife 1999; California Air Resources Board 1999; Klosterboer 1999a, 1999b, 2000, 2001; Linscombe 1999a, 1999b, 2001; Najita 2000, 2001; Schueneman 1999a, 1999b, 2001; Slaton 1999a, 1999b, 2000; Street 1999a, 1999b, 2000, 2001; Wilson 2001) (see Table 5-18 and Table 5-19). The estimates provided for Arkansas and Florida remained constant over the entire 1990 through 2000 period, while the estimates for all other states varied over the time series. For California, it was assumed that the annual percents of rice acreage burned in Sacramento Valley are representative of burning in the entire state, because the Sacramento Valley accounts for over 95 percent of the rice acreage in California (Fife 1999). The annual percents of rice acreage burned in Sacramento Valley were obtained from a report of the California Air Resources Board (2001). These values declined over the 1990 through 2000 period because of a legislated reduction in rice straw burning (see Table 5-19).

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

Protein System. The residue carbon contents and nitrogen contents for all crops except soybeans and peanuts are from Turn et al. (1997). The residue carbon content for soybeans and peanuts is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The nitrogen content of soybeans is from Barnard and Kristoferson (1985). The nitrogen content of peanuts is from Ketzis (1999). These data are listed in Table 5-20. 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 5-21) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

## Uncertainty

The largest 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, as well as among States. The fractions of residue burned used in these calculations were based upon information collected by State agencies and in published literature. It is likely that these emission estimates will continue to change as more information becomes available in the future.

Other sources of uncertainty include the residue/crop product mass ratios, residue dry matter contents, burning and combustion efficiencies, and emission ratios. A residue/crop product ratio for a specific crop can vary among cultivars, and for all crops except sugarcane, generic residue/crop product ratios, rather than ratios specific to the United States, have been used. Residue dry matter contents, burning and combustion efficiencies, and emission ratios, all can vary due to weather and other combustion conditions, such as fuel geometry. Values for these variables were taken from literature on agricultural biomass burning.

**Table 5-20: Key Assumptions for Estimating Emissions from Agricultural Residue Burning***

| Crop | Residue/ Crop Ratio | Fraction of Residue Burned | Dry Matter Fraction | Carbon Fraction | Nitrogen Fraction |
|---|---|---|---|---|---|
| Wheat | 1.3 | 0.03 | 0.93 | 0.4428 | 0.0062 |
| Rice | 1.4 | variable | 0.91 | 0.3806 | 0.0072 |
| Sugarcane | 0.8 | 0.03 | 0.62 | 0.4235 | 0.0040 |
| Corn | 1.0 | 0.03 | 0.91 | 0.4478 | 0.0058 |
| Barley | 1.2 | 0.03 | 0.93 | 0.4485 | 0.0077 |
| Soybeans | 2.1 | 0.03 | 0.87 | 0.4500 | 0.0230 |
| Peanuts | 1.0 | 0.03 | 0.86 | 0.4500 | 0.0106 |

* The burning efficiency and combustion efficiency for all crops were assumed to be 0.93 and 0.88, respectively.

**Table 5-21: 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 carbon compound released (units of C) relative to mass of total carbon released from burning (units of C).
[b] Mass of nitrogen compound released (units of N) relative to mass of total nitrogen released from burning (units of N).

# 6. Land-Use Change and Forestry

This chapter provides an assessment of the net carbon dioxide ($CO_2$) flux[1] caused by 1) changes in forest carbon stocks, 2) changes in carbon stocks in urban trees, 3) changes in agricultural soil carbon stocks, and 4) changes in carbon stocks in landfilled yard trimmings. Seven components of forest carbon stocks are analyzed: trees, understory vegetation, forest floor, down dead wood, soils, wood products in use, and landfilled wood products. The estimated $CO_2$ flux from each of these forest components was derived from U.S. forest inventory data, using methodologies that are consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Changes in carbon stocks in urban trees were estimated based on field measurements in ten U.S. cities and data on national urban tree cover, using a methodology consistent with the *Revised 1996 IPCC Guidelines*. Changes in agricultural soil carbon stocks include mineral and organic soil carbon stock changes due to use and management of cropland and grazing land, and emissions of $CO_2$ due to the application of crushed limestone and dolomite to agricultural soils (i.e., soil liming). The methods in the *Revised 1996 IPCC Guidelines* were used to estimate all three components of changes in agricultural soil carbon stocks. Changes in yard trimming carbon stocks in landfills were estimated using analysis of life-cycle greenhouse gas emissions and sinks associated with solid waste management (EPA 1998). Note that the chapter title "Land-Use Change and Forestry" has been used here to maintain consistency with the IPCC reporting structure for national greenhouse gas inventories; however, the chapter covers land-use activities, in addition to land-use change and forestry activities. Therefore, except in table titles, the term "land use, land-use change, and forestry" will be used in the remainder of this chapter.

Unlike the assessments in other chapters, which are based on annual activity data, the flux estimates in this chapter, with the exception of those from wood products, urban trees, and liming, are based on periodic activity data in the form of forest, land-use, and municipal solid waste surveys. Carbon dioxide fluxes from forest carbon stocks (except the wood product components) and from agricultural soils (except the liming component) are calculated on an average annual basis over five or ten year periods. The resulting annual averages are applied to years between surveys. As a result of this data structure, estimated $CO_2$ fluxes from forest carbon stocks (except the wood product components) and from agricultural soils (except the liming component) are constant over multi-year intervals, with large discontinuities between intervals. For the landfilled yard trimmings, 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 for the year 1997, the estimates of $CO_2$ flux from forests, agricultural soils, and landfilled yard trimmings are based in part on modeled projections. Carbon dioxide fluxes from urban trees are based on neither annual data nor periodic survey data, but instead is data collected over the decade 1990 through 2000. Therefore, this flux has been applied to the entire time series.

[1] The term "flux" is used here to encompass both emissions of greenhouse gases to the atmosphere, and removal of carbon from the atmosphere. Removal of carbon from the atmosphere is also referred to as "carbon sequestration."

**Table 6-1: Net $CO_2$ Flux from Land-Use Change and Forestry (Tg $CO_2$ Eq.)**

| Sink Category | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Forests | (982.7) | (979.0) | (979.0) | (759.0) | (751.7) | (762.7) | (770.0) |
| Urban Trees | (58.7) | (58.7) | (58.7) | (58.7) | (58.7) | (58.7) | (58.7) |
| Agricultural Soils | (37.3) | (60.2) | (60.2) | (60.4) | (67.2) | (67.7) | (67.4) |
| Landfilled Yard Trimmings | (19.1) | (12.2) | (10.2) | (9.5) | (8.3) | (7.3) | (6.4) |
| **Total** | **(1,097.7)** | **(1,110.0)** | **(1,108.1)** | **(887.5)** | **(885.9)** | **(896.4)** | **(902.5)** |

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding. Lightly shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

**Table 6-2: Net $CO_2$ Flux from Land-Use Change and Forestry (Tg C)**

| Sink Category | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Forests | (268) | (267) | (267) | (207) | (205) | (208) | (210) |
| Urban Trees | (16) | (16) | (16) | (16) | (16) | (16) | (16) |
| Agricultural Soils | (10) | (16) | (16) | (17) | (18) | (19) | (18) |
| Landfilled Yard Trimmings | (5) | (3) | (3) | (3) | (2) | (2) | (2) |
| **Total** | **(299)** | **(303)** | **(302)** | **(242)** | **(242)** | **(245)** | **(246)** |

Note: 1 Tg C = 1 teragram carbon = 1 million metric tons carbon. Parentheses indicate net sequestration. Totals may not sum due to independent rounding. Lightly shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

Land use, land-use change, and forestry activities in 2000 resulted in a net sequestration of 903 Tg $CO_2$ Eq. (246 Tg C) (Table 6-1 and Table 6-2). This represents an offset of approximately 15 percent of total U.S. $CO_2$ emissions. Total land use, land-use change, and forestry net sequestration declined by about 18 percent between 1990 and 2000. This decline was primarily due to a decline in the rate of net carbon accumulation in forest carbon stocks. Annual carbon accumulation in landfilled yard trimmings also slowed over this period, while annual carbon accumulation in agricultural soils increased. As described above, the constant rate of carbon accumulation in urban trees is a reflection of limited underlying data (i.e., this rate represents an average for the decade).

## Changes in Forest Carbon Stocks

Carbon in forests can be described as the total of several interrelated carbon storage pools, including:

- Trees (i.e., living trees and standing dead trees, including the roots, stems, branches, and foliage);
- Understory vegetation (i.e., shrubs and bushes, including the roots, stems, branches, and foliage);
- Forest floor (i.e., fine woody debris, tree litter, and humus);
- Down dead wood (i.e., logging residue and other coarse dead wood on the ground, and stumps and roots of stumps); and
- Soil (i.e., organic material in soil).

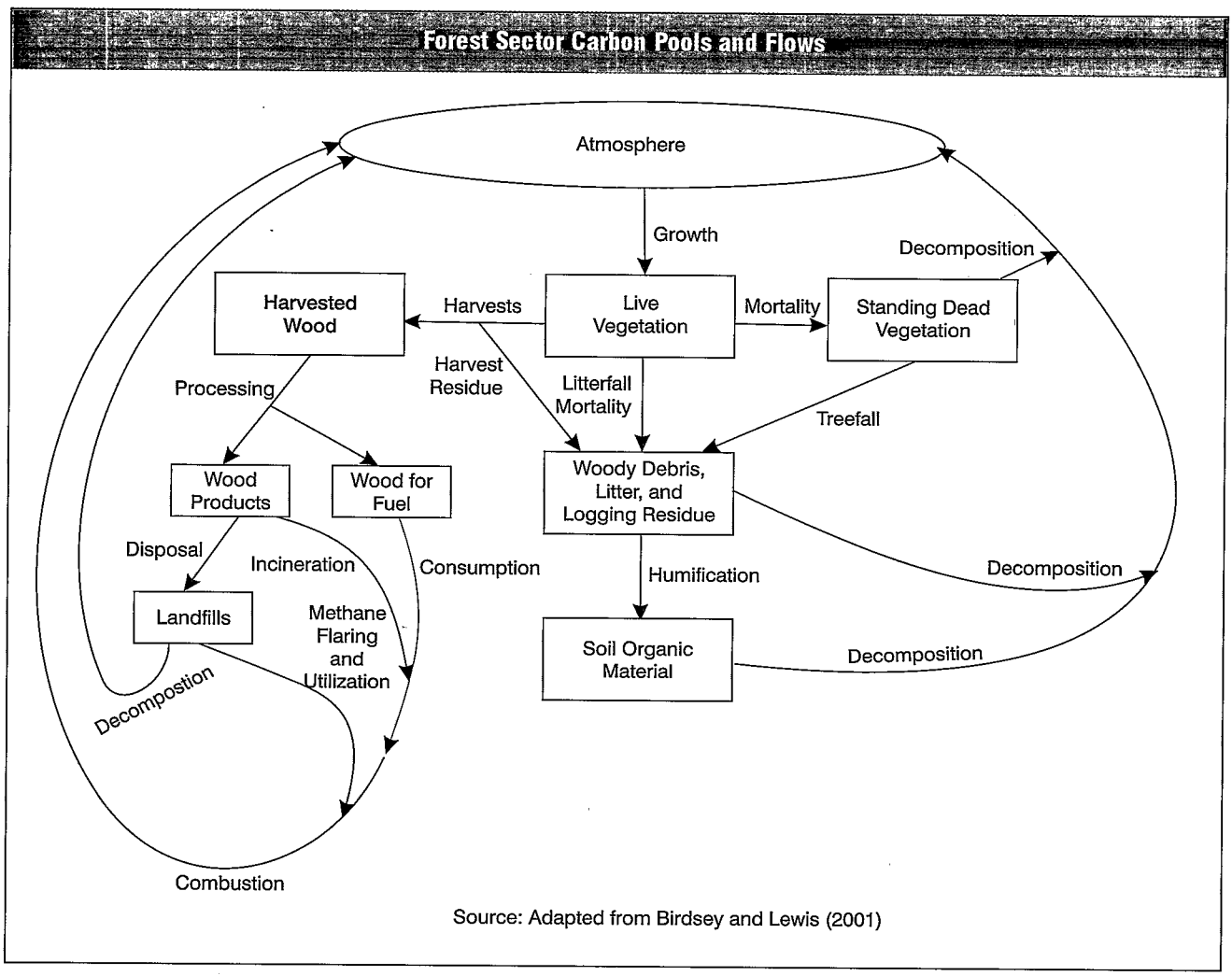
As a result of biological processes in forests (e.g., growth and mortality) and anthropogenic activities (e.g., harvesting, thinning, clearing, and replanting), carbon is continuously cycled through and among these storage pools, as well as between the forest ecosystem and the atmosphere. For example, as trees grow, carbon is removed from the atmosphere and stored in living tree biomass. As trees age, they continue to accumulate carbon until they reach maturity, at which point carbon storage slows. As trees die and otherwise deposit litter and debris on the forest floor, decay processes release carbon to the atmosphere and also increase soil carbon stocks.

The net change in forest carbon, however, may not be equivalent to the net flux between forests and the atmosphere because timber harvests may not always result in an immediate flux of carbon to the atmosphere. Harvesting in effect transfers carbon from one of the "forest pools" to a "product pool." Once in a product pool, the carbon is emitted over time as $CO_2$ if the wood product combusts or decays. The rate of emission varies considerably among different product pools. For example, if timber is harvested for energy use, combustion results in an immediate release of carbon. Conversely, if timber is harvested and subsequently used as lumber in a house, it may be many decades or even centuries before the lumber is allowed to decay and carbon is released to the atmosphere. If wood products are disposed of in landfills, the carbon contained in the wood may be released years or decades later, or may even be stored permanently in the landfill.

This section of the Land-Use Change and Forestry chapter tracks net changes in carbon stocks in five forest carbon 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.

An illustration of forest carbon storage pools, and flows between them via emissions, sequestration, and transfers, is presented in Figure 6-1. In this illustration, forest carbon storage pools are represented by boxes, while flows between storage pools, and between storage pools and the atmosphere, are represented by arrows. Note that boxes are not identical with storage pools identified in this chapter. The storage pools identified in this chapter have been arranged to better illustrate the processes that result in transfers of carbon from one pool to another, and that result in emissions to the atmosphere (adapted from Birdsey and Lewis 2001).

**Figure 6-1**




Source: Adapted from Birdsey and Lewis (2001)

Approximately 33 percent (747 million acres) of the U.S. land area is forested (Smith et al. 2001). Between 1977 and 1987, forest land declined by approximately 5.9 million acres, and between 1987 and 1997, the area increased by about 9.2 million acres. These changes in forest area represent average annual fluctuations of only about 0.1 percent.

Given the low rate of change in U.S. forest land area, the major influences on the recent net carbon flux from forest land are management activities and the ongoing impacts of previous land-use changes. These activities affect the net flux of carbon by altering the amount of carbon stored in forest ecosystems. For example, intensified management of forests can increase both the rate of growth and the eventual biomass density[2] of the forest, thereby increasing the uptake of carbon. Harvesting forests removes much of the aboveground carbon, but trees can grow on this area again and sequester carbon. The reversion of cropland to forest land through natural regeneration also will, over decades, result in increased carbon storage in biomass and soils. The net effect of both forest management and land-use change involving forests is captured in these estimates.

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, and timber harvesting and use have resulted in an annual net (i.e., net sequestration) of carbon during the period from 1990 through 2000. Due to improvements in U.S. agricultural productivity, the rate of forest clearing for crop cultivation and pasture slowed in the late 19th century, and by 1920 this practice had all but ceased. As farming expanded in the Midwest and West, large areas of previously cultivated land in the East were taken out of crop production, primarily between 1920 and 1950, and were allowed to revert to forests or were actively reforested. The impacts of these land-use changes are still affecting carbon fluxes from forests in the East. In addition to land-use changes in the early part of this century, carbon fluxes from Eastern forests have been affected by a trend toward managed growth on private land. Collectively, these changes have produced a near doubling of the biomass density in Eastern forests since the early 1950s. More recently, the 1970s and 1980s saw a resurgence of federally sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests have also affected net carbon fluxes. Because most of the timber that is harvested from U.S. forests is used in wood products and much of the discarded wood products are disposed of by landfilling, rather than incineration, significant quantities of this harvested carbon are transferred to long-term storage pools rather than being released to the atmosphere. The size of these long-term carbon storage pools has also increased over the last century.

Changes in carbon stocks in U.S. forests and harvested wood were estimated to account for an average annual net sequestration of 899 Tg $CO_2$ Eq. (245 Tg C) over the period 1990 through 2000 (see Table 6-3 and Table 6-4).[3] The net sequestration is a reflection of net forest growth and increasing forest area over this period, particularly from 1987 to 1997, as well as net accumulation of carbon in harvested wood pools. The rate of annual sequestration, however, declined by 22 percent between 1990 and 2000. This is due to a greater rate of forest area increase between 1987 and 1997 than between 1997 and 2001. Most of the decline in annual sequestration occurred in the forest soil carbon pool. This is a reflection of modeling assumptions used in this analysis, specifically that soil carbon stocks for each forest type are constant over time, rather than varying by age, whereas biomass carbon stocks are a function of forest type and age class. Therefore, as lands are converted from non-forest to forest, there is a relatively large immediate increase in soil carbon stocks compared to the increase in biomass carbon stocks. The relatively large shifts in annual net sequestration from 1996 to 1997 are the result of calculating average annual forest fluxes from periodic, rather than annual, activity data.

[2] The term "biomass density" refers to the weight of vegetation per unit area. It is usually measured on a dry-weight basis. Dry biomass is about 50 percent carbon by weight.

[3] This average annual net sequestration is based on the entire time series (1990 through 2000), rather than the abbreviated time series presented in Table 6-3 and Table 6-4. Results for the entire time series are presented in Annex N (Methodology for Estimating Net Changes in Forest Carbon Stocks).

**Table 6-3: Net $CO_2$ Flux from U.S. Forests (Tg $CO_2$ Eq.)**

| Description | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Forest Carbon Stocks** | **(773.7)** | **(773.7)** | **(773.7)** | **(546.3)** | **(546.3)** | **(546.3)** | **(546.3)** |
| Trees | (469.3) | (469.3) | (469.3) | (447.3) | (447.3) | (447.3) | (447.3) |
| Understory | (11.0) | (11.0) | (11.0) | (14.7) | (14.7) | (14.7) | (14.7) |
| Forest Floor | (25.7) | (25.7) | (25.7) | 29.3 | 29.3 | 29.3 | 29.3 |
| Down Dead Wood | (55.0) | (55.0) | (55.0) | (58.7) | (58.7) | (58.7) | (58.7) |
| Forest Soils | (212.7) | (212.7) | (212.7) | (55.0) | (55.0) | (55.0) | (55.0) |
| **Harvested Wood Carbon Stocks** | **(209.0)** | **(205.3)** | **(205.3)** | **(212.7)** | **(205.3)** | **(216.3)** | **(223.7)** |
| Wood Products | (47.7) | (55.0) | (55.0) | (58.7) | (51.3) | (62.3) | (66.0) |
| Landfilled Wood | (161.3) | (150.3) | (150.3) | (154.0) | (154.0) | (154.0) | (157.7) |
| **Total** | **(982.7)** | **(979.0)** | **(979.0)** | **(759.0)** | **(751.7)** | **(762.7)** | **(770.0)** |

Note: Parentheses indicate net carbon "sequestration" (i.e., accumulation into the carbon pool minus emissions or stock removal from the carbon pool). The sum of the net stock changes in this table (i.e., total) is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Lightly shaded areas indicate values based on a combination of historical data and projections. Forest values are based on periodic measurements; harvested wood estimates are based on annual surveys. Totals may not sum due to independent rounding.

**Table 6-4: Net $CO_2$ Flux from U.S. Forests (Tg C)**

| Description | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Forest Carbon Stocks** | **(211)** | **(211)** | **(211)** | **(149)** | **(149)** | **(149)** | **(149)** |
| Trees | (128) | (128) | (128) | (122) | (122) | (122) | (122) |
| Understory | (3) | (3) | (3) | (4) | (4) | (4) | (4) |
| Forest Floor | (7) | (7) | (7) | 8 | 8 | 8 | 8 |
| Down Dead Wood | (15) | (15) | (15) | (16) | (16) | (16) | (16) |
| Forest Soils | (58) | (58) | (58) | (15) | (15) | (15) | (15) |
| **Harvested Wood Carbon Stocks** | **(57)** | **(56)** | **(56)** | **(58)** | **(56)** | **(59)** | **(61)** |
| Wood Products | (13) | (15) | (15) | (16) | (14) | (17) | (18) |
| Landfilled Wood | (44) | (41) | (41) | (42) | (42) | (42) | (43) |
| **Total** | **(268)** | **(267)** | **(267)** | **(207)** | **(205)** | **(208)** | **(210)** |

Note: 1 Tg C = 1 Tg carbon = 1 million metric tons carbon. Parentheses indicate net carbon "sequestration" (i.e., accumulation into the carbon pool minus emissions or harvest from the carbon pool). The sum of the net stock changes in this table (i.e., total) is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Lightly shaded areas indicate values based on a combination of historical data and projections. Forest values are based on periodic measurements; harvested wood estimates are based on annual surveys. Totals may not sum due to independent rounding.

## Methodology

The approach to calculating changes in carbon stocks in forests can generically be described as sampling the forest carbon at one time, sampling the forest carbon a second time at a later date, and then subtracting the two estimates for the net stock change. Historically, the main purpose of the national forest inventory has been to estimate areas, volume of growing stock, and timber products output and utilization factors. Growing stock is simply a classification of timber inventory that includes live trees of commercial species meeting specified standards of quality (Smith et al. 2001). Timber products output refers to the production of industrial roundwood products such as logs and other round timber generated from harvesting trees, and the production of bark and other residue at processing mills. Utilization factors relate inventory volume to the volume cut or destroyed when producing roundwood (May 1998). Growth, harvests, land-use change, and other estimates of change are derived from repeated surveys. The inventory data are converted to carbon using conversion factors or a model that estimates basic relationships between forest characteristics and carbon pools like forest floor. Historical carbon stock changes are derived from USDA Forest Service, Forest Inventory & Analysis inventory data (Smith et al. 2001, Frayer and Furnival 1999). Projected carbon stock changes are derived from areas, volumes, growth,

land-use changes and other forest characteristics projected in a system of models (see Haynes et al. 2001a) representing the U.S. forest sector, including a model (FORCARB) that estimates carbon for merchantable and non-merchantable tree pools, and other forest carbon pools.

The USDA Forest Service, Forest Inventory & Analysis (FIA) has conducted consistent scientifically designed forest surveys of much of the forest land in the United States since 1952. Historically, these were conducted periodically, state-by-state within a region. One state within a region would be surveyed, and when finished, another state was surveyed. Eventually (every 5-14 years, depending on the state), all states within a region would be surveyed, and then states would be resurveyed. FIA has adopted a new annualized design, so that a portion of each state will be surveyed each year (Gillespie 1999); however, data are not yet available for all states. The annualized survey also includes a plan to measure attributes that are needed to estimate carbon in various pools, such as soil carbon and forest floor carbon. Characteristics that are measured and readily available from some surveys include individual tree diameter and species, and forest type and age of the plot. For more information about forest inventory data and carbon flux, see Birdsey and Heath (2001).

The USDA Forest Service periodically compiles and reports survey data for a specific base year. Available years relevant to $CO_2$ flux estimates are 1987 and 1997. Live tree carbon and dead tree carbon are estimated from the inventory data using the conversion factors by forest type and region in Smith et al. (in review). Understory carbon is estimated from forest inventory data and equations based on estimates in Birdsey (1992). Forest floor carbon is estimated from the forest inventory data using the equations listed in Smith and Heath (in review). Projections produce estimates of areas and volumes; carbon estimates are produced using this information using procedures similar to those used to produce carbon estimates from forest inventory data. For a detailed description of the modeling system, see Annex N.

In the past, FIA surveyed all productive forest land, which is called timberland, and some reserved forest land and some other forest land.[4] With the introduction of the annualized design (Gillespie 1999), all forest lands will feature the same type of information. Forest carbon stocks on non-timberland forests were estimated based on average carbon estimates derived from representative timberlands. Reserved forests were assumed to contain the same average carbon densities as timberlands of the same forest type, region, and owner group. These averages were multiplied by the areas in the forest statistics, and then aggregated for a national total. Average carbon stocks were derived for other forest land by using average carbon stocks for timberlands, which were multiplied by 50 percent to simulate the effects of lower productivity.

Estimates of carbon stock changes in wood products and wood discarded in landfills are based on the methods described in Skog and Nicholson (1998). The disposition of harvested wood carbon removed from the forest can be described in four general pools: products in use, discarded wood in landfills, emissions from wood burned for energy, and emissions from decaying wood or wood burned in which energy was not captured. The net carbon stock changes presented here represent the amounts of carbon that are stored (i.e., not released to the atmosphere). Annual historical estimates and projections of detailed production were used to divide consumed roundwood into product, wood mill residue, and pulp mill residue. The carbon decay rates for products and landfills were estimated, and applied to the respective pools. The results were aggregated for national estimates. The production approach to accounting for imports and exports was used. Thus, carbon in exported wood is included using the same disposal rates as in the United States, while carbon in imported wood is not included. Over the period 1990 to 2000, carbon in exported wood accounted for an average of 22 Tg $CO_2$ Eq. storage per year, with little variation from year to year. For comparison, imports—which are not included in the harvested wood net flux estimates—increased from 26 Tg $CO_2$ Eq. per year in 1990 to 46 Tg $CO_2$ Eq. per year in 2000.

[4] Forest land in the United States includes all land that is at least 10 percent stocked with trees of any size. Timberland is the most productive type of forest land, growing at a rate of 20 cubic feet per acre per year or more. In 1997, there were about 503 million acres of timberlands, which represented 67 percent of all forest lands (Smith and Sheffield 2000). Forest land classified as timberland is unreserved forest land that is producing or is capable of producing crops of industrial wood. The remaining 33 percent of forest land is classified as reserved forest land, which is forest land withdrawn from timber use by statute or regulation, or other forest land, which includes forests on which timber is growing at a rate less than 20 cubic feet per acre per year.

The methodology described above is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). The IPCC identifies two approaches to developing estimates of net carbon flux from Land-Use Change and Forestry: 1) using average annual statistics on land use, land-use change, and forest management activities, and applying carbon density and flux rate data to these activity estimates to derive total flux values; or 2) using carbon stock estimates derived from periodic inventories of forest stocks, and measuring net changes in carbon stocks over time. The latter approach was employed because the United States conducts periodic surveys of national forest stocks. In addition, the IPCC identifies two approaches to accounting for carbon emissions from harvested wood: 1) assuming that all of the harvested wood replaces wood products that decay in the inventory year so that the amount of carbon in annual harvests equals annual emissions from harvests; or 2) accounting for the variable rate of decay of harvested wood according to its disposition (e.g., product pool, landfill, combustion). The latter approach was applied for this Inventory using estimates of carbon stored in wood products and landfilled wood.[5] The use of direct measurements from forest surveys and associated estimates of product and landfilled wood pools is likely to result in more accurate flux estimates than the alternative IPCC methodology.

## Data Sources

The estimates of forest carbon stocks used to calculate forest carbon fluxes are based largely on areas, volumes, growth, harvests, and utilization factors derived from the forest inventory data collected by the USDA Forest Service. Compilations of these data for 1987 and 1997 are given in Waddell et al. (1989) and Smith et al. (2001), respectively, with trends discussed in the latter citation. The timber volume data used here include timber volumes on forest land classified as timberland, as well as on some reserved forest land and other forest land. Timber volumes on forest land in Alaska, Hawaii, and the U.S. territories are not sufficiently detailed to be used here. Also, timber volumes on non-forest land (e.g., urban trees, rangeland) are not included. The timber volume data include estimates by tree species, size class, and other categories. The forest inventory data are augmented or converted to carbon following the methods described in the methodology section. The carbon storage factors applied to these data are described in Annex N. Soil carbon estimates are based on data from the STATSGO database (USDA 1991). Carbon stocks in wood products in use and wood stored in landfills are based on historical data from the USDA Forest Service (USDA 1964, Ulrich 1989, Howard 2001), and historical data as implemented in the framework underlying the NAPAP (Ince 1994) and TAMM/ATLAS (Haynes et al. 2001a, Mills and Kincaid 1992) models. The carbon conversion factors and decay rates for harvested carbon removed from the forest are taken from Skog and Nicholson (1998).

Table 6-5 presents the carbon stock estimates for forest and harvested wood storage pools. Together, the tree and forest soil pools account for over 80 percent of total carbon stocks. Carbon stocks in all pools, except forest floor, increased over time, indicating that, during these periods, all storage pools except forest floor accumulated carbon (e.g., carbon sequestration by trees was greater than carbon removed from the tree pool through respiration, decay, litterfall, and harvest). Figure 6-2 shows 1997 carbon stocks by the regions that were used in the forest carbon analysis.

## Uncertainty

There are sampling and measurement errors associated with the forest survey data that underlie the forest carbon estimates. These surveys are based on a statistical sample designed to represent the wide variety of growth conditions present over large territories. Although newer inventories are being conducted annually in every state, much of the data currently used may have been collected over more than one year in a state, and data associated with a particular year may have been collected over several earlier years. Thus, there is uncertainty in the year associated with the forest inventory data. In addition, the forest survey data that are currently available exclude timber stocks on most forest land in Alaska, Hawaii, U.S. territories. The assumptions that were used to calculate carbon stocks in reserved forests and other forests in the coterminous United States also contribute to the uncertainty. Although the potential for uncertainty is large, the sample design for the forest surveys contributes to limiting the error in carbon flux. Re-measured

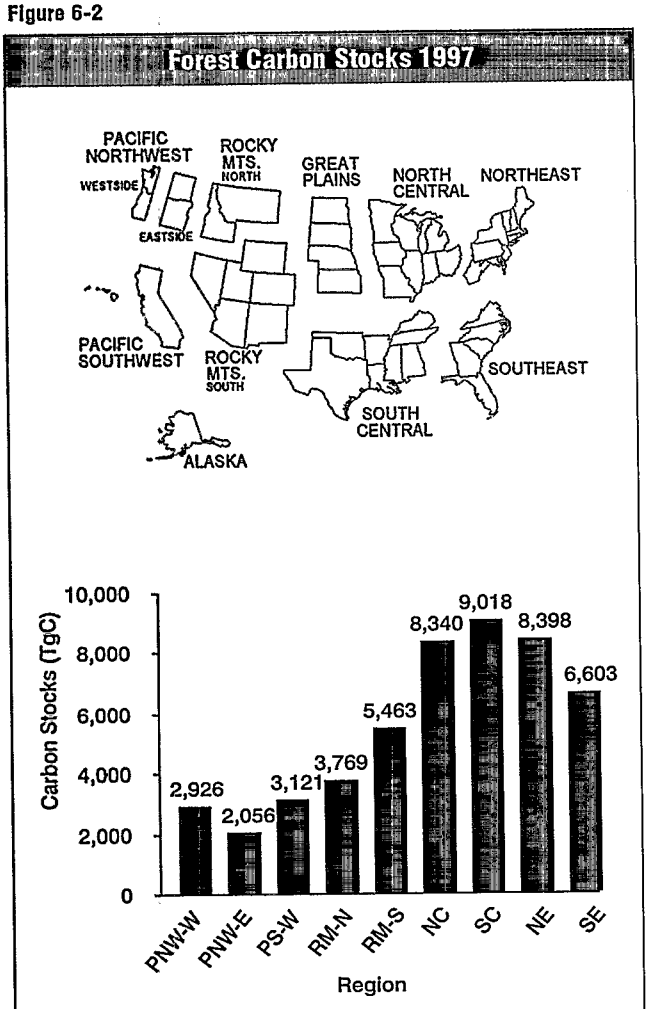
[5] Again, the product estimates in this study do not account for carbon stored in imported wood products. However, they do include carbon stored in exports, even if the logs are processed in other countries (Heath et al. 1996).

**Table 6-5: U.S. Forest Carbon Stock Estimates (Tg C)**

| Description | 1987 | 1997 | 2001 |
|---|---|---|---|
| **Forests** | **47,594** | **49,694** | **50,291** |
| Trees | 15,168 | 16,449 | 16,937 |
| Understory | 448 | 473 | 489 |
| Forest Floor | 4,240 | 4,306 | 4,274 |
| Down Dead Wood | 2,058 | 2,205 | 2,269 |
| Forest Soils | 25,681 | 26,262 | 26,322 |
| **Harvested Wood** | **1,920** | **2,479** | **2,712** |
| Wood Products | 1,185 | 1,319 | 1,384 |
| Landfilled Wood | 735 | 1,159 | 1,328 |
| **Total** | **49,514** | **52,173** | **53,003** |

Note: Forest carbon stocks do not include forest stocks in Alaska, Hawaii, or U.S. territories, or trees on non-forest land (e.g., urban trees); wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Lightly shaded areas indicate values based on a combination of historical data and projections. All other estimates are based on historical data only. Totals may not sum due to independent rounding. Note that the stock is listed for 2001 because stocks are defined as of January 1 of the listed year.

Figure 6-2




This graphic shows total forest carbon stocks in 1997, by region. Harvested wood carbon stocks are not included.

permanent plot estimates are correlated, and greater correlation leads to decreased uncertainties in change estimates. For example, in a study on the uncertainty of the forest carbon budget of private timberlands of the United States, Smith and Heath (2000) estimated that the uncertainty of the flux increased about 3.5 times when the correlation coefficient dropped from 0.95 to 0.5.

Additional sources of uncertainty come from the models used to estimate carbon storage in specific ecosystem components, such as forest floor, understory vegetation, and soil. Extrapolating results of separate ecosystem studies to all forest lands introduces uncertainty through the necessary assumption that the studies adequately describe regional or national averages. These assumptions can potentially introduce the following errors: (1) bias from applying data from studies that inadequately represent average forest conditions, (2) modeling errors (e.g., relying on coefficients or relationships that are not known), and (3) errors in converting estimates from one reporting unit to another (Birdsey and Heath 1995). In particular, the impacts of forest management activities, including harvest, on soil carbon are not well understood. For example, while Johnson and Curtis (2001) found little or no net change in soil carbon following harvest on average across a number of studies, many of the individual studies did exhibit differences. Heath and Smith (2000b) noted that the experimental design in a number of soil studies was such that the usefulness of the studies may be limited in determining harvesting effects on soil carbon. Soil carbon impact estimates need to be precise; even small

changes in soil carbon may sum to large differences over large areas. This analysis assumes that soil carbon density for each forest type stays constant over time. In the future, land-use effects will be incorporated into the soil carbon density estimates.

Recent studies have looked at quantifying the amount of uncertainty in national-level carbon budgets based on the methods adopted here. Smith and Heath (2000) and Heath and Smith (2000a) report on an uncertainty analysis they conducted on carbon sequestration in private timberlands. These studies are not strictly comparable to the estimates in this chapter because they used an older version of the FORCARB model, which was based on older data and produced decadal estimates. However, the magnitudes of the uncertainties should be instructive. Their results indicate that the carbon flux of private timberlands, not including harvested wood, was approximately the average carbon flux (271 Tg $CO_2$ Eq. per year) ±15 percent at the 80 percent confidence level for the period 1990 through 1999. The flux estimate included the tree, soil, understory vegetation, and forest floor components only. The uncertainty in the carbon inventory of private timberlands for 2000 was approximately 5 percent at the 80 percent confidence level. These estimates did not include all uncertainties, such as the ones associated with public timberlands, and reserved and other forest land, but they did include many of the types of uncertainties listed previously. It is expected that the uncertainty should be greater for all forest lands.

## Changes in Carbon Stocks in Urban Trees

Urban forests constitute a significant portion of the total U.S. tree canopy cover (Dwyer et al. 2000). It was estimated that urban areas (cities, towns, and villages), which cover 3.5 percent of the continental United States, contained about 3.8 billion trees. With an average tree canopy cover of 27.1 percent, urban areas accounted for approximately 2.8 percent of total tree cover in the continental United States.

Trees in urban areas of the continental United States were estimated by Nowak and Crane (2001) to account for an average annual net sequestration of 59 Tg $CO_2$ Eq. (16 Tg C). This estimate is representative of the period from 1990 through 2000, as it is based on data collected during that decade. Annual estimates of $CO_2$ flux have not been developed (see Table 6-6).

### Methodology

The methodology used by Nowak and Crane (2001) 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, but more robust than, the default IPCC methodology in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).[6]

Nowak and Crane (2001) developed estimates of annual gross carbon sequestration from tree growth and annual gross carbon emissions from decomposition for ten U.S. cities: Atlanta, GA; Baltimore, MD; Boston, MA; Chicago, IL; Jersey City, NJ; New York, NY; Oakland, CA; Philadelphia, PA, Sacramento, CA; and Syracuse, NY. The gross carbon sequestration estimates were derived from field data that were collected in these ten cities during the period from 1990 through 2000, 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 carbon sequestration rates for each species (or genus), diameter

**Table 6-6: Net $CO_2$ Flux From Urban Trees (Tg $CO_2$ Eq.)**

| Year | Tg $CO_2$ Eq. |
|---|---|
| 1990 | (58.7) |
| 1995 | (58.7) |
| 1996 | (58.7) |
| 1997 | (58.7) |
| 1998 | (58.7) |
| 1999 | (58.7) |
| 2000 | (58.7) |

Note: Parentheses indicate net sequestration.

[6] It is more robust in that both growth and decomposition are accounted for, and data from individual trees are scaled up to state and then national estimates based on data on urban area and urban tree canopy cover.

**Table 6-7: Carbon Storage (Metric Tons C), Carbon Sequestration (Metric Tons C/yr), and Tree Cover (%) for Ten U.S. Cities**

| City | Carbon Storage | Gross Sequestration | Net Sequestration | Tree Cover |
|---|---|---|---|---|
| New York, NY | 1,225,200 | 38,400 | 20,800 | 20.9% |
| Atlanta, GA | 1,220,200 | 42,100 | 32,200 | 36.7% |
| Sacramento, CA | 1,107,300 | 20,200 | NA | 13.0% |
| Chicago, IL | 854,800 | 40,100 | NA | 11.0% |
| Baltimore, MD | 528,700 | 14,800 | 10,800 | 25.2% |
| Philadelphia, PA | 481,000 | 14,600 | 10,700 | 15.7% |
| Boston, MA | 289,800 | 9,500 | 6,900 | 22.3% |
| Syracuse, NY | 148,300 | 4,700 | 3,500 | 24.4% |
| Oakland, CA | 145,800 | NA | NA | 21.0% |
| Jersey City, NJ | 19,300 | 800 | 600 | 11.5% |

NA (Not Available)

class, and land-use condition (forested, park-like, and open growth) by applying allometric equations, a root-to-shoot ratio, moisture contents, a carbon 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 carbon sequestration rates for each species (or genus), diameter class, and land-use condition were then scaled up to city estimates using tree population information (see Table 6-7).

The annual gross carbon emission estimates were derived by applying to carbon stock estimates, which were derived as an intermediate step in the gross sequestration calculations, estimates of annual mortality by tree diameter and condition class, assumptions about whether dead trees would be removed from the site—since removed trees were assumed to decay faster than those left on the site—and assumed decomposition rates for dead trees left standing and dead trees that are removed. The annual gross carbon emission rates for each species (or genus), diameter class, and condition class were then scaled up to city estimates using tree population information.

Annual net carbon sequestration estimates were derived for each of the ten cities by subtracting by the annual gross emission estimates from the annual gross sequestration estimates (see Table 6-7).

National annual net carbon sequestration by urban trees was estimated from the city estimates of gross and net sequestration, and urban area and urban tree cover data for the contiguous United States. Note that the urban areas are based on U.S. Census data, which define "urban" as having a population greater than 2,500. Therefore, urban encompasses most cities, towns, and villages (i.e., it includes both urban and suburban areas). The gross and net carbon 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 (see Table 6-8). The median value for gross sequestration (0.30 kg C/m$^2$-year) was then multiplied by an estimate of national urban tree cover area (76,151 km$^2$) to estimate national annual gross sequestration. To estimate national annual net sequestration, the estimate of national annual gross sequestration was multiplied by the average of the ratios of net to gross sequestration for those cities that had both estimates (0.70).

**Table 6-8: Annual Sequestration per Area of Tree Cover (kg C/m$^2$ cover-year)**

| City | Gross | Net |
|---|---|---|
| New York, NY | 0.23 | 0.12 |
| Atlanta, GA | 0.34 | 0.26 |
| Sacramento, CA | 0.66 | NA |
| Chicago, IL | 0.61 | NA |
| Baltimore, MD | 0.28 | 0.20 |
| Philadelphia, PA | 0.27 | 0.20 |
| Boston, MA | 0.30 | 0.22 |
| Syracuse, NY | 0.30 | 0.22 |
| Oakland, CA | NA | NA |
| Jersey City, NJ | 0.18 | 0.13 |

NA (Not Available)

## Data Sources

The field data from the 10 cities, some of which are unpublished, are described in Nowak and Crane (2001) and references cited therein. The allometric equations were taken from the scientific literature (see Nowak 1994, Nowak et al. in press), and the adjustments to account for smaller volumes in urban conditions were based on information in Nowak (1994). A root-to-shoot ratio of 0.26 was taken from Cairns et al. (1997), and species- or genus-specific moisture contents were taken from various literature sources (see Nowak 1994). Adjustment factors to account for tree condition were based on expert judgement of the authors (Nowak and Crane 2001). Tree growth rates were also taken from existing literature. Average diameter growth was based on the following sources: estimates for trees in forest stands came from Smith and Shifley (1984); estimates for trees on land uses with a park-like structure came from deVries (1987); and estimates for more open-grown trees came from Nowak (1994). Formulas from Fleming (1988) formed the basis for average height growth calculations. 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 and assumed decomposition rates were based on percent crown dieback (Nowak and Crane 2001). Urban tree cover area estimates for each of the 10 cities and the contiguous United States were obtained from Dwyer et al. (2000) and Nowak et al. (2001).

## Uncertainty

The estimates are based on limited field data collected in ten U.S. cities, and the uncertainty in these estimates increases as they are scaled up to the national level. There is also uncertainty associated with the biomass equations, conversion factors, and decomposition assumptions used to calculate carbon sequestration and emission estimates (Nowak et al. in press), as well as with the tree cover area estimates for urban areas, as these are based on interpretation of Advanced Very High Resolution Radiometer (AVHRR) data. In addition, these results do not include changes in soil carbon stocks, and there may be some overlap between the urban tree carbon estimates and the forest tree carbon estimates. However, both the omission of urban soil carbon flux, and the potential overlap with forest carbon, are believed to be relatively minor (Nowak 2002).

# Changes in Agricultural Soil Carbon Stocks

The amount of organic carbon contained in soils depends on the balance between inputs of organic material (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and loss of carbon through decomposition. 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. 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 carbon to or from soils. In addition, the application of carbonate minerals to soils through liming operations results in emissions of $CO_2$. The IPCC methodology for estimation of net $CO_2$ flux from agricultural soils (IPCC/UNEP/OECD/IEA 1997) is divided into three categories of land-use/land-management activities: 1) agricultural land-use and land-management activities on mineral soils; 2) agricultural land-use and land-management activities on organic soils; and 3) liming of soils. Mineral soils and organic soils are treated separately because each responds differently to land-use practices.

Mineral soils contain comparatively low amounts of organic matter, much of which is concentrated near the soil surface. Typical well-drained mineral surface soils contain from 1 to 6 percent organic matter (by weight); mineral subsoils contain even lower amounts of organic matter (Brady and Weil 1999). When mineral soils undergo conversion from their native state to agricultural use, as much as half of the soil organic carbon can be lost to the atmosphere. The rate and ultimate magnitude of carbon loss will depend on native vegetation, conversion method and subsequent management practices, climate, and soil type. In the tropics, 40 to 60 percent of the carbon loss generally occurs within the first 10 years following conversion; after that, carbon stocks continue to decline but at a much slower rate. In temperate regions, carbon loss can continue for several decades. Eventually, the soil will reach a new equilibrium that reflects a balance between carbon accumulation from plant biomass and carbon loss through oxidation. Any changes in land-use or management practices that result in increased organic inputs or decreased oxidation of organic matter (e.g.,

**Table 6-9: Net $CO_2$ Flux From Agricultural Soils (Tg $CO_2$ Eq.)**

| Description | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Mineral Soils | (69.3) | (92.0) | (92.0) | (92.0) | (99.7) | (99.7) | (99.7) |
| Organic Soils | 22.5 | 22.9 | 22.9 | 22.9 | 22.9 | 22.9 | 22.9 |
| Liming of Soils | 9.5 | 8.9 | 8.9 | 8.7 | 9.6 | 9.1 | 9.4 |
| **Total** | **(37.3)** | **(60.2)** | **(60.2)** | **(60.4)** | **(67.2)** | **(67.7)** | **(67.4)** |

Note: Parentheses indicate net sequestration. Lightly shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

improved crop rotations, cover crops, application of organic amendments and manure, and reduction or elimination of tillage) will result in a net accumulation of soil organic carbon until a new equilibrium is achieved.

Organic soils, which are also referred to as histosols, include all soils with more than 20 to 30 percent organic matter by weight, depending on clay content (Brady and Weil 1999). The organic matter layer of these soils is also typically extremely deep. Organic soils form under water-logged conditions, in which decomposition of plant residues is retarded. When organic soils are cultivated, they are first drained which, together with tilling or mixing of the soil, aerates the soil, and thereby accelerates the rate of decomposition and $CO_2$ generation. Because of the depth and richness of the organic layers, carbon loss from cultivated organic soils can continue over long periods of time. When organic soils are disturbed, through cultivation and/or drainage, the rate at which organic matter decomposes, and therefore the rate at which $CO_2$ emissions are generated, is determined primarily by climate, the composition (i.e., decomposability) of the organic matter, and the specific land-use practices undertaken. The use of organic soils for annual crops results in greater carbon loss than conversion to pasture or forests, due to deeper drainage and more intensive management practices (Armentano and Verhoeven 1990, as cited in IPCC/UNEP/OECD/IEA 1997).

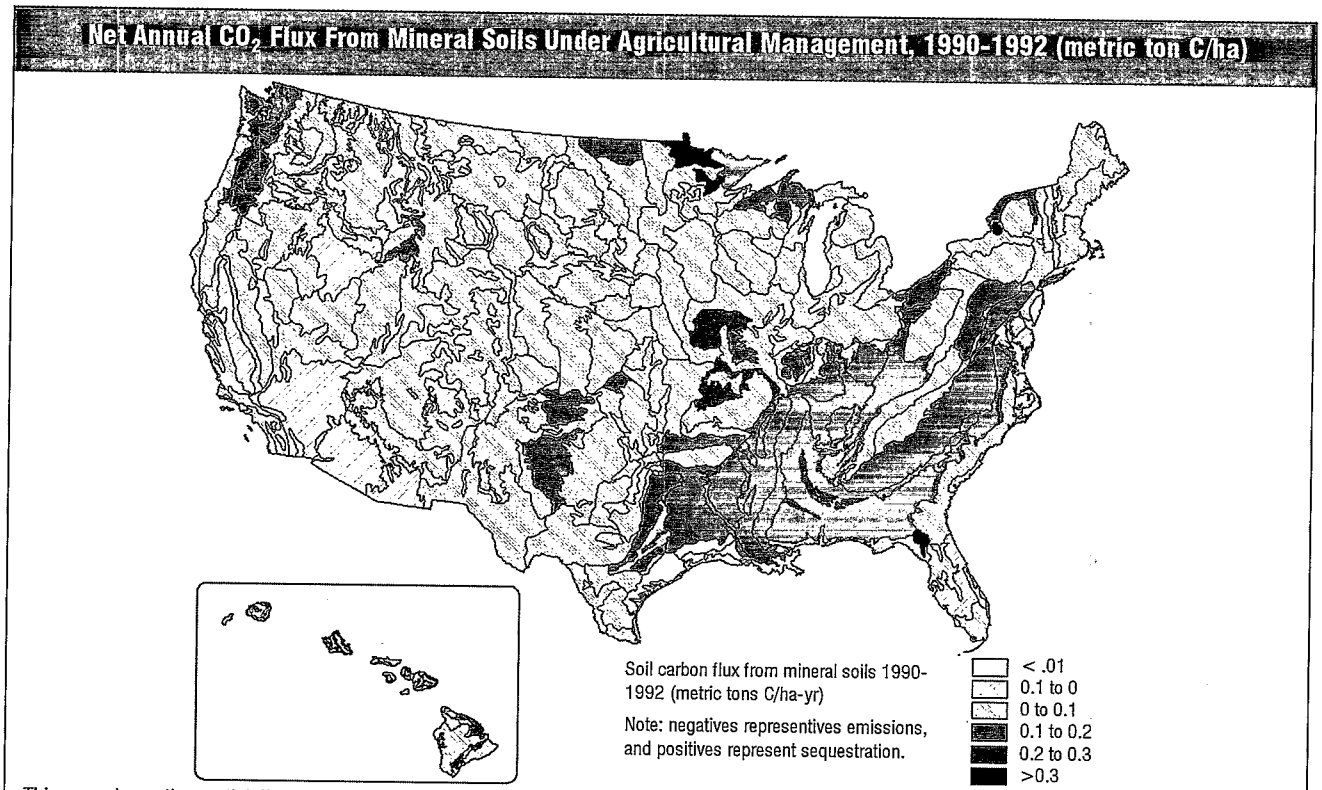
Lime in the form of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) is commonly added to agricultural soils to ameliorate acidification. When these compounds come in contact with acid soils, they degrade, thereby generating $CO_2$. The rate of degradation is determined by soil conditions and the type of mineral applied; it can take several years for applied limestone and dolomite to degrade completely.

Of the three activities, use and management of mineral soils was the most important component of total flux during the 1990 through 2000 period (see Table 6-9). Carbon sequestration in mineral soils in 2000 was estimated at about 100 Tg $CO_2$ Eq. (27 Tg C), while emissions from organic soils were estimated at 23 Tg $CO_2$ Eq. (6 Tg C) and emissions from liming were estimated at 9 Tg $CO_2$ Eq. (3 Tg C). Together, the three activities accounted for net sequestration of about 67 Tg $CO_2$ Eq. (18 Tg C) in 2000. Total annual net $CO_2$ flux was negative (i.e., net sequestration) each year over the 1990 to 2000 period. Between 1990 and 2000, total net carbon sequestration in agricultural soils increased by about 80 percent. The increase is largely due to additional acreage of annual cropland converted to permanent pastures and hay production, a reduction in the frequency of summer-fallow use in semi-arid areas and some increase in the adoption of conservation tillage (i.e., reduced and no-till) practices. The relatively large shifts in annual net sequestration from 1990 to 1995, and from 1997 to 1998 are the result of calculating average annual mineral and organic soil fluxes from periodic, rather than annual, activity data. The results for mineral and organic soils are displayed by region in Figure 6-3, Figure 6-4, Figure 6-5, and Figure 6-6.

The flux estimates presented here are restricted to $CO_2$ fluxes associated with the use and management of agricultural soils. Agricultural soils are also important sources of other greenhouse gases, particularly nitrous oxide ($N_2O$) from application of fertilizers, manure, and crop residues and from cultivation of legumes, as well as methane ($CH_4$) from flooded rice cultivation. These emissions are accounted for in the Agriculture chapter.[7] It should be noted that other land-use and land-use change activities result in fluxes of non-$CO_2$ greenhouse gases to and from soils that

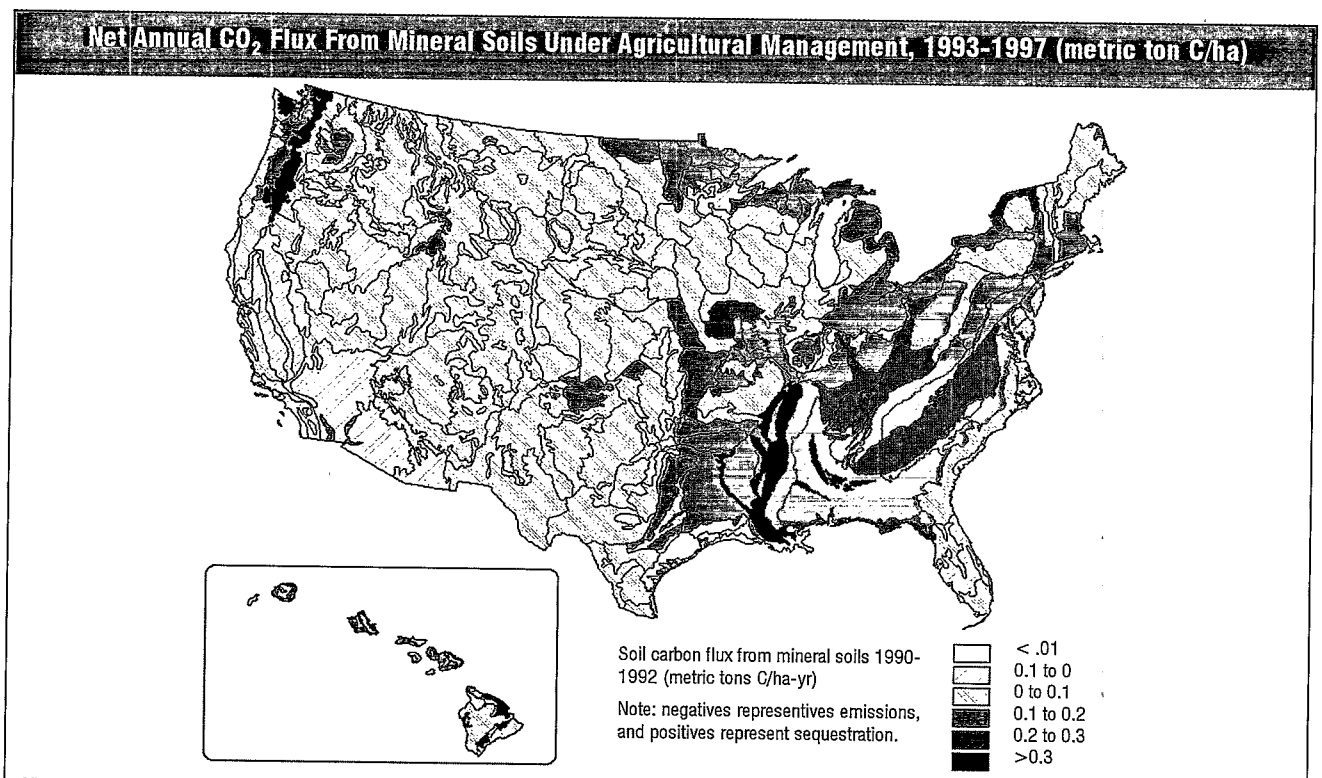
[7] Nitrous oxide emissions from agricultural soils and methane emissions from rice fields are addressed under the Agricultural Soil Management and Rice Cultivation sections, respectively, of the Agriculture chapter.

**Figure 6-3**



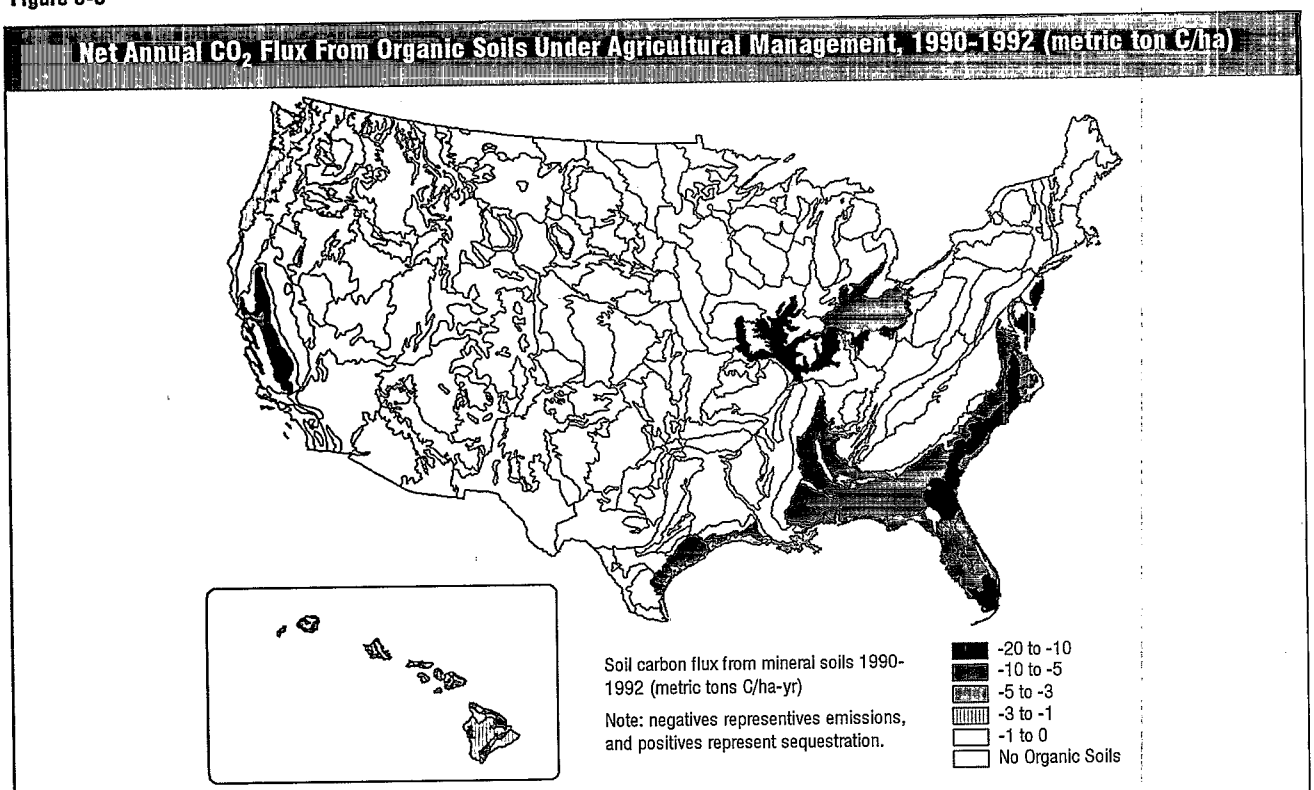

This map shows the spatial distribution of annual flux from mineral soils for the years 1990 through 1992.
Note: Estimates exclude Alaska and U.S. Territories.

**Figure 6-4**



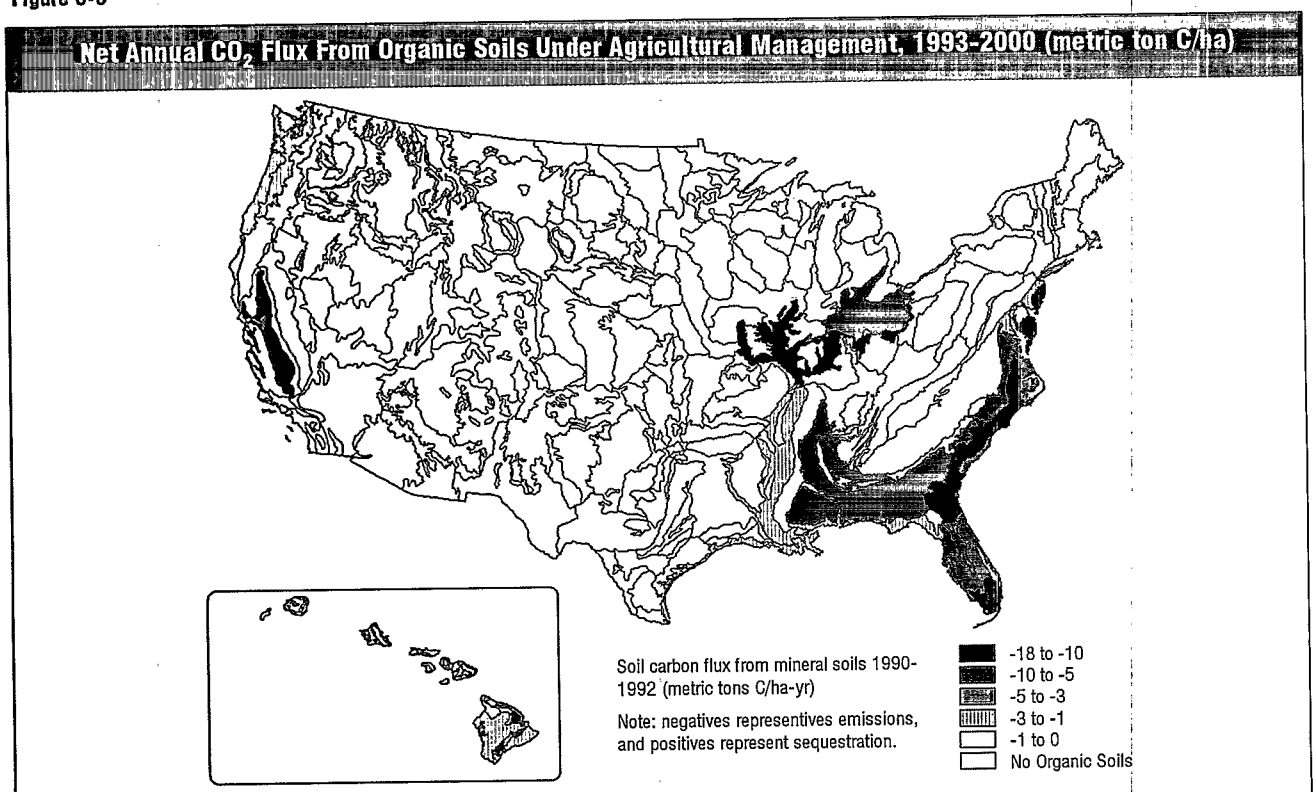

This map shows the spatial distribution of annual flux from mineral soils for the years 1993 through 1997. A similar map cannot be prepared for 1998 through 2000 because the land-use projections for those years are not spatially based.
Note: Estimates exclude Alaska and U.S. Territories.

Figure 6-5




This map shows the spatial distribution of annual flux from organic soils for the years 1993 through 2000.

Figure 6-6




This map shows the spatial distribution of annual flux from organic soils for the years 1993 through 2000.

are not currently accounted for. These include emissions of $CH_4$ and $N_2O$ from managed forest soils (above what would occur if the forest soils were undisturbed), as well as $CH_4$ emissions from artificially flooded lands, resulting from activities such as dam construction. Aerobic (i.e., non-flooded) soils are a sink for $CH_4$, so soil drainage can result in soils changing from a $CH_4$ source to a $CH_4$ sink, but if the drained soils are used for agriculture, fertilization and tillage disturbance can reduce the ability of soils to oxidize $CH_4$. The non-$CO_2$ emissions and sinks from these other land use and land-use change activities were not assessed due to scientific uncertainties about the greenhouse gas fluxes that result from these activities.

## Methodology and Data Sources

The methodologies used to calculate $CO_2$ emissions from use and management of mineral and organic soils and from liming follow the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), except where noted below.

The estimates of annual net $CO_2$ flux from mineral soils were based on application of the *Revised 1996 IPCC Guidelines* as described by Eve et al. (2001). Total mineral soil carbon stock estimates for 1982, 1992, and 1997 were developed for the conterminous United States and Hawaii by applying the default IPCC carbon stock and carbon adjustment factors (with one exception), to cropland and grazing land area estimates, classified by climate, soil type, and management regime. The exception is the base factor for lands set aside for less than 20 years. The IPCC default value is 0.8, but recent research (e.g., Paustian et al. 2001, Follett et al. 2001, Huggins et al. 1998, and Gebhart et al. 1994) indicates that 0.9 is a more accurate factor for the United States. Therefore, 0.9 was used instead of 0.8 for the base factor for grassland set aside through the Conservation Reserve Program. Data on land-use and land-management changes over time were aggregated by Major Land Resource Areas (MLRAs; NRCS 1981), which represent geographic units with relatively similar soils, climate, water resources, and land uses. MLRAs were

**Table 6-10: Mineral Soil Areas by Land-Use Category and IPCC Climatic Region (million hectares)[a]**

| Category | 1982 | 1992 | 1997 |
|---|---|---|---|
| **Cropland (No fallow)** | **117.6** | **107.6** | **109.2** |
| Cold Temperate, Dry | 2.5 | 2.4 | 2.8 |
| Cold Temperate, Moist | 44.9 | 42.9 | 45.6 |
| Warm Temperate, Dry | 12.4 | 10.7 | 10.6 |
| Warm Temperate, Moist | 53.9 | 47.9 | 46.7 |
| Sub-Tropical, Dry | 1.3 | 1.2 | 1.1 |
| Sub-Tropical, Moist | 2.6 | 2.6 | 2.4 |
| **Cropland (Fallow)** | **27.4** | **24.6** | **20.0** |
| Cold Temperate, Dry | 9.4 | 7.6 | 7.0 |
| Cold Temperate, Moist | 9.0 | 8.0 | 5.2 |
| Warm Temperate, Dry | 4.8 | 4.2 | 4.0 |
| Warm Temperate, Moist | 4.0 | 4.7 | 3.5 |
| Sub-Tropical, Dry | 0.0 | 0.0 | 0.0 |
| Sub-Tropical, Moist | 0.2 | 0.2 | 0.2 |
| **Hay** | **19.6** | **21.1** | **22.0** |
| Cold Temperate, Dry | 2.1 | 2.2 | 2.4 |
| Cold Temperate, Moist | 10.7 | 11.0 | 10.9 |
| Warm Temperate, Dry | 0.9 | 1.2 | 1.2 |
| Warm Temperate, Moist | 5.7 | 6.5 | 7.5 |
| Sub-Tropical, Dry | 0.1 | 0.1 | 0.1 |
| Sub-Tropical, Moist | 0.0 | 0.0 | 0.0 |
| **Grazing Land** | **214.1** | **215.6** | **212.5** |
| Cold Temperate, Dry | 38.3 | 38.3 | 38.2 |
| Cold Temperate, Moist | 48.3 | 47.4 | 46.5 |
| Warm Temperate, Dry | 51.0 | 51.5 | 51.2 |
| Warm Temperate, Moist | 64.2 | 66.2 | 64.6 |
| Sub-Tropical, Dry | 6.8 | 6.9 | 6.9 |
| Sub-Tropical, Moist | 5.3 | 5.3 | 5.0 |
| **CRP[b]** | **0.0** | **13.7** | **13.2** |
| Cold Temperate, Dry | 0.0 | 2.4 | 2.3 |
| Cold Temperate, Moist | 0.0 | 4.4 | 4.1 |
| Warm Temperate, Dry | 0.0 | 2.5 | 2.4 |
| Warm Temperate, Moist | 0.0 | 4.4 | 4.3 |
| Sub-Tropical, Dry | 0.0 | 0.1 | 0.1 |
| Sub-Tropical, Moist | 0.0 | 0.0 | 0.0 |
| **Non-Agricultural[c]** | **6.3** | **2.5** | **8.1** |
| Cold Temperate, Dry | 0.8 | 0.2 | 0.4 |
| Cold Temperate, Moist | 1.2 | 0.5 | 1.9 |
| Warm Temperate, Dry | 1.0 | 0.3 | 0.8 |
| Warm Temperate, Moist | 3.1 | 1.4 | 4.4 |
| Sub-Tropical, Dry | 0.0 | 0.0 | 0.1 |
| Sub-Tropical, Moist | 0.1 | 0.1 | 0.6 |
| **Total** | **385.0** | **385.0** | **385.0** |
| Cold Temperate, Dry | 53.1 | 53.1 | 53.1 |
| Cold Temperate, Moist | 114.2 | 114.2 | 114.2 |
| Warm Temperate, Dry | 70.2 | 70.2 | 70.2 |
| Warm Temperate, Moist | 131.0 | 131.0 | 131.0 |
| Sub-Tropical, Dry | 8.3 | 8.3 | 8.3 |
| Sub-Tropical, Moist | 8.3 | 8.3 | 8.3 |

Note: Totals may not sum due to independent rounding.
[a] Based on analysis of the *1997 National Resources Inventory* data (NRCS 2000). Includes all conterminous U.S. land categorized as agricultural in 1992 or 1997.
[b] CRP (Conservation Reserve Program)
[c] Non-agricultural lands are included when they are either cropland or grazing land during 1992 or 1997.

**Table 6-11: Mineral Soil Areas by Land-Use Category and IPCC Mineral Soil Category (thousand hectares)[a]**

| Category | 1982 | 1992 | 1997 |
|---|---|---|---|
| **Cropland (Fallow)** | **27,338** | **24,627** | **20,024** |
| High Clay Activity Mineral Soils | 24,026 | 21,153 | 17,422 |
| Low Clay Activity Mineral Soils | 1,516 | 1,370 | 1,160 |
| Sandy Soils | 635 | 613 | 416 |
| Volcanic Soils | 11 | 11 | 12 |
| Aquic Soils | 1,149 | 1,481 | 1,016 |
| **Cropland (No fallow)** | **117,825** | **107,563** | **109,194** |
| High Clay Activity Mineral Soils | 72,043 | 66,093 | 68,437 |
| Low Clay Activity Mineral Soils | 14,151 | 11,960 | 11,292 |
| Sandy Soils | 9,198 | 7,919 | 7,645 |
| Volcanic Soils | 163 | 137 | 130 |
| Aquic Soils | 22,270 | 21,454 | 21,690 |
| **CRP[b]** | **0** | **13,745** | **13,209** |
| High Clay Activity Mineral Soils | 0 | 10,087 | 9,671 |
| Low Clay Activity Mineral Soils | 0 | 1,555 | 1,491 |
| Sandy Soils | 0 | 1,259 | 1,219 |
| Volcanic Soils | 0 | 18 | 17 |
| Aquic Soils | 0 | 826 | 811 |
| **Grazing Land** | **213,840** | **215,585** | **212,540** |
| High Clay Activity Mineral Soils | 136,731 | 136,669 | 135,273 |
| Low Clay Activity Mineral Soils | 41,876 | 43,445 | 42,665 |
| Sandy Soils | 24,885 | 25,126 | 24,667 |
| Volcanic Soils | 362 | 381 | 365 |
| Aquic Soils | 9,986 | 9,965 | 9,570 |
| **Hay** | **19,616** | **21,056** | **22,001** |
| High Clay Activity Mineral Soils | 13,563 | 14,227 | 14,719 |
| Low Clay Activity Mineral Soils | 2,745 | 3,225 | 3,621 |
| Sandy Soils | 1,132 | 1,318 | 1,369 |
| Volcanic Soils | 228 | 240 | 231 |
| Aquic Soils | 1,948 | 2,047 | 2,061 |
| **Non-Agricultural[c]** | **6,426** | **2,468** | **8,075** |
| High Clay Activity Mineral Soils | 2,782 | 918 | 3,624 |
| Low Clay Activity Mineral Soils | 2,280 | 1,012 | 2,337 |
| Sandy Soils | 651 | 266 | 1,184 |
| Volcanic Soil | 48 | 26 | 57 |
| Aquic Soils | 665 | 246 | 873 |
| **Total** | **385,044** | **385,044** | **385,044** |
| High Clay Activity Mineral Soils | 249,146 | 249,146 | 249,146 |
| Low Clay Activity Mineral Soils | 62,567 | 62,567 | 62,567 |
| Sandy Soils | 36,500 | 36,500 | 36,500 |
| Volcanic Soils | 811 | 811 | 811 |
| Aquic Soils | 36,019 | 36,019 | 36,019 |

Note: Totals may not sum due to independent rounding.

[a] Based on analysis of the *1997 National Resources Inventory* data (NRCS 2000). Includes all conterminous U.S. land categorized as agricultural in 1992 or 1997.

[b] CRP (Conservation Reserve Program)

[c] Non-agricultural land are included when they are either cropland or grazing land during 1992 or 1997.

classified by IPCC climate categories using the climate mapping program in Daly et al. (1994). For each MLRA, area estimates for each combination of soil type and land-use/land-management combination were derived for 1982, 1992, and 1997 using data obtained from the *1997 National Resources Inventory* (NRI; NRCS 2000). Mineral soil areas by broad land-use category and IPCC climatic region, and by broad land-use category and IPCC mineral soil category, are shown in Table 6-10 and Table 6-11, respectively. Estimates of tillage practices for each cropping system were derived from data collected by the Conservation Technology Information Center (CTIC 1998), as adjusted by Towery (2001) (see Table 6-12).

The carbon flux estimate for 1990 is based on the change in stocks between 1982 and 1992, and the carbon flux estimate for 1995 through 1997 is based on the change in stocks between 1982 and 1997. The IPCC base, tillage, and input factors were adjusted to account for use of a ten-year and a fifteen-year accounting period, rather than the 20-year period used in the *Revised 1996 IPCC Guidelines*. The carbon flux estimates for 1998 through 2000 were based on a projection of 1997 land use and management to 2008 (USDA 2000b).

The estimates of annual $CO_2$ emissions from organic soils were also based on the *Revised 1996 IPCC Guidelines* as described by Eve et al. (2001). The IPCC methodology for organic soils utilizes annual $CO_2$ emission factors, rather than a stock change approach. Following the IPCC methodology, only organic soils under intense management were included, and the default IPCC rates of carbon loss were applied to the total 1992 and 1997 areas for the climate/land-use categories defined in the IPCC Guidelines (see Table 6-13).[8] The area estimates were derived from the same climatic, soil, and land-use/land-management databases that were used in the mineral soil calculations (Daly et al. 1994, USDA 2000a). The annual flux estimated for 1992 is applied to 1990, and the annual flux estimated for 1997 is applied to 1995 through 2000.

[8] The default IPCC emission factors for tropical regions was applied to the sub-tropical areas.

**Table 6-12: Tillage Percentages by Management Category and IPCC Climatic Zone[a]**

| Climatic Region/Cropping System | 1982 | | | 1992 | | | 1997 | | |
|---|---|---|---|---|---|---|---|---|---|
| | No Till[b] | Reduced Till[c] | Conv. Till[d] | No Till[b] | Reduced Till[c] | Conv. Till[d] | No Till[b] | Reduced Till[c] | Conv. Till[d] |
| **Sub-Tropical, Dry** | | | | | | | | | |
| Continuous Cropping Rotations[e] | 0 | 3 | 97 | 0 | 4 | 96 | 0 | 15 | 85 |
| Rotations with Fallow[f] | 0 | 0 | 100 | 0 | 2 | 98 | 0 | 5 | 95 |
| Low Residue Agriculture[g] | 0 | 3 | 97 | 0 | 4 | 96 | 0 | 10 | 90 |
| **Sub-Tropical, Moist** | | | | | | | | | |
| Continuous Cropping Rotations[e] | 0 | 0 | 100 | 0 | 20 | 80 | 1 | 10 | 89 |
| Rotations with Fallow[f] | 0 | 0 | 100 | 0 | 10 | 90 | 1 | 10 | 89 |
| Low Residue Agriculture[g] | 0 | 3 | 97 | 0 | 4 | 96 | 0 | 5 | 95 |
| **Warm Temperate, Dry** | | | | | | | | | |
| Continuous Cropping Rotations[e] | 0 | 0 | 100 | 0 | 10 | 90 | 1 | 15 | 84 |
| Rotations with Fallow[f] | 0 | 3 | 97 | 0 | 15 | 85 | 2 | 20 | 78 |
| Low Residue Agriculture[g] | 0 | 3 | 97 | 0 | 1 | 99 | 0 | 0 | 100 |
| **Warm Temperate, Moist** | | | | | | | | | |
| Continuous Cropping Rotations[e] | 0 | 6 | 94 | 10 | 30 | 60 | 12 | 28 | 60 |
| Rotations with Fallow[f] | 0 | 6 | 94 | 5 | 30 | 65 | 8 | 27 | 65 |
| Low Residue Agriculture[g] | 0 | 9 | 91 | 1 | 10 | 89 | 2 | 13 | 85 |
| **Cold Temperate, Dry** | | | | | | | | | |
| Continuous Cropping Rotations[e] | 0 | 3 | 97 | 2 | 25 | 73 | 8 | 12 | 80 |
| Rotations with Fallow[f] | 0 | 6 | 94 | 4 | 25 | 71 | 12 | 13 | 75 |
| Low Residue Agriculture[g] | 0 | 0 | 100 | 1 | 2 | 97 | 2 | 6 | 92 |
| **Cold Temperate, Moist** | | | | | | | | | |
| Continuous Cropping Rotations[e] | 0 | 11 | 89 | 5 | 30 | 65 | 3 | 17 | 80 |
| Rotations with Fallow[f] | 0 | 11 | 89 | 5 | 30 | 65 | 3 | 27 | 70 |
| Low Residue Agriculture[g] | 0 | 0 | 100 | 1 | 2 | 97 | 1 | 7 | 92 |

[a] Based on annual survey conducted by Conservation Technology Information Center (CTIC), with modifications for long-term adoption of no-till agriculture (Towery 2001).
[b] No-till includes CTIC survey data designated as no-tillage.
[c] Conventional till includes CTIC survey data designated as intensive tillage and conventional tillage.
[d] Reduced-till includes CTIC survey data designated as ridge tillage, mulch tillage, and reduced tillage.
[e] Includes medium and high input rotations. CTIC survey data for corn, soybeans, and sorghum were used in this category.
[f] Includes rotations with fallow. CTIC survey data on fallow and small grain cropland were used in this category.
[g] Includes low input rotations (low residue crops and vegetables in rotation). CTIC survey data on cotton were used in this category.

Carbon dioxide emissions from degradation of limestone and dolomite applied to agricultural soils were calculated by multiplying the annual amounts of limestone and dolomite applied (see Table 6-14) by $CO_2$ emission factors (0.120 metric ton C/metric ton limestone, 0.130 metric ton C/metric ton dolomite).[9] These emission factors are based on the assumption that all of the carbon in these materials evolves as $CO_2$ in the same year in which the minerals are applied. 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; USGS 2001). To develop these data, 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).

[9] Note: the default emission factor for dolomite provided in the Workbook volume of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) is incorrect. The value provided is 0.122 metric ton carbon/metric ton of dolomite; the correct value is 0.130 metric ton carbon/metric ton of dolomite.

**Table 6-13: Organic Soil Areas by IPCC Land-Use Category and Climatic Region (thousand hectares)[a]**

| Climatic Region/ Land-Use Category | 1982 | 1992 | 1997 |
|---|---|---|---|
| **Cold Temperate, Dry** | **4** | **4** | **4** |
| Non-Agricultural[b] | 3 | 3 | 3 |
| Pasture/Forest | 1 | 1 | 1 |
| Cropland | 0 | 0 | 0 |
| **Cold Temperate, Moist** | **757** | **757** | **757** |
| Non-Agricultural[b] | 79 | 53 | 52 |
| Pasture/Forest | 368 | 419 | 411 |
| Cropland | 310 | 285 | 294 |
| **Sub-Tropical, Dry** | **2** | **2** | **2** |
| Non-Agricultural[b] | 2 | 2 | 2 |
| Pasture/Forest | 0 | 0 | 0 |
| Cropland | 0 | 0 | 0 |
| **Sub-Tropical, Moist** | **391** | **391** | **391** |
| Non-Agricultural[b] | 143 | 131 | 117 |
| Pasture/Forest | 63 | 66 | 77 |
| Cropland | 185 | 194 | 196 |
| **Warm Temperate, Dry** | **47** | **47** | **47** |
| Non-Agricultural[b] | 1 | <1 | 1 |
| Pasture/Forest | 2 | 1 | 2 |
| Cropland | 44 | 45 | 44 |
| **Warm Temperate, Moist** | **140** | **140** | **140** |
| Non-Agricultural[b] | 13 | 3 | 2 |
| Pasture/Forest | 34 | 39 | 38 |
| Cropland | 93 | 98 | 101 |
| **Total** | **1,341** | **1,341** | **1,341** |
| Non-Agricultural[b] | 240 | 193 | 176 |
| Pasture/Forest | 469 | 526 | 530 |
| Cropland | 633 | 623 | 635 |

Note: Totals may not sum due to independent rounding.

[a] Based on analysis of the 1997 *National Resources Inventory* data (NRCS 2000). Includes all conterminous U.S. land categorized as agricultural in 1992 or 1997.

[b] Non-agricultural lands are included for informational purposes only; only pasture/forest areas and cropland areas contribute to emissions.

To estimate the "unspecified" and "estimated" amounts of crushed limestone and dolomite applied to agricultural soils, it was assumed that the fractions of "unspecified" and "estimated" production that were applied to agricultural soils in a specific year were equal to the fraction of "specified" production that was applied to agricultural soils in that same year. In addition, data were not available for 1990, 1992, and 2000 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 2000 data, the 1999 fractions were applied to a 2000 estimate of total crushed stone found in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2001* (USGS 2001).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1994 and by the U.S. Geological Survey from 1995 to the present. In 1994, the "Crushed Stone" chapter in *Minerals Yearbook* began rounding (to the nearest thousand) quantities for total crushed stone produced or used. It then reported revised (rounded) quantities for each of the years from 1990 to 1993. In order to minimize the inconsistencies in the activity data, these revised production numbers have been used in all of the subsequent calculations.

## Uncertainty

Uncertainties in the flux estimates for mineral and organic soils result from both the activity data and the carbon stock and adjustment factors. Each of the datasets used in deriving the area estimates has a level of uncertainty that is passed on through the analysis, and the aggregation of data over large areas necessitates a certain degree of generalization. The default IPCC values for mineral soil carbon stocks under native vegetation as well as values for the base, tillage, and input factors represent broad regional averages. Thus, the values have potentially high uncertainty when applied to specific combinations of climate, soil, and

**Table 6-14: Quantities of Applied Minerals (Thousand Metric Tons)**

| Description | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Limestone | 19,012 | 20,312 | 17,984 | 15,609 | 16,686 | 17,297 | 17,479 | 16,539 | 14,882 | 16,894 | 17,443 |
| Dolomite | 2,360 | 2,618 | 2,232 | 1,740 | 2,264 | 2,769 | 2,499 | 2,989 | 6,389 | 3,420 | 3,531 |

land management conditions. Similarly, measured carbon loss rates from cultivated organic soils vary by as much as an order of magnitude, depending on climate, land use history and management intensity.

Revised inventory approaches to better quantify uncertainty and to better represent between-year variability in annual fluxes are being developed and are currently under review. A modification of the inventory based on the *Revised 1996 IPCC Guidelines* uses field data specific to the United States to statistically estimate land-use and management factor values and baseline carbon stocks (see Box 6-1). These are combined with other error estimates in a Monte-Carlo simulation to generate 95 percent confidence intervals for average annual fluxes for mineral and organic soils. An annual activity-based inventory using a dynamic simulation model is also being tested (see Box 6-2). The method uses similar climate, soil, and land-use/land-management databases as the IPCC approach, but is more capable of estimating annual variation in fluxes, and including the effects of long-term trends in agricultural productivity on soil carbon stocks.

Uncertainties in the estimates of emissions from liming result from both the methodology and the activity data. It can take several years for agriculturally-applied limestone and dolomite to degrade completely. The IPCC method assumes that the amount of mineral applied in any year is equal to the amount that degrades in that year, so annual application rates can be used to derive annual emissions. Further research is required to determine actual degradation rates, which would vary with varying soil and climatic conditions. However, application rates are fairly constant over the entire time series, so this assumption may not contribute significantly to overall uncertainty.

**Box 6-1: Estimating Uncertainty Using a Revised IPCC Approach**

A modification of the IPCC methodology, which incorporates estimates of factor values and baseline carbon stocks based on U.S.-specific data and a Monte Carlo uncertainty analysis, is currently under peer-review (Ogle et al. in prep.). Based on an extensive literature review of more than 1,000 published studies, IPCC factor values and organic soil emission rates have been re-estimated using field studies specific to U.S. conditions. Linear mixed-effect models were used to derive probability density functions (PDF) for each factor value. In addition, PDFs for baseline soil carbon levels were derived from the National Soil Characterization Database, which contains carbon measurements for thousands of soil pedons sampled in the United States (NRCS 1997). Finally, PDFs were derived for the area estimates of individual land-use/management categories based on the expansion factors from the *National Resources Inventory* and tillage management data provided by the Conservation Technology Information Center. The expansion factors are a statistical representation of the land area in the inventory. Probability density functions for the climate/soil/land-use/land-management categories were based on mean and variance estimates for individual land areas, assuming normality, while accounting for the inter-dependence in land use between starting and ending years in the inventory. A Monte Carlo approach (Smith and Heath 2001) was used to estimate overall uncertainty for carbon fluxes associated with each agricultural management activity. The Monte Carlo procedure simulated 50,000 estimates, using an iterative process in which random selections were made from the probability density functions described above. This method provides estimates of carbon flux between U.S. agricultural soils and the atmosphere with statistically valid 95 percent confidence intervals.

Preliminary results suggest that basing the inventory on U.S.-specific data sources gives somewhat lower estimates for carbon sequestration on mineral soils and higher estimates for carbon emissions from cultivated organic soils. Preliminary results show confidence intervals of about ±45 percent of the mean for mineral soil fluxes and ±30 percent for organic soil fluxes.

### Box 6-2: Century Model Estimates of Soil Carbon Stock Changes on Cropland

Soil carbon stock changes on U.S. cropland were estimated using a dynamic ecosystem simulation model called Century (Metherell et al. 1993, Parton et al. 1994). This method differs from the IPCC approach in that annual changes are computed dynamically as a function of inputs of carbon to soil (i.e., crop residues, manure, and sewage sludge) and soil carbon decomposition rates, which are governed by climate and soil factors as well as management practices. The model simulates all major field crops (maize, wheat and other small grains, soybean, sorghum, cotton) as well as hay and pasture (grass, alfalfa, clover). Management variables included tillage, fertilization, irrigation, drainage, and manure addition.

Input data were the same as that used in the IPCC-based method, (i.e., mean climate variables were from the PRISM database; crop rotation, irrigation and soil characteristics were from the *National Resources Inventory* (NRI); and tillage data were from the Conservation Technology Information Center). Differences with respect to the IPCC-based method were as follows: 1) climate values were applied to each individual MLRA to drive the simulation (as opposed to their use for classification into broad climate zones in the IPCC method) and 2) soil physical parameters, which influence decomposition rates and soil water balance, specific to each MLRA point were used with Century, while, in the IPCC method, soils information were used to group NRI points by broad soil taxonomic classes. In the Century-based analysis, land areas having less than 5 percent of total area in crop production were excluded and several less-dominant crops (e.g., vegetables, sugar beets and sugar cane, potatoes, tobacco, orchards, and vineyards), for which the model has not yet been parameterized, were not included. Thus, the total area included in the Century analysis (149 million hectares) was smaller than the corresponding area of cropland (165 million hectares) included in the IPCC estimates.

Preliminary results using the Century model suggest (as with the IPCC model) that U.S. cropland soils (excluding organic soils) are currently acting as a carbon sink, of about 21 Tg C/year (77 Tg $CO_2$ Eq./year) (average rates for 1992 through 1997). The main management changes responsible for the increase in mineral soil carbon stocks, according to the Century approach, are the same as those indicated by the IPCC method: reduced tillage intensity; establishment of the Conservation Reserve Program; reduced bare fallow; and some increase in hay area. In addition, the Century analysis includes the effect of increasing residues inputs due to higher productivity on cropland in general, which contributes to the increase in soil carbon stocks.

Potential advantages of a dynamic simulation based approach include the ability to use actual observed weather, observed annual crop yields, and more detailed soils and management information to drive the estimates of soil carbon change. This would facilitate annual estimates of carbon stock changes and $CO_2$ emissions from soils that would better reflect interannual variability in cropland production and weather influences on carbon cycle processes.

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 could lead to an overestimation of limestone and an underestimation of dolomite. In addition, the lack of comprehensive limestone and dolomite end-use data makes it necessary to derive amounts of "unspecified" and "estimated" crushed limestone and dolomite applied to agricultural soils based on "specified" production data. Lastly, 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. The *Mineral Industry Surveys* further excludes Alaska and Hawaii from its totals.

## Changes in Yard Trimming Carbon Stocks in Landfills

As is the case with carbon in landfilled forest products, carbon contained in landfilled yard trimmings can be stored indefinitely. In the United States, yard trimmings (i.e., grass clippings, leaves, branches) comprise a significant portion of the municipal waste stream, and a large fraction of the collected yard trimmings are discarded in landfills. However, both the amount of yard trimmings collected annually and the fraction that is landfilled have declined over the last decade. In 1990, nearly 32 million metric tons (wet weight) of yard trimmings were collected at landfills and transfer stations (Franklin Associates 1999). Since then, programs banning or discouraging disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent 35 percent decrease in the amount of yard trimmings collected. At the same time, a dramatic increase in the number of municipal composting facilities has reduced the proportion of collected yard trimmings that are discarded in landfills—from 72 percent in 1990 to 36 percent by 2000. The decrease in the yard trimmings landfill disposal rate has resulted in a decrease in the rate of landfill carbon storage from about 19.1 Tg $CO_2$ Eq. in 1990 to 6.4 Tg $CO_2$ Eq. in 2000 (see Table 6-15).

**Table 6-15: Net $CO_2$ Flux from Landfilled Yard Trimmings**

| Year | Tg $CO_2$ Eq. |
|---|---|
| 1990 | (19.1) |
| 1995 | (12.2) |
| 1996 | (10.2) |
| 1997 | (9.5) |
| 1998 | (8.3) |
| 1999 | (7.3) |
| 2000 | (6.4) |

Note: Parentheses indicate net storage. Lightly shaded area indicates values based on projections.

## Methodology

The methodology for estimating carbon storage is based on a life-cycle analysis of greenhouse gas emissions and sinks associated with solid waste management (EPA 1998). According to this methodology, carbon storage is the product of the weight of landfilled yard trimmings and a storage factor. The storage factor, which is the ratio of the weight of the carbon that is stored indefinitely to the wet weight of the landfilled yard trimmings, is based on a series of experiments designed to evaluate methane generation and residual organic material in landfills (Barlaz 1998). These experiments analyzed grass, leaves, branches, and other materials, and were designed to promote biodegradation by providing ample moisture and nutrients.

Barlaz (1998) determined carbon storage factors, on a dry weight basis, for each of the three components of yard trimmings: grass, leaves, and branches (see Table 6-16). For purposes of this analysis, these were converted to wet weight basis using assumed moisture contents of 0.6, 0.2, and 0.4, respectively. To develop a weighted average carbon storage factor, the composition of yard trimmings was assumed to consist of 50 percent grass clippings, 25 percent leaves, and 25 percent branches on a wet weight basis. The weighted average carbon storage factor is 0.23 (weight of carbon stored indefinitely per unit weight of wet yard trimmings).

**Table 6-16: Storage Factor (kg C/kg dry yard trimmings) Moisture Content (kg water/kg wet yard trimmings), Composition (percent) and Converted Storage Factor (kg C/kg wet yard trimmings) of Landfilled Yard Trimmings**

| Component | Grass | Leaves | Branches |
|---|---|---|---|
| Storage Factor[a] | 0.32 | 0.54 | 0.38 |
| Moisture Content | 0.60 | 0.20 | 0.40 |
| Composition | 50% | 25% | 25% |
| Converted Storage Factor[b] | 0.13 | 0.43 | 0.23[c] |

[a] From Barlaz (1998)
[b] The converted storage factor for each component is the product of the original storage factor and one minus the moisture content; the weighted average storage factor is obtained by weighting the component storage factors by the composition percents.
[c] Value is also value of weighted average.

## Data Sources

The yard trimmings discards data were taken from the report *Characterization of Municipal Solid Waste in the United States: 1998 Update* (Franklin Associates 1999), which provides estimates for 1990 through 1997 and forecasts for 2000 and 2005 (Table 6-17). Yard trimmings discards for 1998 through 2000 were projected using the Franklin Associates (1999) forecast of generation and recovery rates (i.e., decrease of 6 percent per year, increase of 8 percent per year, respectively) for 1998 through 2000. This report does not subdivide discards of individual materials into volumes landfilled and combusted, although it does provide an estimate of the overall distribution of solid waste between these two management methods (i.e., ranging from 81 percent and 19 percent respectively in 1990, to 76 percent and 24 percent in 2000) for the waste stream as a whole.[10] Thus, yard trimmings disposal to landfills is the product of the quantity discarded and the proportion of discards managed in landfills. As discussed above, the carbon storage factor was derived from the results of Barlaz (1998), and assumed moisture contents and component fractions for yard trimmings.

## Uncertainty

The principal source of uncertainty for the landfill carbon storage estimates stems from an incomplete understanding of the long-term fate of carbon in landfill environments. Although there is ample field evidence that many landfilled organic materials remain virtually intact for long periods, the quantitative basis for predicting long-term storage is based on limited laboratory results under experimental conditions.[11] In reality, there is likely to be considerable heterogeneity in storage rates, based on 1) actual composition of yard trimmings (e.g., oak leaves decompose more slowly than grass clippings) and 2) landfill characteristics (e.g., availability of moisture, nitrogen, phosphorus, etc.). Other sources of uncertainty include the estimates of yard trimmings disposal rates, which are based on extrapolations of waste composition surveys, and the extrapolation of values for 1998 through 2000 disposal from estimates for the period from 1990 through 1997.

**Table 6-17: Collection and Destination of Yard Trimmings (Million Metric Tons, wet)**

| Destination | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Municipal Composting Facilities | 3.8 | 8.2 | 9.4 | 10.4 | 10.6 | 10.8 | 10.9 |
| Discarded | 27.9 | 27.4 | 26.9 | 23.9 | 13.0 | 11.4 | 10.0 |
| Landfill | 22.8 | 22.2 | 21.7 | 19.2 | 17.1 | 14.5 | 7.6 |
| Incineration | 5.2 | 4.3 | 3.8 | 3.5 | 3.1 | 2.7 | 2.4 |
| **Total** | **31.8** | **26.9** | **25.3** | **25.2** | **23.6** | **22.2** | **20.9** |

Note: Lightly shaded area indicates values based on projections.

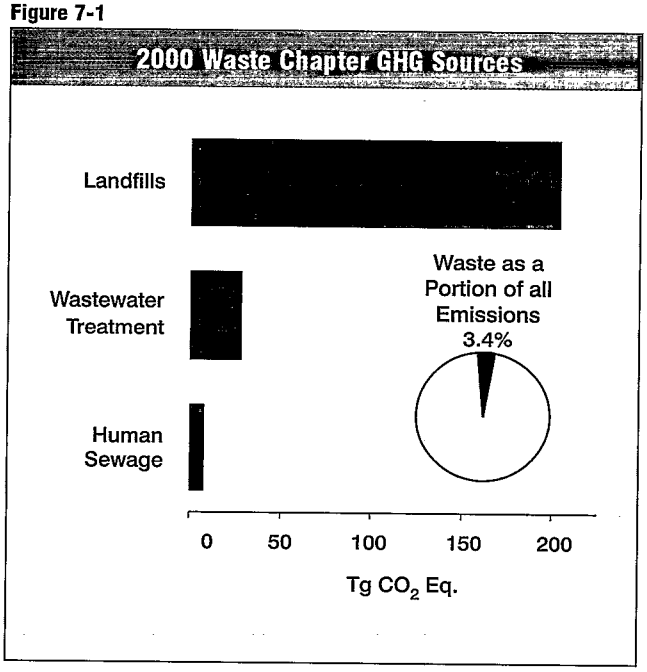
[10] These percents represent the percent of total MSW discards, after recovery for recycling or composting.

[11] In addition, there was a mass balance problem with the experimental results that are used here to derive the yard trimmings carbon storage factor. In particular, the carbon storage factor for leaves that was determined experimentally by Barlaz (1998) was greater than Barlaz's measured carbon content of the leaves.

# 7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1). Landfills were the largest source of anthropogenic methane ($CH_4$) emissions, accounting for 33 percent of the U.S. total.[1] Smaller amounts of methane are emitted from wastewater systems by bacteria used in various treatment processes. Wastewater treatment systems are also a potentially significant source of $N_2O$ emissions; however, methodologies are not currently available to develop a complete estimate. Nitrous oxide emissions from the treatment of the human sewage component of wastewater were estimated, however, using a simplified methodology. Nitrogen oxide ($NO_x$), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) are emitted by waste activities, and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 7-1 and Table 7-2.

Figure 7-1




Overall, in 2000, waste activities generated emissions of 240.6 Tg $CO_2$ Eq., or 3.4 percent of total U.S. greenhouse gas emissions.

## Landfills

Landfills are the largest anthropogenic source of methane ($CH_4$) emissions in the United States. In 2000, landfill $CH_4$ emissions were approximately 203.5 Tg $CO_2$ Eq. (9,690 Gg). Emissions from municipal solid waste (MSW) landfills, which received about 61 percent of the total solid waste generated in the United States, accounted for about 94 percent of total landfill emissions, while industrial landfills accounted for the remainder. Over 2,100 operational landfills exist in the United States (*BioCycle* 2001), with the largest landfills receiving most of the waste and generating the majority of the methane.

Methane emissions result from the decomposition of organic landfill materials such as paper, food scraps, and yard trimmings. This decomposition process is a biological process through which microorganisms derive energy. After being placed in a landfill, organic waste is initially digested by aerobic (in the presence of oxygen) bacteria. After the oxygen supply has been depleted, the remaining waste is consumed 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. Methane-

[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 Change and Forestry chapter.

**Table 7-1: Emissions from Waste (Tg $CO_2$ Eq.)**

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CH_4$** | **237.7** | **243.4** | **238.5** | **233.9** | **228.8** | **231.4** | **232.2** |
| Landfills | 213.4 | 216.6 | 211.5 | 206.4 | 201.0 | 203.1 | 203.5 |
| Wastewater Treatment | 24.3 | 26.8 | 27.0 | 27.5 | 27.8 | 28.3 | 28.7 |
| **$N_2O$** | **7.0** | **7.7** | **7.8** | **7.9** | **8.1** | **8.4** | **8.5** |
| Human Sewage | 7.0 | 7.7 | 7.8 | 7.9 | 8.1 | 8.4 | 8.5 |
| **Total** | **244.7** | **251.1** | **246.3** | **241.9** | **236.9** | **239.8** | **240.6** |

Note: Totals may not sum due to independent rounding.

**Table 7-2: Emissions from Waste (Gg)**

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CH_4$** | **11,317** | **11,591** | **11,359** | **11,138** | **10,897** | **11,021** | **11,056** |
| Landfills | 10,162 | 10,315 | 10,072 | 9,827 | 9,571 | 9,671 | 9,690 |
| Wastewater Treatment | 1,155 | 1,275 | 1,287 | 1,311 | 1,326 | 1,350 | 1,367 |
| **$N_2O$** | **23** | **25** | **25** | **26** | **26** | **27** | **27** |
| Human Sewage | 23 | 25 | 25 | 26 | 26 | 27 | 27 |

Note: Totals may not sum due to independent rounding.

## Box 7-1: Biogenic Emissions and Sinks of Carbon

For many countries, $CO_2$ emissions from the combustion or degradation of biogenic materials are important because of the significant amount of energy they derive from biomass (e.g., burning fuelwood). The fate of biogenic materials is also important when evaluating waste management emissions (e.g., the decomposition of paper). The carbon contained in paper was originally stored in trees during photosynthesis. Under natural conditions, this material would eventually degrade and cycle back to the atmosphere as $CO_2$. The quantity of carbon that these degradation processes cycle through the Earth's atmosphere, waters, soils, and biota is much greater than the quantity added by anthropogenic greenhouse gas sources. But the focus of the United Nations Framework Convention on Climate Change is on anthropogenic emissions—emissions resulting from human activities and subject to human control—because it is these emissions that have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle, and enhancing the atmosphere's natural greenhouse effect.

Carbon dioxide emissions from 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. However, $CH_4$ 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.

The removal of carbon from the natural cycling of carbon between the atmosphere and biogenic materials—which occurs when wastes of biogenic origin are deposited in landfills—sequesters carbon. When wastes of sustainable, biogenic origin are landfilled, and do not completely decompose, the carbon that remains is effectively removed from the global carbon cycle. Landfilling of forest products and yard trimmings results in long-term storage of about 70 Tg $CO_2$ Eq. and 7 to 18 Tg $CO_2$ Eq. per year, respectively. Carbon storage that results from forest products and yard trimmings disposed in landfills is accounted for in the Land-Use Change and Forestry chapter, as recommended in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) regarding the tracking of carbon flows.

**Box 7-2: Recycling and Greenhouse Gas Emissions and Sinks**

U.S. waste management patterns changed dramatically over the past decade in response to changes in economic and regulatory factors. Perhaps the most significant change from a greenhouse gas perspective was the increase in the national average recycling rate, which climbed from 16 percent in 1990 to 28 percent in 1999 (EPA 2000).

This change has affected emissions in several ways, primarily by reducing emissions from waste and energy activities, as well as by enhancing forestry sinks. The impact of increased recycling on greenhouse gas emissions can be best understood when emissions are considered from a life cycle perspective (EPA 1998). When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed and managed as waste. The substitution of recycled inputs for virgin inputs reduces three types of emissions throughout the product life cycle. First, manufacturing processes involving recycled inputs generally require less energy than those using virgin inputs. Second, the use of recycled inputs leads to reductions in process non-energy emissions (e.g., perfluorocarbon emissions from aluminum smelting). Third, recycling reduces disposal and waste management emissions, including methane from landfills and nitrous oxide and non-biogenic carbon dioxide emissions from combustion. In addition to greenhouse gas emission reductions from manufacturing and disposal, recycling of paper products—the largest component of the U.S. wastestream—results in increased forest carbon sequestration. When paper is recycled, fewer trees are needed as inputs in the manufacturing process; reduced harvest levels result in older average forest ages, with correspondingly more carbon stored.

producing anaerobic bacteria convert these fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent carbon dioxide ($CO_2$) and 50 percent methane ($CH_4$), by volume.[2] Methane production typically begins one or two years after waste disposal in a landfill and may last from 10 to 60 years.

Between 1990 and 2000, net methane emissions from landfills were relatively constant (see Table 7-3 and Table 7-4). The roughly constant emissions estimates are a result of two offsetting trends: (1) the amount of MSW in landfills contributing to methane emissions increased, thereby increasing the potential for emissions; and (2) the amount of landfill gas collected and combusted by landfill operators also increased, thereby reducing emissions.

Methane emissions from landfills are a function of several factors, including: (1) the total amount of MSW in landfills, which is related to total MSW landfilled annually for the last 30 years; (2) the characteristics of landfills receiving waste (i.e., composition of waste-in-place; size, climate); (3) the amount of methane that is recovered and either flared or used for energy purposes; and (4) the amount of methane oxidized in landfills instead of being released into the atmosphere. The estimated total quantity of waste-in-place contributing to emissions increased from about 4,926 Tg in 1990 to 6,147 Tg in 2000, an increase of 25 percent (see Annex O). During this period, the estimated methane recovered and flared from landfills increased as well. In 1990, for example, approximately 1,119 Gg of methane was recovered and combusted (i.e., used for energy or flared) from landfills. In 2000, the estimated quantity of methane recovered and combusted increased to 4,874 Gg.

Over the next several years, the total amount of MSW generated is expected to increase slightly. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In addition, the quantity of methane that is recovered and either flared or used for energy purposes is expected to increase, partially as a result of a 1996 regulation that requires large MSW landfills to collect and combust landfill gas (see 40 CFR Part 60, Subparts Cc and WWW).

## Methodology

Based on available information, methane emissions from landfills were estimated to equal the methane produced from municipal landfills, minus the methane recovered and combusted, minus the methane oxidized before being released into the atmosphere, plus the methane produced by industrial landfills.

[2] The percentage of $CO_2$ in biogas released from a landfill may be smaller because some $CO_2$ dissolves in landfill water (Bingemer and Crutzen 1987). Additionally, less than 1 percent of landfill gas is composed of non-methane volatile organic compounds (NMVOCs).

**Table 7-3: $CH_4$ Emissions from Landfills (Tg $CO_2$ Eq.)**

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| MSW Landfills | 221.6 | 255.5 | 261.8 | 268.4 | 274.0 | 280.9 | 286.5 |
| Industrial Landfills | 15.3 | 17.5 | 17.8 | 18.2 | 18.5 | 19.0 | 19.3 |
| Recovered | | | | | | | |
| Gas-to-Energy | (14.5) | (21.4) | (24.6) | (29.7) | (36.3) | (41.7) | (46.1) |
| Flared | (9.0) | (35.0) | (43.5) | (50.5) | (55.3) | (55.1) | (56.2) |
| **Total** | **213.4** | **216.6** | **211.5** | **206.4** | **201.0** | **203.1** | **203.5** |

Note: Totals may not sum due to independent rounding.

**Table 7-4: $CH_4$ Emissions from Landfills (Gg)**

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| MSW Landfills | 10,551 | 12,165 | 12,465 | 12,779 | 13,050 | 13,374 | 13,642 |
| Industrial Landfills | 731 | 833 | 850 | 868 | 883 | 904 | 921 |
| Recovered | | | | | | | |
| Gas-to-Energy | (692) | (1,017) | (1,171) | (1,415) | (1,729) | (1,984) | (2,196) |
| Flared | (427) | (1,665) | (2,073) | (2,405) | (2,633) | (2,623) | (2,678) |
| **Total** | **10,162** | **10,315** | **10,072** | **9,827** | **9,571** | **9,671** | **9,690** |

Note: Totals may not sum due to independent rounding.

The methodology for estimating $CH_4$ emissions from municipal landfills is based on a model that updates the population of U.S. landfills each year. This model is based on the pattern of actual waste disposal, as evidenced in an extensive landfill survey by the EPA's Office of Solid Waste in 1987. A second model was employed to estimate emissions from the landfill population (EPA 1993). For each landfill in the data set, the amount of waste-in-place contributing to methane generation was estimated using its year of opening, its waste acceptance rate, year of closure, and design capacity. Data on national waste disposed in landfills each year was apportioned by landfill. Emissions from municipal landfills were then estimated by multiplying the quantity of waste contributing to emissions by emission factors (EPA 1993). For further information see Annex O.

The estimated landfill gas recovered per year was based on updated data collected from vendors of flaring equipment and a database of landfill gas-to-energy (LFGTE) projects. Based on the information provided by vendors, the methane combusted by the 585 flares in operation from 1990 to 2000 were estimated. This quantity likely underestimates flaring. Additionally, the database provided sufficient data on landfill gas flow and energy generation for 306 of the approximately 314 operational LFGTE projects. If both flare data and LFGTE recovery data for a particular landfill were available, then the emissions recovery was based on the LFGTE data, which provides actual 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 was likely to also have had a flare, double counting reductions from flares and LFGTE projects 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.[3]

Emissions from industrial landfills were assumed to be equal to 7 percent of the total methane emissions from municipal landfills. The amount of methane oxidized was assumed to be 10 percent of the methane generated that is

[3] Due to the differences in referencing landfills and incomplete data on the national population of flares, matching flare vendor data with the LFGTE data was problematic and a flare could not be identified for each of the LFGTE projects. Because each LFGTE project likely has a flare, the aggregate estimate of emission reductions through flaring was reduced by the LFGTE projects for which a specific flare could not be identified. This approach eliminated the potential for double counting emissions reductions at landfills with both flares and a LFGTE project.

not recovered (Liptay et al. 1998). To calculate net methane emissions, both methane recovered and methane oxidized were subtracted from methane generated at municipal and industrial landfills.

## Data Sources

The landfill population model, including actual waste disposal data from individual landfills, was developed from a survey performed by the EPA's Office of Solid Waste (EPA 1988). National landfill waste disposal data for 1990 through 2000 were obtained from *BioCycle* (2001). Documentation on the landfill methane emissions methodology employed is available in the EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993). Information on flares was obtained from vendors, and information on landfill gas-to-energy projects was obtained from the EPS's Landfill Methane Outreach Program database.

## Uncertainty

Several types of uncertainties are associated with the estimates of methane emissions from landfills. The primary uncertainty concerns the characterization of landfills. Information is lacking on the area landfilled and total waste-in-place —the fundamental factors that affect methane production. In addition, the statistical model used to estimate emissions is based upon methane generation at landfills that currently have developed energy recovery projects, and may not precisely capture the relationship between emissions and various physical characteristics of individual landfills. Overall, uncertainty in the landfill methane emission rate is estimated to be roughly ±30 percent.

# Wastewater Treatment

Wastewater from domestic sources (municipal sewage) and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants. Treatment may either occur off-site or on-site. For example, in the United States, approximately 25 percent of domestic wastewater is treated in septic systems or other on-site systems. 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 methane. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. Untreated wastewater may also produce methane if contained under anaerobic conditions.

The organic content, expressed in terms of either biochemical oxygen demand (BOD) or chemical oxygen demand (COD), determines the methane producing potential of wastewater. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes. COD refers to the amount of oxygen consumed under specified conditions in the oxidation of the organic and oxidizable inorganic matter and is a parameter typically used to characterize industrial wastewater. Under anaerobic conditions and with all other parameters, such as temperature, being the same, wastewater with higher organic content will produce more methane than wastewater with lower BOD or COD.

In 2000, methane emissions from domestic wastewater treatment were 13.9 Tg $CO_2$ Eq. (660 Gg). Emissions have increased since 1990 in response to the increase in the U.S. human population. Industrial emission sources include wastewater from the pulp and paper, meat and poultry processing, and the vegetables, fruits and juices processing industry.[4] In 2000, methane emissions from industrial wastewater treatment were 14.8 Tg $CO_2$ Eq. (707 Gg). Table 7-5 and Table 7-6 provide emission estimates from domestic and industrial wastewater treatment.

## Methodology

Domestic wastewater methane emissions were estimated using the default IPCC methodology (IPCC 2000). The total population for each year was multiplied by a per capita wastewater BOD production rate to determine total

[4] Industrial wastewater emissions from petroleum systems is included in the petroleum systems section in the Energy chapter.

**Table 7-5: $CH_4$ Emissions from Domestic and Industrial Wastewater Treatment (Tg $CO_2$ Eq.)**

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Domestic | 12.3 | 13.1 | 13.2 | 13.4 | 13.5 | 13.7 | 13.9 |
| Industrial* | 12.0 | 13.7 | 13.8 | 14.2 | 14.3 | 14.6 | 14.8 |
| **Total** | **24.3** | **26.8** | **27.0** | **27.5** | **27.8** | **28.3** | **28.7** |

* Industrial activity includes the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industry.
Note: Totals may not sum due to independent rounding.

**Table 7-6: $CH_4$ Emissions from Domestic and Industrial Wastewater Treatment (Gg)**

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Domestic | 584 | 622 | 630 | 637 | 645 | 653 | 660 |
| Industrial* | 571 | 653 | 658 | 674 | 681 | 697 | 707 |
| **Total** | **1,155** | **1,275** | **1,287** | **1,311** | **1,326** | **1,350** | **1,367** |

* Industrial activity includes the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industry.
Note: Totals may not sum due to independent rounding.

wastewater BOD produced. It was assumed that, per capita, 0.065 kilograms of wastewater BOD5[5] was produced per day and that 16.25 percent of wastewater BOD5 was anaerobically digested. This proportion of BOD was then multiplied by an emission factor of 0.6 kg $CH_4$/kg BOD5.

A top-down approach was used to develop estimates of methane emissions from industrial wastewater according to the methodology described in the IPCC *Good Practice Guidance* (IPCC 2000). Industry categories identified by IPCC were analyzed to identify industries likely to have significant methane emissions from industrial wastewater. Industries were chosen that typically have both a high volume of wastewater generated and a high organic COD wastewater load. The top three industries that met these criteria were:

- Pulp and paper manufacturing
- Meat and poultry packing
- Vegetables, fruits and juices processing

Methane emissions from these categories were estimated by multiplying the annual product output (metric tons/year) by the average outflow ($m^3$/ton of output), the organics loading in the outflow (grams of organic COD/$m^3$), the emission factor (grams $CH_4$/grams COD), and the percentage of organic COD assumed to degrade anaerobically.

Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (Worldbank 1999, Nemerow 1991). The most important step is lagooning for storage, settling, and biological treatment (secondary treatment). In developing estimates for this category BOD was used instead of COD, because more accurate BOD numbers were available. In determining the percent that degraded anaerobically, both primary and secondary treatment were considered. Primary treatment lagoons are aerated to reduce anaerobic activity. However, the lagoons are large and zones of anaerobic activity may occur. Approximately 42 percent of the BOD passes on to secondary treatment, which are less likely to be aerated (EPA 1993). It was assumed that 25 percent of the BOD in secondary treatment lagoons degrades anaerobically, while 10 percent passes through to be discharged with the effluent (EPA 1997a). Overall, the percentage of wastewater organics that degrade anaerobically was determined to be 10.3 percent. The emission factor that was used is 0.6 kg $CH_4$/kg BOD, which is the default emission factor from IPCC (2000).

[5] The 5-day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 1991).

The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence to screening, fat traps and dissolved air flotation, and it was estimated that 77 percent of all wastewater organics from this industry degrades anaerobically (EPA 1997b).

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. Therefore, it was assumed that this industry is likely to use lagoons intended for aerobic operation, but that the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used. Consequently, it was estimated that 5 percent of these wastewater organics degrade anaerobically.

## Data Sources

National population data for 1990 to 2000, used in the domestic wastewater emissions estimates, were supplied by the U.S. Census Bureau (2000). Per-capita production of BOD5 for domestic wastewater was obtained from the EPA (1997b). The emission factor (0.6 kg $CH_4$/kg BOD5) employed for domestic wastewater treatment was taken from IPCC (2000). The same emission factor was used for pulp and paper wastewater, whereas the emission factor for meat and poultry, and vegetables, fruits and juices category is 0.25 kg $CH_4$/kg COD (IPCC 2000).

Table 7-7 provides U.S. population and wastewater BOD data.

**Table 7-7: U.S. Population (Millions) and Wastewater BOD Produced (Gg)**

| Year | Population | BOD5 |
|---|---|---|
| 1990 | 249.4 | 5,920 |
| 1991 | 252.0 | 5,984 |
| 1992 | 254.9 | 6,052 |
| 1993 | 257.7 | 6,118 |
| 1994 | 260.2 | 6,179 |
| 1995 | 262.7 | 6,238 |
| 1996 | 265.2 | 6,296 |
| 1997 | 267.7 | 6,356 |
| 1998 | 270.2 | 6,415 |
| 1999 | 272.6 | 6,473 |
| 2000 | 275.1 | 6,531 |

For pulp and paper, a time series of methane emissions for post-1990 years was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post Directory 1992-2001). The overall wastewater outflow was estimated to be 85 $m^3$/ton and the average BOD loading entering the secondary treatment lagoons was estimated to be 0.4 gram BOD/liter. Both values are based on information from multiple handbooks.

Production data for the meat and poultry industry were obtained from the U.S. Census (2001). EPA (1997b) provides wastewater outflows of 13 (out of a range of 8 to 18) $m^3$/ton and an average COD value of 4.1 (out of a range of 2 to 7) g/liter.

The USDA National Agricultural Statistics Service (USDA 2001) provided production data for the fruits, vegetables, and juices processing sector. Outflow data for various subsectors (canned fruit, canned vegetables, frozen vegetables, fruit juices, jams, baby food) were obtained from World Bank (1999) and an average wastewater outflow of 5.6 $m^3$/ton was used. For the organics loading, a COD value of 5 (out of a range of 2 to 10) g/liter was used (EPA 1997b).

Table 7-8 provides U.S. pulp and paper; meat and poultry; and vegetables, fruits, and juices production data.

## Uncertainty

Domestic wastewater emissions estimates are uncertain due to the lack of data on the occurrence of anaerobic conditions in treatment systems, especially incidental occurrences.

**Table 7-8: U.S. Pulp and Paper, Meat and Poultry, and Vegetables, Fruits and Juices Production (Million Metric Tons)**

| Year | Pulp and Paper | Meat and Poultry | Vegetables, Fruits and Juices |
|---|---|---|---|
| 1990 | 128.9 | 28.2 | 29.7 |
| 1991 | 129.2 | 29.0 | 30.8 |
| 1992 | 134.5 | 30.0 | 32.9 |
| 1993 | 134.1 | 31.0 | 33.6 |
| 1994 | 139.3 | 32.0 | 36.7 |
| 1995 | 140.9 | 33.6 | 36.2 |
| 1996 | 140.3 | 34.2 | 35.9 |
| 1997 | 145.6 | 34.6 | 37.1 |
| 1998 | 144.0 | 35.7 | 35.9 |
| 1999 | 145.1 | 37.0 | 36.8 |
| 2000 | 144.4 | 38.0 | 38.0 |

Large uncertainties are associated with the industrial wastewater emission estimates. Wastewater outflows and organics loadings may vary greatly for different plants and different sub-sectors (e.g. paper vs. board, poultry vs. beef, baby food vs. juices, etc.). Also, the degree to which anaerobic degradation occurs in treatment systems is very difficult to assess. In addition, it is believed that pulp and paper, meat and poultry and vegetables, fruits and juices are the most significant industrial sources, but there may be additional sources that also produce wastewater organics that may degrade under anaerobic conditions (e.g., organic chemicals and plastics production).

## Human Sewage

Domestic human sewage (termed "blackwater") is usually mixed with other household wastewater (known as "graywater"), which includes shower drains, sink drains, washing machine effluent, etc. and transported by a collection system to either a direct discharge, an on-site or decentralized wastewater system, or a centralized wastewater system. Decentralized wastewater systems are septic systems and package plants that may include several process steps. Centralized treatment systems may include a variety of treatment processes, ranging from lagooning to advanced tertiary wastewater treatment technology for removing nutrients. After processing, treated effluent may be discharged to a receiving water environment (e.g., river, lake, estuary, etc.), applied to soils, or disposed of below the surface.

Nitrous oxide ($N_2O$) may be generated during both nitrification and denitrification of the nitrogen that is present, usually in the form of urea and proteins. Some of these primary nitrogen-containing compounds are rapidly broken down to ammonia-nitrogen while others persist as organic nitrogen. Both forms are converted to nitrate via nitrification, an aerobic process converting ammonia-nitrogen into nitrate ($NO_3^-$). Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas ($N_2$). Nitrous oxide ($N_2O$) can be an intermediate product of both processes, but is more often associated with denitrification. In general, temperature, pH/alkalinity, biochemical oxygen demand (BOD), and nitrogen concentration affect $N_2O$ generation from domestic wastewater treatment processes, while the amount of protein consumed by humans determines the quantity of nitrogen contained in sewage. Emissions of $N_2O$ from sewage nitrogen discharged into aquatic environments were estimated to be 8.5 Tg $CO_2$ Eq. (27 Gg) in 2000. (See Table 7-9).

**Table 7-9: $N_2O$ Emissions from Human Sewage**

| Year | Tg $CO_2$ Eq. | Gg |
|---|---|---|
| 1990 | 7.0 | 23 |
| 1995 | 7.7 | 25 |
| 1996 | 7.8 | 25 |
| 1997 | 7.9 | 26 |
| 1998 | 8.1 | 26 |
| 1999 | 8.4 | 27 |
| 2000 | 8.5 | 27 |

## Methodology

Nitrous oxide emissions from human sewage effluent disposal were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997) with one modification. The IPCC methodology assumes that nitrogen disposal and thus $N_2O$ emissions associated with land disposal, subsurface disposal, as well as sewage treatment are negligible and all sewage nitrogen is discharged directly into aquatic environments. In the United States, however, a certain amount of sewage nitrogen is incinerated or applied to soils or landfills via sewage sludge applications, and therefore, not all sewage nitrogen enters aquatic environments.[6] The nitrogen disposal into aquatic environments is reduced to account for the sewage sludge application.

[6] The IPCC methodology is based on the total amount of nitrogen in sewage, which is in turn based on human protein consumption and the fraction of nitrogen in protein (i.e., $Frac_{NPR}$). A portion of the total nitrogen in sewage in the United States is incinerated or applied to soils or landfills in the form of sewage sludge each year. This amount is subtracted here from total nitrogen in human sewage to estimate sewage $N_2O$ emissions. The amount applied to soils is estimated as part of agricultural soil management (see Chapter 6).

With the modification described above, $N_2O$ emissions from human sewage were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997). This methodology is illustrated below:

$$N_2O(s) = \{[(\text{Protein}) \times (\text{Frac}_{NPR}) \times (\text{U.S. Population})] - N_{sludge}\} \times (EF) \times (^{44}/_{28})$$

where,

$N_2O(s)$ = $N_2O$ emissions from human sewage

Protein = Annual, per capita protein consumption

$\text{Frac}_{NPR}$ = Fraction of nitrogen in protein

$N_{sludge}$ = Quantity of sewage sludge N not entering aquatic environments

EF = Emission factor (kg $N_2O$-N/kg sewage-N produced)

$(^{44}/_{28})$ = The molecular weight ratio of $N_2O$ to $N_2$

## Data Sources

U.S. population data were taken from the U.S. Census Bureau (2001). Data on annual per capita protein consumption were provided by the United Nations Food and Agriculture Organization (FAO 2001) (see Table 7-10). Because data on protein intake were unavailable for 2000, the value of per capita protein consumption for the previous year was used. An emission factor has not been specifically estimated for the United States, so the default IPCC value (0.01 kg $N_2O$-N/kg sewage-N produced) was applied. Similarly, the fraction of nitrogen in protein (0.16 kg N/kg protein) was also obtained from IPCC/UNEP/OECD/IEA (1997).

## Uncertainty

The U.S. population, per capita protein intake data (Protein), and fraction of nitrogen in protein ($\text{Frac}_{NPR}$) are believed to be fairly accurate. Significant uncertainty exists, however, in the emission factor (EF). This uncertainty is due to regional differences in the receiving waters that would likely affect $N_2O$ emissions but are not accounted for in the default IPCC factor. Moreover, the underlying methodological assumption that negligible $N_2O$ emissions result from sewage treatment may be incorrect. A related uncertainty results from assuming all sewage nitrogen is discharged directly into aquatic environments. Although the above methodology takes this into account for a portion of emissions, there are additional discharge pathways that need to be investigated. Taken together, these uncertainties present significant difficulties in estimating $N_2O$ emissions from human sewage.[7]

# Waste Sources of Ambient Air Pollutants

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of criteria air pollutant emissions. Total emissions of nitrogen oxides ($NO_x$), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs) from waste sources for the years 1990 through 2000 are provided in Table 7-11.

## Methodology and Data Sources

These emission estimates were taken directly from the EPA (2001). This EPA report provides emission estimates of these gases 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.

**Table 7-10: U.S. Population (Millions) and Average Protein Intake (kg/Person/Year)**

| Year | Population | Protein |
|---|---|---|
| 1990 | 252.2 | 39.2 |
| 1991 | 255.5 | 39.8 |
| 1992 | 258.8 | 40.0 |
| 1993 | 262.1 | 40.2 |
| 1994 | 265.4 | 41.2 |
| 1995 | 268.7 | 40.6 |
| 1996 | 272.0 | 40.7 |
| 1997 | 275.3 | 41.0 |
| 1998 | 278.6 | 41.1 |
| 1999 | 281.9 | 41.9 |
| 2000 | 285.2 | 41.9 |

[7] The 1999 protein consumption estimate was used as a proxy for the 2000 estimate, as these data are not yet available.

**Table 7-11: Emissions of $NO_x$, CO, and NMVOC from Waste (Gg)**

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$NO_x$** | **83** | **89** | **78** | **78** | **79** | **79** | **81** |
| Landfills | + | 1 | 2 | 2 | 2 | 2 | 2 |
| Wastewater Treatment | + | + | + | + | + | + | + |
| Waste Combustion[a] | 82 | 88 | 75 | 75 | 76 | 76 | 78 |
| Miscellaneous[b] | + | 1 | 1 | 1 | 1 | 1 | 1 |
| **CO** | **979** | **1,075** | **3,215** | **3,217** | **3,220** | **3,220** | **3,273** |
| Landfills | 1 | 2 | 5 | 5 | 5 | 5 | 5 |
| Wastewater Treatment | + | + | + | + | + | + | + |
| Waste Combustion[a] | 978 | 1,073 | 3,210 | 3,211 | 3,214 | 3,214 | 3,268 |
| Miscellaneous[b] | + | 1 | + | + | + | + | + |
| **NMVOCs** | **895** | **968** | **508** | **509** | **513** | **518** | **528** |
| Landfills | 58 | 68 | 32 | 32 | 33 | 33 | 34 |
| Wastewater Treatment | 57 | 61 | 61 | 62 | 63 | 64 | 65 |
| Waste Combustion[a] | 222 | 237 | 352 | 352 | 353 | 354 | 360 |
| Miscellaneous[b] | 558 | 602 | 64 | 64 | 65 | 67 | 69 |

[a] Includes waste incineration and open burning (EPA 2001)
[b] 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

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

Uncertainties in these estimates are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.

# 8. References

## Executive Summary


BEA (2001) Department of Commerce/Bureau of Economic Analysis, National Income and Product Accounts. August 2001.

EIA (2001) *Annual Energy Review 2000 and other EIA data.* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA- 0384(00)-annual.

EIA (2000a) *Electric Power Annual 1999: Volume III,* Energy Information Administration, U.S. Department of Energy, Washington, DC, October. <http://www.eia.doe.gov/cneaf/electricity/epav2/epav2.pdf>.

EIA (2000b) *Electric Power Annual 1999, Volume II,* Energy Information Administration, U.S. Department of Energy, Washington, D.C., DOE/EIA-0348(99)/2, October.

EIA (2000c) *Emissions of Greenhouse Gases in the United States 1999*, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0573(99) October.

EPA (2001) Unpublished data provided by Emission Factors and Inventory Group, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC.

EPA (2000) *National Air Pollutant Emissions Trends Report, 1900-1999.* U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

EPA (1997) National Air Pollutant Emissions Trends Report, 1900-1996. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

IPCC (2001) *Climate Change 2001: A Scientific Basis,* Intergovernmental Panel on Climate Change; J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell, eds.; Cambridge University Press. Cambridge, U.K.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, Montreal, IPCC-XVI/Doc. 10 (1.IV.2000), May 2000.

IPCC (1996) *Climate Change 1995: The Science of Climate Change.* Intergovernmental Panel on Climate Change; J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, eds.; Cambridge University Press. Cambridge, U.K.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Keeling, C.D. and T.P. Whorf (2000) *Atmospheric $CO_2$ records from sites in the SIO air sampling network.* In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. Oak Ridge, TN.

Marland, G., T.A. Boden, and R. J. Andres. 2001. Global, Regional, and National Fossil Fuel $CO_2$ Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge,Tenn., U.S.A.

Powell, D.S., J.L. Faulkner, D.R. Darr, Z. Zhu, and D.W. MacCleery (1993) *Forest Resources of the United States, 1992.* Gen. Tech. Rep. RM-234. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, 132 p.

U.S. Census Bureau (2000) U.S. Bureau of the Census Internet Release date April 11, 2000; revised June 28, 2000. <http://www.census.gov/population/estimates/nation/popclockest.txt>.

WMO (1999) *Scientific Assessment of Ozone Depletion, Global Ozone Research and Monitoring Project-Report No. 44*, World Meteorological Organization, Geneva, Switzerland.

## Changes in this Year's Inventory


AAPFCO (2000a) *1999-2000 Commercial Fertilizers Data.* ASCII files. Available: David Terry, Secretary, AAPFCO.

AAPFCO (2000b) *Commercial Fertilizers 2000.* Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1999) *Commercial Fertilizers 1999.* Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.AAPFCO (1995) *Commercial Fertilizers 1995.* Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1998) *Commercial Fertilizers 1998.* Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1997) *Commercial Fertilizers 1997.* Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1996) *Commercial Fertilizers 1996.* Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1995) *Commercial Fertilizers 1995.* Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.AAPFCO (1995) *Commercial Fertilizers 1995.* Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AGA (1999, 2000) *Personal Communication with Paul Pierson* (telephone: 202-824-7133). American Gas Association, Washington, DC.

AGA (1998, 1999) *Gas Facts 1990-1999.* American Gas Association, Washington, DC.

ACC (2001) American Chemistry Council. Personal Communication with Emily Meyers. August.

Anderson, S. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Steve Anderson, Agricultural Statistician, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. 31 May.

API (1999) *Basic Petroleum Data Book.* American Petroleum Institute, Washington, DC.

Barnard, G.W. and L.A. Kristoferson (1985) *Agricultural Residues as Fuel in the Third World.* Technical Report No. 5. Earthscan, London, UK.

BEA (2000) Unpublished BE-36 survey data, Bureau of Economic Analysis (BEA), U.S. Department of Commerce.

BioCycle (2000) "12th Annual BioCycle Nationwide Survey: The State of Garbage in America," N. Goldstein, *BioCycle,* November.

Birdsey, R.A. and Heath, L.S. (1995) "Carbon Changes in U.S. Forests." In: *Productivity of America's Forests and Climate Change.* Gen. Tech. Rep. RM-271. Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Fort Collins, CO, pp. 56-70.

C&EN (2001) "Facts and figures in the chemical industry." *Chemical and Engineering News,* June 25, 2001.

California Air Resources Board (2001) *Progress Report on the Phase Down and the 1998-2000 Pause in the Phase Down of Rice Straw Burning in the Sacramento Valley Air Basin,* Proposed 2001 Report to the Legislature, June.

Carpenter, G.H. (1992) "Current Litter Practices and Future Needs." In: *1992 National Poultry Waste Management Symposium Proceedings,* Blake, J.P., Donald, J.O., and Patterson, P.H., (eds.), pp. 268-273, Auburn University Printing Service, Auburn, AL.

Deal, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Peter B. Deal, Rangeland Management Specialist, Florida Natural Resource Conservation Service, 21 June.

DESC (2001) Unpublished data from the Defense Fuels Automated Management System (DFAMS), Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense, Washington, DC.

DESC (2000) Unpublished data from the Defense Fuels Automated Management System (DFAMS), Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense, Washington, DC.

DOC (2000) Unpublished "Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries," Form-563, Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce.

DOE (1993 through 2001) *Transportation Energy Data Book.* Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory, ORNL-6959.

Donovan, K. and L. Baldwin (1999) Results of the AAMOLLY model runs for the Enteric Fermentation Model. University of California, Davis.

EIA (2001a) *Annual Energy Review 2000 and other EIA data.* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA- 0384(00)-annual.

EIA (2000b) *Emissions of Greenhouse Gases in the United States 1999.* Energy Information Administration, U.S. Department of Energy, Washington, DC. Draft. October 5, 1999, DOE/EIA-0535(99)-annual.

EIA (2000c) *Fuel Oil and Kerosene Sales 1999.* Energy Information Administration, U.S. Department of Energy, Washington, DC, DOE/EIA-0535(99)-annual.

EIA (2000d) *Natural Gas Annual 1999*, DOE/EIA 0131(99)-annual, Energy Information Administration, U.S. Department of Energy, Washington, DC. October 2000.

EIA (2000e) *U.S. Coal Supply and Demand: 1999 Review*, U.S. Department of Energy, Energy Information Administration, Washington, DC, Table 1.

EIA (1999a) *Coal Industry Annual 1991-1998*. U.S. Department of Energy, Energy Information Administration, Washington, DC, Table 3.

EIA (1999b) Form EIA-767 "Steam Electric Plant Operation and Design Report." U.S. Department of Energy, Energy Information Administration. Washington, DC.

EIA (1998) *Manufacturing Energy Consumption Survey (MECS)* U.S. Department of Energy, Energy Information Administration, Washington D.C. Available online at <http://www.eia.doe.gov/emeu/mecs/mecs98/datatables/contents.html.>

EPA (2000a) *Mobile6 Vehicle Emission Modeling Software*. U.S. Environmental Protection Agency, Office of Mobile Sources, EPA. Ann Arbor, Michigan.

EPA (2000b) *National Air Pollutant Emissions Trends Report, 1900-1999*, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

EPA (1999) *Characterization of Municipal Solid Waste in the US: 1998 Update*. U.S. Environmental Protection Agency, Washington, DC.

EPA (1997) *Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment*. United States Environmental Protection Agency, Office of Policy, Planning, and Evaluation. EPA-600/R-97-091, Washington, DC, September, 1997.

EPA (1993) Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to Congress. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC.

EPA, DOE (2001) *Fuel Economy 2001 Datafile*. U.S. Environmental Protection Agency, Department of Energy. Washington, DC, dataset 01guide0918. (Available on the internet at <http://www.fueleconomy.gov/feg/download.shtml>.)

ERG (2000) Calculations: Percent Distribution of Manure for Waste Management Systems. August.

Eve, M.D., Paustian, K., Follett, R., and Elliott, E.T. (2001) "An Inventory of Carbon Emissions and Sequestration in U.S. Cropland Soils." In: Lal, R. and McSweeney, K. (eds.) *Soil Carbon Sequestration and the Greenhouse Effect*. SSSA Special Publication, Madison, WI (in press).

Eve, M.D., Paustian, K., Follett, R., and Elliott, E.T. (2000) "A National Inventory of Changes in Soil Carbon from National Resources Inventory Data." In: Lal, R., Kimble, J.M., Follett, R.F., and Stewart, B.A. (eds.) *Assessment Methods for Soil Carbon*. Lewis Publishers, Boca Raton, FL.

FAO (2001). FAOSTAT Statistical Database. Food and Agriculture Organization of the United Nations. <http://apps.fao.org.>

FAO (2000) *FAOSTAT Statistical Database*, United Nations Food and Agriculture Organization. (Available on the Internet at <http://apps.fao.org/lim500/nph-wrap.pl?FoodBalanceSheet&Domain=FoodBalanceSheet> (Accessed July 25, 2000)).

FHWA (1996 through 2001) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation. Washington, DC, report FHWA-PL-96-023-annual.

FHWA (1999) *Draft 1998 Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation. Washington, DC, report FHWA-PL-96-023-annual.

Freedonia Group, Inc. (2000) *Report 1091: Industrial Gases To 2003, Record 4, Carbon Dioxide Shipments and Production, 1989-2009*. Cleveland, OH.

Gjestland, H. and D. Magers (1996) "Practical Usage of Sulphur [Sulfur] Hexafluoride for Melt Protection in the Magnesium Die Casting Industry," #13, *1996 Annual Conference Proceedings*, Ube City, Japan, International Magnesium Association.

Guethle, D. (2001) Telephone conversation between Caren Mintz of ICF Consulting and David Guethle, Agronomy Specialist at Missouri Cooperative Extension Service, 4 September.

Heath, L.S., Birdsey, R.A., Row, C., and Plantinga, A.J. (1996) "Carbon Pools and Fluxes in U.S. Forest Products." In: Apps, M.J. and Price, D.T. (eds.) *Forest Ecosystems, Forest Management and the Global Carbon Cycle*. Springer-Verlag, Berlin, pp. 271-278.

IPAA (1999) *The Oil & Gas Producing Industry in Your State 1990-1999*. Independent Petroleum Association of America.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, Montreal, IPCC-XVI/Doc. 10 (1.IV.2000), May 2000.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Johnson, Dan (2000) Telephone conversation between Lee-Ann Tracy of ERG and Dan Johnson, State Water Management Engineer, California Natural Resource Conservation Service, 23 June.

Johnson, D. (1999) Personal Communication, Colorado State University, Fort Collins, 1999.

Ketzis, J. (1999) Telephone and Email conversations between Marco Alcaraz of ICF Consulting and Jen Ketzis regarding the Animal Science Department Computer Model, Cornell University, June/July.

Lange, J. (2000) Telephone conversation between Lee-Ann Tracy of ERG and John Lange, Agricultural Statistician, U. S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC, 8 May.

Martin, J. (2000) "A Comparison of the Performance of Three Swine Waste Stabilization Systems," paper submitted to Eastern Research Group, Inc. October, 2000.

Metcalf and Eddy, Inc. (1991) *Wastewater Engineering: Treatment, Disposal, and Reuse*, Third Edition, McGraw-Hill Publishing Company, NY.

Miller, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Paul Miller, Iowa Natural Resource Conservation Service, 12 June.

Milton, B. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Bob Milton, Chief of Livestock Branch, U.S. Department of Agriculture, National Agriculture Statistics Service, 1 May.

Najita, T. (2000) Telephone conversation between Payton Deeks of ICF Consulting and Theresa Najita, Air Pollution Specialist, California Air Resouces Board, 17 August.

Nowak, D.J. and Crane, D.E. (2001) "Carbon Storage and Sequestration by Urban Trees in the United States." *Environmental Pollution* 116(3): 381-389.

NRCS (2000) *1997 National Resources Inventory*, Natural Resources Conservation Service, Washington, DC. (data also available online at <http://www.nhq.nrcs.usda.gov/NRI/1997/intro.html>).

OPS (2001). Natural Gas Transmission Pipeline Annual Mileage. Office of Pipeline Safety, Department of Transportation. Washington, DC. (Available on the Internet at http://ops.dot.gov/stats/gtannual.pdf.)

Poe, G., Bills, N., Bellows, B., Crosscombe, P., Koelsch, R., Kreher, M., and Wright, P. (1999) Staff Paper *Documenting the Status of Dairy Manure Management in New York: Current Practices and Willingness to Participate in Voluntary Programs*, Department of Agricultural, Resource, and Managerial Economics, Cornell University, Ithaca, New York, September.

Powell, D.S., Faulkner, J.L., Darr, D.R., Zhu, Z., and MacCleery, D.W. (1993) *Forest Resources of the United States, 1992*. Gen. Tech. Rep. RM-234. Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Fort Collins, CO, 132 pp.

Radian (1996a) *Methane Emissions from the Natural Gas Industry, V7: Blow and Purge Activities*. Prepared for the Gas Research Institute and EPA. April 1996.

Radian (1996b) *Methane Emissions from the Natural Gas Industry, V11: Compressor Driver Exhaust*. Prepared for GRI and EPA. April 1996.

Radian (1996c) *Methane Emissions from the Natural Gas Industry, V12: Pneumatic Devices*. Prepared for GRI and EPA. April 1996.

Radian (1996d) *Methane Emissions from the Natural Gas Industry, V13: Chemical Injection Pumps*. Prepared for GRI and EPA. April 1996.

Radian (1996e) *Methane Emissions from the US Petroleum Industry*. Draft. Prepared for GRI and EPA. June 1996.

RAND (2000) Katie D. Smythe, RAND Environmental Science and Policy Center, "Production and Distribution of $SF_6$ by End-Use Application," November, 2000.

Safley (2000) Telephone conversation between Deb Bartram of ERG and L.M. Safley, President, Agri-Waste Technology, June and October.

Safley, L.M., Jr. and P.W. Westerman (1998) "Anaerobic Lagoon Biogas Recovery Systems." *Biological Wastes*. 27:43-62.

Safley, L.M., Jr. and P.W. Westerman (1992) "Performance of a Low Temperature Lagoon Digester." *Biological Wastes*. 9060-8524/92/S05.00.

Safley, L.M., Jr. and P.W. Westerman (1990) "Psychrophilic Anaerobic Digestion of Animal Manure: Proposed Design Methodology." *Biological Wastes*. 34:133-148.

Skog, K.E., and G.A. Nicholson (1998) "Carbon cycling through wood products: the role of wood and paper products in carbon sequestration." *Forest Products Journal* 48:75-83.

Smith, W.B., et al. (2000) *1997 Forest Resource Statistics Review Draft*. USDA Forest Service. In review.

Smith, W.B. and Sheffield, R.M. (2000) *1997 RPA Assessment: The United States Forest Resource Current Situation (Final Statistics)*. Forest Service, U.S. Department of Agriculture. July 2000 Review Draft. Downloaded from <http://www.srsfia.usfs.msstate.edu/wo/review.htm>.

Stettler, D. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Don Stettler, Environmental Engineer, National Climate Center, Oregon Natural Resource Conservation Service, 27 June.

Street, J. (2001) Telephone conversation between Caren Mintz of ICF Consulting and Dr. Joe Street, Mississippi State University, Delta Research and Extension Center and Delta Branch Station, 3 October.

Strehler, A. and Stützle, W. (1987) "Biomass Residues". In: *Biomass,* Hall, D.O. and Overend, R.P. (eds.), pp. 75-102, John Wiley and Sons, Ltd. Chichester, UK.

Sweeten, J. (2000) Telephone conversation between Indra Mitra of ERG and John Sweeten, Texas A&M University, June 2000.

Tepordei, V. V. (2001) "Crushed Stone," In: *Minerals Yearbook 1999.* U.S. Department of the Interior/U.S. Geological Survey, Washington, DC. (Available at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/630499.pdf>) Accessed August 2001.

Tepordei, V. V. (2000) "Crushed Stone," In: *Minerals Yearbook 1998.* U.S. Department of the Interior/U.S. Geological Survey, Washington, DC. (Available at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/630498.pdf>) Accessed August 2000.

TVA (1994) Commercial Fertilizers 1994. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1993) Commercial Fertilizers 1993. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1992) Commercial Fertilizers 1992. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1991) Commercial Fertilizers 1991. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1990) Commercial Fertilizers 1991. Tennessee Valley Authority, Muscle Shoals, AL.

Turn, S.Q., Jenkins, B.M., Chow, J.C., Pritchett, L.C., Campbell, D., Cahill, T., and Whalen, S.A. (1997) "Elemental characterization of particulate matter emitted from biomass burning: Wind tunnel derived source profiles for herbaceous and wood fuels." *Journal of Geophysical Research* 102 (D3): 3683-3699.

UEP (1999) Voluntary Survey Results - Estimated Percentage Participation/Activity, Caged Layer Environmental Management Practices, Industry data submissions for EPA profile development, United Egg Producers and National Chicken Council. Received from John Thorne, Capitolink. June 2000.

U.S. Census Bureau (2000) *Monthly Estimates of the United States Population: April 1, 1980 to July 1, 1999,* Population Estimates Program, Population Division, U.S. Census Bureau, Washington, DC. (Available on the Internet at <http://www.census.gov/population/estimates/nation/intfile1-1.txt> (Accessed July 24, 2000).

U.S. Census Bureau (1997) *Vehicle Inventory and Use Survey.* U.S. Census Bureau. Washington, DC, database CD-EC97-VIUS. January 2000.

USDA (2001a). *Hogs and Pigs,* U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. June 29, 2001. Data also available from <http://jan.mannlib.cornell.edu/reports/nassr/livestock/php-bb/>.

USDA (2001b). *Livestock Slaughter,* U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 19, 2001. Data also available from <http://www.usda.gov/nass/pubs/reportname.htm#livestock-slaughter>.

USDA (2001c). *Milk Production,* U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. February 16, 2000. Data also available from <http://www.nass.usda.gov:81/ipedb/>.

USDA (2001d) *Crop Production 2000 Summary.* National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/>. Accessed July 2001.

USDA (2000a) *1997 National Resources Inventory.* U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

USDA (2000b) *Crop Production 1999 Summary.* National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC.

USDA (2000c) *Hogs and Pig,* U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. March 24. (Data also available from <http://www.nass.usda.gov:81/ipedb/>).

USDA (2000d) Re-aggregated data from the National Animal Health Monitoring System's (NAHMS) Dairy '96 study provided by Stephen L. Ott of the U.S. Department of Agriculture, Animal and Plant Health Inspection Service. June 19.

USDA (2000e) *Layers '99 – Part II: References of 1999 Table Egg Layer Management in the U.S.,* U.S. Department of Agriculture, Animal and Plant Health Inspection Service (APHIS), National Animal Health Monitoring System (NAHMS). January.

USDA (2000f) Published Estimates Database, U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC. Downloaded from <http://www.nass.usda.gov:81/ipedb/>. September 26.

USDA (1999) *Sheep and Goats - Final Estimates 1994-1998,* U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January.

USDA (1998a) *Hogs and Pigs - Final Estimates 1993-97,* U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. December. (Data also available from <http://www.nass.usda.gov:81/ipedb/>).

USDA (1998b) Re-aggregated data from the National Animal Health Monitoring System's (NAHMS) Swine '95 study aggregated by Eric Bush of the U.S. Department of Agriculture, Centers for Epidemiology and Animal Health.

USDA (1998c) *Field Crops Final Estimates 1992-97.* Statistical Bulletin Number 947 a. National Agricultural Statistics Service, U.S. Department of Agriculture. Available at <http://usda.mannlib.cornell.edu/>. Accessed July 2001.

USDA (1996a) *Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH)*, Part 651, U.S. Department of Agriculture, Natural Resources Conservation Service. July.

USDA (1996b) *Swine '95: Grower/Finisher Part II: Reference of 1995 U.S. Grower/Finisher Health & Management Practices*, U.S. Department of Agriculture, Animal Plant Health and Inspection Service, Washington, DC. June.

USDA (1994) *Field Crops: Final Estimates, 1987-1992.* Statistical Bulletin Number 896. National Agriculture Statistics Service, U.S. Department of Agriculture, GPO, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/data-sets/crops/94896/sb896.txt>.

USGS (2001a) *Mineral Industry Surveys*: Cement in December 2000. U.S. Geological Survey, Reston, VA.

USGS (2001b) *Mineral Yearbook: Lime Annual Report 2000.* U.S. Geological Survey, Reston, VA.

USGS (2001c) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the Fourth Quarter of 2000.* U.S. Geological Survey, Reston, VA.

USGS (2001d) *Minerals Yearbook: Soda Ash Annual Report 2000.* U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Crushed Stone Annual Report 1998.* U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Crushed Stone Annual Report 1994.* U.S. Geological Survey, Reston, VA.

Wright, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Peter Wright, Cornell University, College of Agriculture and Life Sciences, 23 June.

## Introduction

BEA (2000) *Survey of Current Business.* Bureau of Economic Analysis, Department of Commerce, Table 2A, p. 152, August. (Available on the internet at <http://www.bea.doc.gov/bea/dn/st-tabs.htm>.)

Duffield, Jim (2002) Telephone and Email conversation between Caren Mintz of ICF Consulting and Jim Duffield, Office of Energy Policy and New Uses, USDA, January.

EIA (2001) *Annual Energy Review 2000 and other EIA data.* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA- 0384(00)-annual.

EIA (2000a) *Electric Power Annual 1999: Volume III*, Energy Information Administration, U.S. Department of Energy, Washington, DC, October. <http://www.eia.doe.gov/cneaf/electricity/epav2/epav2.pdf>.

EIA (2000b) *Electric Power Annual 1999, Volume II*, Energy Information Administration, U.S. Department of Energy, Washington, D.C., DOE/EIA-0348(99)/2, October.

EIA (2000c) *Emissions of Greenhouse Gases in the United States 1999*, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0573(99) October.

EPA (2001) Unpublished data provided by U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

EPA (2000) *Characterization of Municipal Solid Waste in the United States: Source Data on the 1999 Update.* Report No. EPA530-F-00-024. U.S. Environmental Protection Agency, Office of Solid Waste, EPA. Washington, DC.

FCCC (1996) *Report of the Conference of the Parties, July 1996.* Addendum; Part Two: Action taken by the Conference of the Parties at its second session; Decision 9/CP.2, Communications from Parties included in Annex I to the Convention: guidelines, schedule and process for consideration; Annex: Revised Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention; p. 18.

IPCC (2001) *Climate Change 2001: A Scientific Basis*, Intergovernmental Panel on Climate Change; J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell, eds.; Cambridge University Press. Cambridge, U.K.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.* IPCC National Greenhouse Gas Inventories Programme Technical Support Unit, Kanagawa, Japan. Available online at <http://www.ipcc-nggip.iges.or.jp/gp/report.htm>.

IPCC (1999) *Aviation and the Global Atmosphere.* Intergovernmental Panel on Climate Change; Penner, J.E., et al., eds.; Cambridge University Press. Cambridge, U.K.

IPCC (1996) *Climate Change 1995: The Science of Climate Change.* Intergovernmental Panel on Climate Change; J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, eds.; Cambridge University Press. Cambridge, U.K.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Jacobson, M.Z. (2001) Strong Radiative Heating Due to the Mixing State ofBlack Carbon in Atmospheric Aerosols. Nature. In press.

Keeling, C.D. and T.P. Whorf (2000) *Atmospheric $CO_2$ records from sites in the SIO air sampling network.* In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. Oak Ridge, TN.

Keeling, C.D. and T.P. Whorf (1999) *A Compendium of Data on Global Change.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN. (Available on the internet at <http://cdiac.esd.ornl.gov/trends/co2/contents.htm>.)

NRCS (2000) *1997 National Resources Inventory*, Natural Resources Conservation Service, Washington, DC. (Data also available online at <http://www.nhq.nrcs.usda.gov/NRI/1997/intro.html>).

UNEP/WMO (2000) *Information Unit on Climate Change.* Framework Convention on Climate Change (Available on the internet at <http://www.unfccc.de>.)

U.S. Census Bureau (2000) Historical National Population Estimates: July 1, 1900 to July 1, 1999. Department of Commerce, Washington DC. June 28, 2000. (Available on the internet at <http://www.census.gov/population/estimates/nation/popclockest.txt>.)

USDA (1999) *1997 Census of Agriculture*, U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC. (Data also available online at <http://www.nass.usda.gov/census/>).

WMO (1999) *Scientific Assessment of Ozone Depletion, Global Ozone Research and Monitoring Project-Report No. 44*, World Meteorological Organization, Geneva, Switzerland.

# Energy

Marland, G., T.A. Boden, and R. J. Andres. 2001. Global, Regional, and National Fossil Fuel $CO_2$ Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A.

## Carbon Dioxide Emissions from Fossil Fuel Combustion

BEA (1991 through 2001) Unpublished BE-36 survey data. Bureau of Economic Analysis (BEA), U.S. Department of Commerce.

Bechtel (1993) *A Modified EPRI Class II Estimate for Low $NO_x$ Burner Technology Retrofit.* Prepared for Radian Corporation by Bechtel Power, Gaithersburg, Maryland. April.

DESC (2001) Unpublished data from the Defense Fuels Automated Management System (DFAMS), Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense, Washington, DC.

DOC (1991 through 2001) Unpublished "Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries." Form-563, Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce.

DOE (1993 through 2001) *Transportation Energy Data Book.* Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory, ORNL-6959.

DOE and EPA (1999) *Report to the President on Carbon Dioxide Emissions from the Generation of Electric Power in the United States*, U.S. Department of Energy and U.S. Environmental Protection Agency, 15 October.

DOT (1991 through 2001) *Fuel Cost and Consumption*, Federal Aviation Administration, U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, DC, DAI-10.

EIA (2001a) *Annual Energy Review 2000* and other EIA data. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA- 0384(00)-annual.

EIA (2001b) *Electric Power Annual 2000, Volume I.* Energy Information Administration, U.S. Department of Energy, Washington, DC, DOE/EIA-0348(00)/1-annual.

EIA (2001c) *Emissions of Greenhouse Gases in the United States 2000.* Energy Information Administration, U.S. Department of Energy, Washington, DC. November, DOE/EIA-0573(00)-annual.

EIA (2001f) *Natural Gas Annual 2000.* Energy Information Administration, U.S. Department of Energy, Washington, DC, DOE/EIA-0131(00)-annual.

EIA (1998) *U.S. Coal Supply and Demand: 1997 Review: by B.D. Hong.* Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA (1997 through 2001) *Short-Term Energy Outlook.* Energy Information Administration, U.S. Department of Energy, Washington, DC, DOE/EIA-0202- monthly. (Available on the internet at <http://www.eia.doe.gov/emeu/steo/pub/contents.html>.)

EIA (1997) *Manufacturing Consumption of Energy 1994*, Energy Information Administration, U.S. Department of Energy, Washington, DC, December, DOE/EIA-0512(94).

FAA (1995 through 2001) *FAA Aerospace Forecasts, Fiscal Years 2000-2012.* Federal Aviation Administration, U.S. Department of Transportation, Washington, DC. Table 30: General Aviation Aircraft Fuel Consumption. (Available on the internet at <http://www.api.faa.gov/foreca00/Tabofcont.html>.)

FRB (2001) "Industrial Production and Capacity Utilization," Federal Reserve Board, Federal Reserve Statistical Release, G.17, accessed 27 November 2001, < http://www.federalreserve.gov/Releases/G17/>.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Marland, G. and A. Pippin (1990) "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity." *Energy Systems and Policy*, 14(4):323.

N42 (2001) Unpublished data from the Naval Operations Navy Strategic Mobility/Combat Logistics Division, U.S. Department of Defense, Washington DC.

N45 (1998) Unpublished data from the *Chief of Naval Operations Flying Hour Projection System Budget Analysis Report for FY 1998*, Naval Operations Environmental Protection, Safety and Occupational Health Division, U.S. Department of Defense, Washington DC. NOAA (2000b)

NOAA (2000) U.S. Department of Commerce, National Oceanic and Atmospheric Administration. Heating and Cooling Degree Day Data. Available online at <http://lwf.ncdc.noaa.gov/oa/documentlibrary/hcs/hcs.html>.

USAF (1998) U.S. Air Force document AFPAM23-221, May 1, 1998.

U.S. Census Bureau (2000) Historical National Population Estimates: July 1, 1900 to July 1, 1999. Department of Commerce, Washington DC. June 28, 2000. (Available on the internet at <http://www.census.gov/population/estimates/nation/popclockest.txt>.)

## Carbon Stored in Products from Non-Energy Uses of Fossil Fuels

APC (2000) as reported in "Facts & Figures for the Chemical Industry," *Chemical and Engineering News,* Vol. 78 (26), June 26, 2000. American Plastics Council. Arlington, VA. Available online at <http://www.plasticsindustry.org/industry/stat3.htm>.

CMA (1999) *U.S. Chemical Industry Statistical Handbook.* Chemical Manufacturer's Association. Washington, DC.

Connolly, Una (2000) Personal communication between Suzanne Bratis of ICF Consulting and Una Connelly of National Asphalt Pavement Association. August 2000. (Tel: 859-288-4960).

EIA (2001a) *Annual Energy Review 1999.* DOE/EIA-0384(00)- Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA (2001b) *Manufacturing Energy Consumption Survey (MECS)* U.S. Department of Energy, Energy Information Administration, Washington D.C. Available online at <http://www.eia.doe.gov/emeu/mecs/mecs98/datatables/contents.html.>

EIA (2001c) *Petroleum Supply Annual 2000.* Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA (2000) *Annual Energy Review 1998.* DOE/EIA-0384(99)- unpublished full table presentation (table 1.15), Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIIP (1999) *Methods for Estimating Greenhouse Gas Emissions from Combustion of Fossil Fuels,* Emissions Inventory Improvement Program: State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officials and U.S. Environmental Protection Agency, EIIP Document Series Volume VIII, Chapter 1. (STAPPA/ALAPCO/EPA), Washington DC, August 2000. <http://www.epa.gov/ttn/chief/eiip/viii01.pdf> (Accessed August 28, 2000).

EIIP (1998) "Area Sources" *Asphalt Paving,* Emissions Inventory Improvement Program: State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officials and U.S. Environmental Protection Agency, EIIP Document Series Volume III, Chapter 17. (STAPPA/ALAPCO/EPA), Washington DC, August 2000. <http://www.epa.gov/ttn/chief/eiip/iii17.pdf> (Accessed July 27, 2000).

Eldredge-Roebuck (2000) Personal communication between Joe Casola of ICF Consulting and Brandt Eldredge-Roebuck of the American Plastics Council. July, 11 2000. (Tel: 703-253-0611).

EPA (2000a) *Biennial Reporting System (BRS).* U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, DC. Available online at <http://www.epa.gov/enviro/html/brs/brs_query.html>.

EPA (2000b) *National Air Quality and Emissions Trends Report, 1900-1999.* U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

EPA (2000c) *Toxics Release Inventory, 1998.* U.S. Environmental Protection Agency, Office of Environmental Information, Office of Information Analysis and Access, Washington, DC. Available online at <http://www.epa.gov/triexplorer/chemical.htm>.

EPA (2000d) *Hot Mix Asphalt Plants Emission Assessment Report (Draft Report), AP-42.* U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, June. <http://www.epa.gov/ttn/emc/asphalt/ea-report.pdf> (Accessed July 25, 2000).

EPA (1999) *Pesticides Industry Sales and Usage: 1996 and 1997 Market Estimates.* U.S. Environmental Protection Agency, Office of Prevention, Pesticides and Toxic Substances, Washington, DC.

EPA (1995) *Asphalt Paving Operations, AP-42*, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

FEB (2000) as reported in "Facts & Figures for the Chemical Industry," *Chemical and Engineering News,* Vol. 78 (26), June 26, 2000. Fiber Economics Bureau. Washington, DC. Available online at <http://www.fibersource.com/f-info/fiber%20production.htm>.

IISRP (2000) as reported in "Facts & Figures for the Chemical Industry," *Chemical and Engineering News,* Vol. 78 (26), June 26, 2000. International Institute of Synthetic Rubber Producers. Houston, Texas. Available online in IISRP's February 18, 2000, News Release: <http://www.iisrp.com/Press%20Releases/2000%20Press%20Releases/ASPR2000-2004.PDF>.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

James, Alan (2000) Personal communication between Suzanne Bratis of ICF Consulting and Alan James of Akzo Nobel Coatings, Inc. July 2000. (Tel: 614-294-3361).

Kelly, Peter (2000) Personal communication between Tom Smith of ICF Consulting and Peter Kelly of Asphalt Roofing Manufacturers Association. August 2000. (Tel: 301-348-2002).

U.S. Census Bureau (1999) 1997 Economic Census, Manufacturing - Industry Series, Petroleum Lubricating Oil and Grease Manufacturing, document number EC97M-3241D, and Petroleum Refining, document number EC97M-3241A (2 reports).

NPRA (2001) *Selected Petrochemical Statistics – U.S. Trade, Production and Consumption.* National Petrochemical & Refiners Association, Washington, DC.

Marland, G. and Rotty, R.M. (1984) "Carbon dioxide emissions from fossil fuels: a procedure for estimation and results for 1950-1982." *Tellus.* 36B, 4, 232-261.

Rinehart, T. (2000) Personal communication between Thomas Rinehart of U.S. Environmental Protection Agency, Office of Solid Waste, and Randall Freed of ICF Consulting. July 2000. (Tel: 703-308-4309).

## Stationary Combustion (excluding $CO_2$)

EIA (2001) *Annual Energy Review 2000* and other EIA data. Energy Information Administration, U.S. Department of Energy, Washington, DC, DOE/EIA-0384(00)-annual.

EPA (2001) Unpublished data provided by Emission Factors and Inventory Group, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

## Mobile Combustion (excluding $CO_2$)

Barton, Peter and Jackie Simpson (1994) "The effects of aged catalysts and cold ambient temperatures on nitrous oxide emissions." Mobile Source Emissions Division (MSED), Environment Canada, MSED Report #94-21.

BEA (1991 through 2001) Unpublished BE-36 survey data. Bureau of Economic Analysis (BEA), U.S. Department of Commerce.

Dasch, Jean Muhlbaler (1992) *Journal of the Air and Waste Management Association.* "Nitrous Oxide Emissions from Vehicles," 42(1):63-67, January.

DESC (2001) Unpublished data from the Defense Fuels Automated Management System (DFAMS), Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense, Washington, DC.

DOC (1991 through 2001) Unpublished "Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries." Form-563, Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce.

DOE (1993 through 2001) *Transportation Energy Data Book.* Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory, ORNL-6959.

DOT (1991 through 2001) *Fuel Cost and Consumption,* Federal Aviation Administration, U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, DC, DAI-10.

EIA (2001a) *Annual Energy Review 2000* and other EIA data. Energy Information Administration, U.S. Department of Energy, Washington, DC, DOE/EIA-0384(00)-annual.

EIA (2001b) *Emissions of Greenhouse Gases in the United States 2000.* Energy Information Administration, U.S. Department of Energy, Washington, DC. November, DOE/EIA-0573(00)-annual.

EIA (2001c) *International Energy Annual 1999,* "World Petroleum Supply and Disposition, 1998" <http://www.eia.doe.gov/iea/pet.html>. Table 3.1.

EIA (2001e) Personal Communication with Joel Lou. Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island.

EIA (1991-2001) *Fuel Oil and Kerosene Sales 2000.* Energy Information Administration, U.S. Department of Energy, Washington, DC, DOE/EIA-0535(00)-annual.

EPA (2001) Unpublished data provided by Emission Factors and Inventory Group, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC.

EPA (2000) *Mobile6 Vehicle Emission Modeling Software.* Office of Mobile Sources, U.S. Environmental Protection Agency. Ann Arbor, Michigan.

EPA (1999) *Emission Facts: The History of Reducing Tailpipe Emissions.* Office of Mobile Sources, May, EPA 420-F-99-017. (Available on the internet at <http://www.epa.gov/oms/consumer/f99017.pdf>)

EPA (1998) *Emissions of Nitrous Oxide from Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-1996.* Office of Mobile Sources, Assessment and Modeling Division, U.S. Environmental Protection Agency, August, EPA420-R-98-009. (Available on the internet at <http://www.epa.gov/oms/climate.htm>.)

EPA (1997) *Mobile Source Emission Factor Model (MOBILE5a).* Office of Mobile Sources, U.S. Environmental Protection Agency. Ann Arbor, Michigan.

EPA (1994a) *Automobile Emissions: An Overview.* Office of Mobile Sources, August, EPA 400-F-92-007. (Available on the internet at <http://www.epa.gov/otaq/05-autos.htm>.)

EPA (1994b) *Milestones in Auto Emissions Control.* Office of Mobile Sources, August, EPA 400-F-92-014. (Available on the internet at <http://www.epa.gov/otaq/12-miles.htm>.)

EPA (1993) *Automobiles and Carbon Monoxide.* Office of Mobile Sources, January, EPA 400-F-92-005. (Available on the internet at <http://www.epa.gov/otaq/03-co.htm>.)

EPA, DOE (2001) *Fuel Economy 2001 Datafile.* U.S. Environmental Protection Agency, Department of Energy. Washington, DC, dataset 01guide0918. (Available on the internet at <http://www.fueleconomy.gov/feg/download.shtml>.)

FAA (1995 through 2001) *FAA Aerospace Forecasts, Fiscal Years 2000-2012.* Federal Aviation Administration, U.S. Department of Transportation, Washington, DC. Table 30: General Aviation Aircraft Fuel Consumption. (Available on the internet at <http://www.api.faa.gov/foreca00/Tabofcont.html>.)

FHWA (1996 through 2001) *Highway Statistics.* Federal Highway Administration, U.S. Department of Transportation. Washington, DC, report FHWA-PL-96-023-annual.

ICF (2001) *Revised U.S. VMT estimates and $N_2O$ emission factors.* Memorandum from ICF Consulting to Ed Coe, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. December 2001.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Prigent, Michael and Gerard De Soete (1989) "Nitrous oxide ($N_2O$) in engines exhaust gases—a first appraisal of catalyst impact," Society of Automotive Engineers, SAE Paper 890492.

Smith, Lawrence R. and Penny M. Carey (1982) "Characterization of exhaust emissions from high mileage catalyst-equipped automobiles," Society of Automotive Engineers, SAE Paper 820783.

Urban, Charles M. and Robert J. Garbe (1980) "Exhaust Emissions from Malfunctioning Three-Way Catalyst-Equipped Automobiles," Society of Automotive Engineers, SAE Paper 800511.

U.S. Census Bureau (1997) *Vehicle Inventory and Use Survey.* U.S. Census Bureau. Washington, DC, database CD-EC97-VIUS. January 2000.

Weaver, Christopher S. and Lit-Mian Chan (1996) "Mobile source emission factors for global warming gases," Draft Final Report, 24 June, submitted to ICF, Inc. by Engine, Fuel, and Emissions Engineering, Inc., Sacramento, CA.

## Coal Mining

EIA (2001) Personal Communication on August 29, 2001, U.S. Department of Energy, Energy Information Administration, Washington, DC.

EIA (2000) *Coal Industry Annual 1991-1999.* U.S. Department of Energy, Energy Information Administration, Washington, DC, Table 3.

EPA (1990) *Methane Emissions from Coal Mining: Issues and Opportunities for Reduction.* U.S. Environmental Protection Agency, Air and Radiation, September.

Mutmansky, Jan M. and Yanebi Wang (2000) *Analysis of Potential Errors in Determination of Coal Mine Annual Methane Emissions,* Mineral Resources Engineering, Vol. 9, No. 4, December 2000.

## Natural Gas Systems

AGA (1991-1999) *Gas Facts.* American Gas Association, Washington, DC.

DOI (1998, 1999, 2000, 2001) *Offshore Development Activity.* U.S. Department of Interior, Minerals Management Service Internet site. (Available on the Internet at <http://www.mms.gov>.)

EIA (2001). *Natural Gas Monthly,* Energy Information Administration, U.S. Department of Energy. Washington, DC. (Available on the Internet at <http://www.eia.doe.gov>.)

EIA (2001) *Natural Gas Annual 1999*. Energy Information Administration, U.S. Department of Energy. Washington, DC. (Available on the Internet at <http://www.eia.doe.gov>.)

EPA/GRI (1996) *Methane Emissions from the Natural Gas Industry, Volume 1: Executive Summary*. Prepared by Harrison, M., T. Shires, J. Wessels, and R. Cowgill, eds. Radian International LLC for National Risk Management Research Laboratory, Air Pollution Prevention and Control Division, Research Triangle Park, NC, EPA-600/R-96-080a.

GSAM (1997) Gas Systems Analysis Model. Federal Energy Technology Center, U.S. Department of Energy. Washington, DC.

IPAA (1998, 1999, 2000) *The Oil & Gas Producing Industry in Your State*. Independent Petroleum Association of America.

OPS (2001a). Natural Gas Transmission Pipeline Annual Mileage. Office of Pipeline Safety, Department of Transportation. Washington, DC. (Available on the Internet at <http://ops.dot.gov/stats/gtannual.pdf.>)

OPS (2001b). Natural Gas Distribution Annuals Data. Office of Pipeline Safety, Department of Transportation. Washington, DC. (Available on the Internet at <http://ops.dot.gov/DT98.htm>.)

PennWell Corporation (1999, 2000, 2001) *Oil & Gas Journal*. PennWell Corporation, Tulsa, OK.

## Petroleum Systems

API (1999) *Basic Petroleum Data Book*. American Petroleum Institute, Washington, DC.

API (1997 and 1999) *Basic Petroleum Data Book*. American Petroleum Institute, Washington, DC.

API (1996) *Calculation Workbook for Oil and Gas Production Equipment Fugitive Emissions*. American Petroleum Institute; Publication No. 4638.

API and GRI. *E&P Tank Software Package*, Version 1.0.

CAPP (1993) *Options for Reducing Methane and VOC Emissions from Upstream Oil & Gas Operations*. Canadian Association of Petroleum Producers, Canada.

CAPP (1992) *A Detailed Inventory of $CH_4$ and VOC Emissions From Upstream Oil & Gas Operations in Alberta*. Canadian Association of Petroleum Producers, Canada. Vols. 1-3. March 1992.

DOS (1997) *Climate Action Report: 1997 Submission of the United States of America under the United Nations Framework Convention on Climate Change*. U.S. Department of State, Washington, DC.

Doud, Ted. Personal communication. Pipeline Systems Incorporated, Walnut Creek, California.

EIA (2001) *Monthly Energy Review*. Energy Information Administration, U.S. Department of Energy, Washington, DC. (Available on the Internet at <www.eia.doe.gov/emeu/mer>.)

EIA (2001) *Annual Energy Review*. Energy Information Administration, U.S. Department of Energy, Washington, DC. (Available on the Internet at <www.eia.doe.gov/emeu/mer>.)

EIA (2001) *Petroleum Supply Annual 1990-2000*. Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA (1998) *U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, Annual Report 1990-1997*. Energy Information Administration, U.S. Department of Energy, Washington, DC.

Energy Resources Company (1977) *Atmospheric Emissions from Offshore Oil and Gas Production and Development*. Prepared for EPA. June 1977.

Entropy Limited (1989) *Aboveground Storage Tank Survey*. Prepared for the American Petroleum Institute. April 1989.

EPA (1999) *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report)*. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC.

EPA (1997) *Installing Vapor Recovery Units on Crude Oil Storage Tanks*. Natural Gas STAR Program, draft Lessons Learned. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC.

EPA (1996) *Best Management Practice III*. Natural Gas STAR 1996 Workshop and Implementation Guide, Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC.

EPA (1995) *Compilation of Air Pollution Emission Factors*. Office of Air and Radiation, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. AP-42.

EPA (1993a) *Anthropogenic Methane Emissions in the US: Estimates for 1990, Report to Congress*. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC.

EPA (1993b) *Opportunities to Reduce Anthropogenic Methane Emissions in the United States, Report to Congress*. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC.

Gallagher, T. (1999) Personal Communication. Chicago Bridge and Iron. July 1999.

ICF Kaiser International (1996) *Estimation of Activity Factors for the Natural Gas Exploration and Production Industry in the United States*. Prepared for the Environmental Protection Agency. August 1996.

MMS (1999) Personal communication on 8/31/99. Minerals Management Service, U.S. Department of the Interior, New Orleans, LA.

MMS (1995) *Gulf of Mexico Air Quality Study*. Final Report. Minerals Management Service, U.S. Department of the Interior, Washington, DC.

ODS (1999) Personal communication on 9/21/99. Offshore Data Services, Houston. TX.

OGJ (2000a) *Oil and Gas Journal 1990-1998*, Pipeline Economics Issue, late August.

OGJ (2000b) *Oil and Gas Journal 1990-1998*, Worldwide Refining Issue, late December.

Pipeline Systems Incorporated (1989) *Annual Methane Emission Estimate of the Natural Gas and Petroleum Systems in the US*. Prepared for ICF Incorporated, Washington, DC.

Radian (1996a) *Methane Emissions from the Natural Gas Industry, V7: Blow and Purge Activities*. Prepared for the Gas Research Institute and EPA. April 1996.

Radian (1996b) *Methane Emissions from the Natural Gas Industry, V11: Compressor Driver Exhaust*. Prepared for GRI and EPA. April 1996.

Radian (1996c) *Methane Emissions from the Natural Gas Industry, V12: Pneumatic Devices*. Prepared for GRI and EPA. April 1996.

Radian (1996d) *Methane Emissions from the Natural Gas Industry, V13: Chemical Injection Pumps*. Prepared for GRI and EPA. April 1996.

Radian (1996e) *Methane Emissions from the US Petroleum Industry*. Draft. Prepared for GRI and EPA. June 1996.

Radian (1996f) *Methane and Carbon Dioxide Emissions Estimate From U.S. Petroleum Sources*. Prepared for API. July 1996.

Radian (1992) *Global Emissions of Methane from Petroleum Sources (#DR 140)*. Prepared for American Petroleum Institute, Washington, DC.

Radian (1977) *Revision of Emission Factors for Petroleum Refining*. Prepared for EPA. October 1977.

Rayman, Ron (1997) Personal communication. Dresser Texsteam, Houston, Texas (manufacturer of chemical injection pumps).

Star Environmental (1996) *Calculation Workbook for Oil and Gas Production Equipment Fugitive Emissions*. Prepared for API. API Document No. 4638. July 1996.

Star Environmental (1994) *Emission Factors for Oil & Gas Operations*. Prepared for API. API Document No. 4615. December 1994.

Star Environmental (1993) *Fugitive Hydrocarbon Emissions from Oil and Gas Production Operations*. Prepared for API. API Document No 4589. December 1993.

True, W. R. (1996) "U.S. Pipelines Continue Gains into 1996." *Oil & Gas Journal*, 25 November 1996: 39-58.

United States Army Corps of Engineers (1995, 1996, and 1997) *Waterborne Commerce of the United States 1995, Part 5: National Summaries*. U.S. Army Corps of Engineers, Washington, DC.

## Waste Combustion

APC (2000) as reported in "Facts & Figures for the Chemical Industry," *Chemical and Engineering News*, Vol. 78 (26), June 26, 2000. American Plastics Council. Arlington, VA. Available online at <http://www.plasticsindustry.org/industry/stat3.htm>.

BioCycle (2000) "12th Annual BioCycle Nationwide Survey: The State of Garbage in America, Part I" Nora Goldstein, *BioCycle*, April 2000. JG Press, Emmaus, PA.

De Soete, G. G. (1993) *Nitrous Oxide from Combustion and Industry: Chemistry, Emissions and Control*. In Van Amstel, A. R. (ed) Proc. of the International Workshop Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control, Amersfoort (NL) 3-5 February.

DeZan, D. (2000) Personal communication between Diane DeZan of the Fiber Economics Bureau and Joe Casola of ICF Consulting, August 4, 2000.

Eldredge-Roebuck, B. (2000) Personal communication between Brandt Eldredge-Roebuck of the American Plastics Council and Joe Casola of ICF Consulting, July 11, 2000.

EPA (2000a) *Biennial Reporting System (BRS)*. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, DC. Available online at <http://www.epa.gov/enviro/html/brs/brs_query.html>.

EPA (2000b) *Characterization of Municipal Solid Waste in the United States: 1999 Update Fact Sheet*. Report No. EPA530-F-00-024. U.S. Environmental Protection Agency, Office of Solid Waste, EPA. Washington, DC.

EPA (2000c) *Characterization of Municipal Solid Waste in the United States: Source Data on the 1999 Update*. Report No. EPA530-F-00-024. U.S. Environmental Protection Agency, Office of Solid Waste, EPA. Washington, DC.

EPA (1999) *Characterization of Municipal Solid Waste in the United States: 1998 Update*. Report No. EPA530-R-99-021. U.S. Environmental Protection Agency, Office of Solid Waste, EPA. Washington, DC.

EPA (1998) Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Resposne, Washington, DC, EPA530-R-98-013.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC. October.

FEB (2000) as reported in "Facts & Figures for the Chemical Industry," *Chemical and Engineering News,* Vol. 78 (26), June 26, 2000. Fiber Economics Bureau. Washington, DC. Available online at <http://www.fibersource.com/f-info/fiber%20production.htm>.

Glenn, Jim (1999) "11th Annual BioCycle Nationwide Survey: The State of Garbage in America." *BioCycle,* April 1999. JG Press, Emmaus, PA.

IISRP (2000) as reported in "Facts & Figures for the Chemical Industry," *Chemical and Engineering News,* Vol. 78 (26), June 26, 2000. International Institute of Synthetic Rubber Producers. Houston, Texas. Available online in IISRP's February 18, 2000, News Release: <http://www.iisrp.com/Press%20Releases/2000%20Press%20Releases/ASPR2000-2004.PDF>.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Marland, G. and Rotty, R.M. (1984) "Carbon dioxide emissions from fossil fuels: a procedure for estimation and results for 1950-1982." *Tellus.* 36B, 4, 232-261.

Olivier, J. G. J. (1993) *Working Group Report: Nitrous Oxide Emissions from Fuel Combustion and Industrial Processes.* In Van Amstel, A. R. (ed) Proc. Of the International Workshop Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control, Amersfoort (NL), 3-5 February.

STMC (2000) *Scrap Tire Facts and Figures.* Scrap Tire Management Council of the Rubber Manufacturers Association. Washington, DC. Downloaded from <http://www.rma.org/scrapfctn.html> July 26, 2000.

STMC (1999) *Scrap Tire Use/Disposal Study 1998/1999 Update Executive Summary.* Scrap Tire Management Council of the Rubber Manufacturers Association. Washington, DC. Published September 15, 1999. Downloaded from http://www.rma.org/excsumn.html, July 26, 2000.

Watanabe, M., Sato, M., Miyazaki, M. and Tanaka, M. (1992) *Emission Rate of $N_2O$ from Municipal Solid Waste Incinerators.* NIRE/IFP/EPA/SCEJ 5th International Workshop on $N_2O$ Emissions, July 1-3, 1992. Tsukuba, Japan, Paper 3-4.

## Natural Gas Flaring and Ambient Air Pollutant Emissions from Oil and Gas Activities

Barns, D. and Edmonds, J. (1990) "An Evaluation of the Relationship Between the Production and Use of Energy and Atmospheric Methane Emissions." DOE/NBB-0088P. Pacific Northwest Laboratory. Richland, WA.

EIA (2001) *Natural Gas Annual 2000,* DOE/EIA 0131(99)-annual, Energy Information Administration, U.S. Department of Energy, Washington, DC. October 2001.

EPA (2001) Unpublished data provided by U.S. Environmental Protection Agency, Emission Factors and Inventory Group, Office of Air Quality Planning and Standards. Research Triangle Park, NC.

## International Bunker Fuels

BEA (1991 through 2001) Unpublished BE-36 survey data, Bureau of Economic Analysis (BEA), U.S. Department of Commerce.

DESC (2001) Unpublished data from the Defense Fuels Automated Management System (DFAMS), Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense, Washington, DC.

DOC (1991 through 2001) Unpublished "Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries," Form-563, Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce.

DOT (1991 through 2001) *Fuel Cost and Consumption,* Federal Aviation Administration, U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, DC, DAI-10.

EIA (2001) *Annual Energy Review 2000* and other EIA data. Energy Information Administration, U.S. Department of Energy. Washington, DC, DOE/EIA-0384(00)-annual.

EPA (2001) Unpublished data provided by Emission Factors and Inventory Group, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC.

FAA (1995 through 2001) *FAA Aerospace Forecasts, Fiscal Years 2000-2012.* Federal Aviation Administration, U.S. Department of Transportation, Washington, DC. Table 30: General Aviation Aircraft Fuel Consumption. (Available on the internet at <http://www.api.faa.gov/foreca00/Tabofcont.html>.)

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

NASA (1996) *Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis,* Prepared for Langley Research Center, NASA Contractor Report # 4700, April.

N42 (2001) Unpublished data from the Naval Operations Navy Strategic Mobility/Combat Logistics Division, U.S. Department of Defense, Washington DC.

N45 (1998) Unpublished data from the *Chief of Naval Operations Flying Hour Projection System Budget Analysis Report for FY 1998*, Naval Operations Environmental Protection, Safety and Occupational Health Division, U.S. Department of Defense, Washington DC.

USAF (1998) U.S. Air Force document AFPAM23-221, May 1, 1998.

### Wood Biomass and Ethanol Consumption

EIA (2001) *Annual Energy Review*. Energy Information Administration, U.S. Department of Energy. Washington, DC. July. Tables 10.2 and Tables 10.3. DOE/EIA-0384(98).

EIA (1997) *Renewable Energy Annual*. Energy Information Administration, U.S. Department of Energy. Washington, DC. March. DOE/EIA-0603(96).

EIA (1994) *Estimates of U.S. Biomass Energy Consumption 1992*. Energy Information Administration, U.S. Department of Energy. Washington, DC. May. DOE/EIA-0548(92).

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

OTA (1991) *Changing by Degrees: Steps to Reduce Greenhouse Gases*. Office of Technology Assessment, U.S. Government Printing Office. Washington, DC. February. OTA-0-482.

## Industrial Processes

### Cement Manufacture

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme.

IPCC (1996) *Climate Change 1995: The Science of Climate Change*, Intergovernmental Panel on Cliamte Change; J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, eds.; Cambridge University Press. Cambridge, U.K.

USGS (2001) *Mineral Industry Surveys*: Cement in December 2000. U.S. Geological Survey, Reston, VA.

USGS (2000) *Mineral Yearbook: Cement Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Mineral Yearbook: Cement Annual Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Cement Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Cement Annual Report 1996*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Cement Annual Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1995a) *Cement: Annual Report 1993*. U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC. June.

USGS (1995b) *Cement: Annual Report 1994*. U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC.

USGS (1992) *Cement: Annual Report 1990*. U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC. April.

### Lime Manufacture

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme.

Males, E. (2001) Personal communication between Eric Males of the National Lime Association and Wiley Barbour of the U.S. Environmental Protection Agency. Memorandum dated February 20, 2001.

USGS (2001) *Mineral Yearbook: Lime Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Mineral Yearbook: Lime Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Lime Annual Report 1998*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Lime Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Lime Annual Report 1996*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Lime Annual Report 1995*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Lime Annual Report 1994*. U.S. Geological Survey, Reston, VA.

USGS (1994) *Lime: Annual Report 1993*. U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC. September.

USGS (1992) *Lime: Annual Report 1991*. U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC. November.

### Limestone and Dolomite Use

EIA (1999) Form EIA-767 "Steam Electric Plant Operation and Design Report." U.S. Department of Energy, Energy Information Administration. Washington, DC.

EIA (1998) Form EIA-767 "Steam Electric Plant Operation and Design Report." U.S. Department of Energy, Energy Information Administration. Washington, DC.

EIA (1997) Form EIA-767 "Steam Electric Plant Operation and Design Report." U.S. Department of Energy, Energy Information Administration. Washington, DC.

USGS (2001) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the Fourth Quarter of 2000.* U.S. Geological Survey, Reston, VA.

USGS (2000) *Mineral Yearbook: Crushed Stone Annual Report 1999.* U.S. Geological Survey, Reston, VA.

USGS (1999) *Mineral Yearbook: Crushed Stone Annual Report 1998.* U.S. Geological Survey, Reston, VA.

USGS (1998) *Mineral Yearbook: Crushed Stone Annual Report 1997.* U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Crushed Stone Annual Report 1996.* U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Crushed Stone Annual Report 1995.* U.S. Geological Survey, Reston, VA.

USGS (1995a) *Crushed Stone: Annual Report 1993.* U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC. January.

USGS (1995b) *Crushed Stone: Annual Report 1994.* U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC.

USGS (1993) *Crushed Stone: Annual Report 1991.* U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC. March.

## Soda Ash Manufacture and Consumption

USGS (2001) *Minerals Yearbook: Soda Ash Annual Report 2000.* U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Soda Ash Annual Report 1999.* U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Soda Ash Annual Report 1998.* U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Soda Ash Annual Report 1997.* U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Soda Ash Annual Report 1996.* U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Soda Ash Annual Report 1995.* U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Soda Ash Annual Report 1994.* U.S. Geological Survey, Reston, VA.

USGS (1994) *Soda Ash: Annual Report 1993.* U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC. July.

## Carbon Dioxide Consumption

Freedonia Group, Inc. (2000) *Report 1091: Industrial Gases To 2003, Record 4, Carbon Dioxide Shipments and Production, 1989-2009.* Cleveland, OH.

Freedonia Group, Inc. (1999a) *Report 1091: Industrial Gases To 2003, Record 4, Carbon Dioxide Shipments and Production, 1989-2008.* Cleveland, OH.

Freedonia Group, Inc. (1999b) *Report 1091: Industrial Gases To 2003, Record 20, Enhanced Oil Recovery Applications for Carbon Dioxide, 1989-2008.* Cleveland, OH. Protection Agency, August.

Freedonia Group, Inc. (1996) *Carbon Dioxide Merchant Markets Report 1990-1995.* Cleveland, OH.

Freedonia Group, Inc. (1994) *Industry Study No. 564: Carbon Dioxide.* The Freedonia Group, Incorporated. Cleveland, OH.

Freedonia Group Inc. (1991) *Carbon Dioxide.* Business Research Report B286. Cleveland, OH, November, p. 46.

Hangebrauk, R.P., Borgwardt, R.H., and Geron, C.D. (1992) *Carbon Dioxide Sequestration.* U.S. Environmental.

Ita, Paul (1997) Personal communication between Heike Mainhardt of ICF, Inc. and Paul Ita of Freedonia Group, Inc. October. (Tel: 216/921-6800).

## Iron and Steel Production

AISI (2002) 2001 Annual Statistical Report, American Iron and Steel Institute, Washington, DC.

AISI (2001) 2000 Annual Statistical Report, American Iron and Steel Institute, Washington, DC.

AISI (1996) 1995 Annual Statistical Report, American Iron and Steel Institute, Washington, DC.

AISI (1995) 1994 Annual Statistical Report, American Iron and Steel Institute, Washington, DC.

DOE (1997) Office of Industrial Technologies - Energy and Environmental Profile of the US Aluminum Industry, July 1997.

EIA (2001) U.S. Coal, Domestic and International Issues, Energy Information Administration, U.S. Department of Energy, Washington, DC, March 2001.

EIA (2000) Quarterly Coal Report October-December 2000, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0121 (2000/4Q).

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, Montreal, IPCC-XVI/Doc. 10 (1.IV.2000), May 2000.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

USGS (2001) *Minerals Yearbook: Aluminum Annual Report 2000.* U.S. Geological Survey, Reston, VA.

USGS (2000a) *Minerals Yearbook: Iron and Steel Annual Report 1999.* U.S. Geological Survey, Reston, VA.

USGS (2000b) *Minerals Yearbook: Aluminum Annual Report 1999.* U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Iron and Steel Annual Report 1998.* U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Aluminum Annual Report 1997.* U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Iron and Steel Annual Report 1996.* U.S. Geological Survey, Reston, VA.

USGS (1995a) *Minerals Yearbook: Iron and Steel Annual Report 1994.* U.S. Geological Survey, Reston, VA.

USGS (1995b) *Minerals Industries Surveys: Aluminum Annual Review 1994.* U.S. Geological Survey, U.S. Department of the Interior. Washington, DC. May.

USGS (1993) *Minerals Yearbook: Iron and Steel Annual Report 1992.* U.S. Geological Survey, Reston, VA.

## Ammonia Manufacture

EIA (1998) *Manufacturing Energy Consumption Survey (MECS)* U.S. Department of Energy, Energy Information Administration, Washington D.C. Available online at <http://www.eia.doe.gov/emeu/mecs/mecs98/datatables/contents.html.>

EIA (1994) *Manufacturing Energy Consumption Survey (MECS)* U.S. Department of Energy, Energy Information Administration, Washington D.C.

EFMA, 1995. *Production of Ammonia.* European Fertilizer Manufacturers Association. March 1.

EPA (1997) National Air Pollutant Emissions Trends Report, 1900-1996. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

IPCC/UNEP/OECD/IEA (1997) Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

U.S. Census Bureau (2000) "Facts & Figures for the Chemical Industry," Chemical and Engineering News, Bureau of the Census, United States Department of Commerce, Vol. 78 (26), June 26, 2000.

U.S. Census Bureau (1998) "Facts & Figures for the Chemical Industry," Chemical and Engineering News, Bureau of the Census, United States Department of Commerce, Vol. 76 (26), June 1998.

## Ferroalloy Production

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Onder, H; and Bagdoyan, E.A. (1993) *Everything You've Always Wanted to Know about Petroleum Coke.* Allis Mineral Systems.

USGS (2001) *Mineral Industry Surveys – Silicon in December 2000.* U.S. Geological Survey, Reston, VA.

USGS (2000) *Mineral Yearbook: Silicon Annual Report 1999.* U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Silicon Annual Report 1998.* U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Silicon Annual Report 1997.* U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Silicon Annual Report 1996.* U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Silicon Annual Report 1995.* U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Silicon Annual Report 1994.* U.S. Geological Survey, Reston, VA.

USGS (1994) *Silicon: Annual Report 1993.* U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC.

USGS (1993) *Silicon: Annual Report 1992.* U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC.

USGS (1992) *Silicon: Annual Report 1991.* U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC.

USGS (1991) *Silicon: Annual Report 1990.* U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC.

## Titanium Dioxide Production

Chemical Market Reporter (2000). May 22, 2000.

Onder, H; and Bagdoyan, E.A. (1993) *Everything You've Always Wanted to Know about Petroleum Coke.* Allis Mineral Systems.

USGS (2001) *Mineral Industry Surveys – Titanium in December 2000.* U.S. Geological Survey, Reston, VA.

USGS (2000) *Mineral Yearbook: Titanium Annual Report 1999.* U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Titanium Annual Report 1998.* U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Titanium Annual Report 1997.* U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Titanium Annual Report 1996.* U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Titanium Annual Report 1995.* U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Titanium Annual Report 1994.* U.S. Geological Survey, Reston, VA.

USGS (1994) *Minerals Yearbook: Titanium Annual Report 1993.* U.S. Geological Survey, Reston, VA.

USGS (1993) *Minerals Yearbook: Titanium Annual Report 1992.* U.S. Geological Survey, Reston, VA.

USGS (1992) *Minerals Yearbook: Titanium Annual Report 1991.* U.S. Geological Survey, Reston, VA.

USGS (1991) *Minerals Yearbook: Titanium Annual Report 1990.* U.S. Geological Survey, Reston, VA.

## Petrochemical Production

ACC (2001) American Chemistry Council. Personal Communication with Emily Meyers. August.

CMA (1999) *U.S. Chemical Industry Statistical Handbook.* Chemical Manufacturer's Association. Washington, DC.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

## Silicon Carbide Production

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

USGS (2001) *Minerals Yearbook: Manufactured Abrasives Annual Report 2000.* U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Manufactured Abrasives Annual Report 1999.* U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Manufactured Abrasives Annual Report 1998.* U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Manufactured Abrasives Annual Report 1997.* U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Manufactured Abrasives Annual Report 1996.* U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Manufactured Abrasives Annual Report 1995.* U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Manufactured Abrasives Annual Report 1994.* U.S. Geological Survey, Reston, VA.

USGS (1994) *Manufactured Abrasives: Annual Report 1993.* U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC.

USGS (1993) *Manufactured Abrasives: Annual Report 1992.* U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC.

USGS (1992) *Manufactured Abrasives: Annual Report 1991.* U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC.

USGS (1991) *Manufactured Abrasives: Annual Report 1990.* U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC.

## Adipic Acid Production

*Chemical Market Reporter* (1998) "Chemical Profile: Adipic Acid." *Chemical Market Reporter,* June 15, 1998.

C&EN (1996) "Facts and Figures for the Chemical Industry." *Chemical and Engineering News,* 74(25):38. June 24.

C&EN (1995) "Production of Top 50 Chemicals Increased Substantially in 1994." *Chemical and Engineering News.* 73(15): 17. April 10.

C&EN (1994) "Top 50 Chemicals Production Rose Modestly Last Year." *Chemical & Engineering News,* 72(15): 13. April 11.

C&EN (1993) "Top 50 Chemicals Production Recovered Last Year." *Chemical & Engineering News,* 71(15): 11. April 12.

C&EN (1992) "Production of Top 50 Chemicals Stagnates in 1991." *Chemical and Engineering News,* 70(15): 17. April 13.

CW (1999) "Product Focus: Adipic Acid/Adiponitrile." *Chemical Week,* March 10, 1999, pg. 31.

Childs, D. (2000). Personal communication between Dave Childs of DuPont, USA and Laxmi Palreddy of ICF, Consulting, USA. August 21, 2000.

Reimer, R.A., Slaten, C.S., Seapan, M., Koch, T.A., and Triner, V.G. (1999) "Implementation of Technologies for Abatement of $N_2O$ Emissions Associated with Adipic Acid Manufacture." Presented at the Second International Symposium on Non-$CO_2$ Greenhouse Gases, September 8-10, 1999, Noordwijkerhout, the Netherlands.

Reimer, Ron (2000). Personal communication between Ron Reimer of DuPont, USA and Heike Mainhardt of ICF, Consulting, USA. September 12, 2000.

Reimer, Ron (1999). Personal communication between Ron Reimer of DuPont, USA and Heike Mainhardt of ICF, Consulting, USA. May 19, 1999.

Thiemens, M.H. and W.C. Trogler (1991) "Nylon production; an unknown source of atmospheric nitrous oxide." *Science*: 251:932-934.

Westervelt, Robert. "Inolex Acquires AlliedSignal's Adipic Acid Business." *Chemical Week*, July 28, 1999.

## Nitric Acid Production

C&EN (2001) "Facts and Figures in the Chemical Industry." *Chemical and Engineering News*, June 25,2001.

C&EN (2000) "Facts and Figures in the Chemical Industry." *Chemical and Engineering News*, June 26,2000.

Choe, J.S., P.J. Cook, and F.P. Petrocelli (1993) "Developing $N_2O$ Abatement Technology for the Nitric Acid Industry." Prepared for presentation at the 1993 ANPSG Conference. Air Products and Chemicals, Inc., Allentown, PA.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, October.

Reimer, R.A., R.A. Parrett, and C.S. Slaten (1992) *Abatement of $N_2O$ Emissions Produced in Adipic Acid Manufacture*. Proceedings of the 5th International Workshop on Nitrous Oxide Emissions. Tsukuba, Japan. July 1-3.

## Substitution of Ozone Depleting Substances

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

## Aluminum Production

EPA (1993) Proceedings: *Workshop on Atmospheric Effects, Origins, and Options for Control of Two Potent Greenhouse Gases: $CF_4$ and $C_2F_6$*, Sponsored by the U.S. Environmental Protection Agency, Global Change Division, Office of Air and Radiation, April 21-22.

Gariepy, B. and G. Dube (1992) "Treating Aluminum with Chlorine." U.S. Patent 5,145,514. Issued September 8, 1992.

IAI (2000), Anode Effect Survey 1994-1997 and Perfluorocarbon Compounds Emissions Survey 1990-1997, International Aluminum Institute, London, United Kingdom. 2000.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Ko, M.K.W., N.D. Sze, W.-C. Wang, G. Shia, A. Goldman, F.J. Murcray, D.G. Murcray, and C.P. Rinsland (1993) "Atmospheric Sulfur Hexafluoride: Sources, Sinks, and Greenhouse Warming." Journal of Geophysical Research, 98, 10499-10507.

MacNeal, J., T. Rack, and R. Corns (1990) "Process for Degassing Aluminum Melts with Sulfur Hexafluoride." U.S. Patent 4,959,101. Issued September 25, 1990.

Maiss, M. and C.A.M. Brenninkmeijer (1998) "Atmospheric $SF_6$: Trends, Sources and Prospects," *Environmental Science and Technology*, v. 32, n. 20, pp. 3077-3086.

Ten Eyck, N. and M. Lukens (1996) "Process for Treating Molten Aluminum with Chlorine Gas and Sulfur Hexafluoride to Remove Impurities." U.S. Patent 5,536,296. Issued July, 16, 1996.

USGS (2001) *Minerals Yearbook: Aluminum Annual Report 2000*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Aluminum Annual Report 1999*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Aluminum Annual Report 1997*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Mineral Industry Surveys: Aluminum Annual Review 1994*. U.S. Geological Survey, U.S. Department of the Interior, formerly Bureau of Mines. Washington, DC. May.

Victor, D.G. and G.J. MacDonald (1998) "A Model for Estimating Future Emissions of Sulfur Hexafluoride and Perfluorcarbons." Interim Report for the International Institute for Applied Systems Analysis (IIASA), July, 1998. Downloaded from the IIASA website <http://www.iiasa.ac.at/>, May 23, 2000.

Zurecki, Z. (1996) "Effect of Atmosphere Composition on Homogenizing Al-Mg and Al-Li Alloys." Gas Interactions in Nonferrous Metals Processing - Proceedings of the 1996 125th The Minerals, Metals & Materials Society (TMS) Annual Meeting (Anaheim, CA, USA), pp. 77-93.

## HCFC-22 Production

Rand, S., Branscome, M., and Ottinger, D. (1999) "Opportunities for the Reduction of HFC-23 Emissions from the Production of HCFC-22." In: *Proceedings from the Joint IPCC/TEAP Expert Meeting On Options for the Limitation of Emissions of HFCs and PFCs*. Petten, the Netherlands, 26-28 May 1999.

## Semiconductor Manufacture

International SEMATECH. *International Technology Roadmap: 2000 Update.* <http://public.itrs.net>

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme.

Semiconductor Equipment and Materials International. *World Fab Watch*, July 2001 Edition.

VLSI Research, Inc. April 2001. Document 327031F, Volume D1.1, Table 2.2.2 - Worldwide Silicon Demand by Wafer Size. <http://www.vlsiresearch.com>

## Electrical Transmission and Distribution

M. Maiss and CAM Brenninkmeijer, "A reversed trend in emissions of $SF_6$ to the atmosphere?" *Non-$CO_2$ Greenhouse Gases: Scientific Understanding, Control, and Implementation, Proceedings of the Second International Symposium, Noordwijkerhout, The Netherlands, 8-10 September 1999,* Kluwer Academic Publishers, 2000, p. 199.

O'Connell, P. F. Heil, J. Henriot, G. Mauthe, H. Morrison, L. Neimeyer, M. Pittroff, R. Probst, J.P. Tailebois, (2001), *SF6 in the Electric Industry, Status 2000,* Cigre, May 2001.

RAND (2000) Katie D. Smythe, RAND Environmental Science and Policy Center, "Production and Distribution of $SF_6$ by End-Use Application," November, 2000.

## Magnesium Production and Processing

Gjestland, H. and D. Magers (1996) "Practical Usage of Sulphur [Sulfur] Hexafluoride for Melt Protection in the Magnesium Die Casting Industry," #13, *1996 Annual Conference Proceedings*, Ube City, Japan, International Magnesium Association.

IPCC (2000). *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme.

USGS (2001). *Minerals Yearbook: Magnesium Annual Report 2000.* U.S. Geological Survey, Reston, VA.

## Industrial Sources of Ambient Air Pollutants

EPA (2001) Unpublished data provided by U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, October.

# Solvent Use

EPA (2001) Unpublished data provided by U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, October.

# Agriculture

## Enteric Fermentation

Becket, J.L. and J.W. Oltjen (1993) Estimation of the water requirement for beef production in the United States. *Journal of Animal Science*. 71:818-826.

Crutzen, P.J., I. Aselmann, and W. Seiler (1986). "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivores, Fauna, and Humans." *Tellus* 38B:271-284.

Donovan, K. (1999) Personal Communication, University of California, Davis.

Donovan, K. and L. Baldwin (1999). Results of the AAMOLLY model runs for the Enteric Fermentation Model. University of California, Davis.

EPA (2000) Draft Enteric Fermentation Model Documentation. U.S. Environmental Protection Agency, Office of Air and Radiation, Washington, DC. June 13, 2000.

EPA (1993). Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to Congress. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC.

FAO (2001). FAOSTAT Statistical Database. Food and Agriculture Organization of the United Nations. <http://apps.fao.org.>

FAO (2000). FAOSTAT Statistical Database. Food and Agriculture Organization of the United Nations. <http://apps.fao.org.>

Feedstuffs (1998). "Nutrient requirements for pregnant replacement heifers." *Feedstuffs*, Reference Issue, p. 50.

IPCC (2000). *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.* Chapter 4. IPCC National Greenhouse Gas Inventories Programme Technical Support Unit, Kanagawa, Japan. Data also available at <http://www.ipcc-nggip.iges.or.jp/gp/report.htm>.

IPCC/UNEP/OECD/IEA (1997). Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Cooperation and Development, International Energy Agency.

Johnson, D. (1999). Personal Communication, Colorado State University, Fort Collins, 1999.

NRC (1999). 1996 Beef NRC, Appendix Table 22, p227. National Research Council.

USDA (2001a). *Cattle*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 26, 2000. Data also available from <http://www.usda.gov/nass/pubs/reportname.htm#cattle>.

USDA (2001b). *Hogs and Pigs*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. June 29, 2001. Data also available from <http://jan.mannlib.cornell.edu/reports/nassr/livestock/php-bb/>.

USDA (2001c). *Livestock Slaughter*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 19, 2001. Data also available from <http://www.usda.gov/nass/pubs/ reportname.htm#livestock-slaughter>.

USDA (2001d). *Milk Production*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. February 16, 2000. Data also available from <http://www.nass.usda.gov:81/ipedb/>.

USDA (2001e). *Sheep and Goats*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 26, 2001. Data also available from <http://usda.mannlib.cornell.edu/reports/ nassr/livestock/pgg-bb/>.

USDA (2001f). *Sheep*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. July 20, 2001. Data also available from <http://usda.mannlib.cornell.edu/reports/ nassr/livestock/pgg-bb/>.

USDA (2001g). *Cattle on Feed*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. February 16, 2001. Data also available from <http://www.nass.usda.gov:81/ipedb/>.

USDA (2000a). *Cattle*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 1, 2000. Data also available from <http://www.usda.gov/nass/pubs/reportname.htm#cattle>.

USDA (2000b). *Hogs and Pigs*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. March 24, 1999. Data also available from <http://jan.mannlib.cornell.edu/reports/nassr/livestock/php-bb/>.

USDA (2000c). *Livestock Slaughter*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 21 – December 22. Data also available from <http://www.usda.gov/nass/pubs/reportname.htm#livestock-slaughter>.

USDA (2000d). *Milk Production*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 18, 2000. Data also available from <http://www.nass.usda.gov:81/ipedb/>.

USDA (2000e). *Sheep and Goats*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 28. Data also available from <http://usda.mannlib.cornell.edu/reports/ nassr/livestock/pgg-bb/>.

USDA (2000f). *Cattle on Feed*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. February 18, 2000. Data also available from <http://www.nass.usda.gov:81/ipedb/>.

USDA (1999a). *Cattle*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 1, 2000. Data also available from <http://www.usda.gov/nass/pubs/reportname.htm#cattle>.

USDA (1999b). *Cattle on Feed*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January. Data also available from <http://www.nass.usda.gov:81/ipedb/>.

USDA (1999c). *Cattle, Final Estimates 1994-1998*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington DC. 1999. Data also available from <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1999d). *Hogs and Pigs*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. March 26, 1999. Data also available from <http://jan.mannlib.cornell.edu /reports/ nassr/livestock/php-bb/>.

USDA (1999e). *Hogs and Pigs, Final Estimates 1993-97*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. Data also available from <http://jan.mannlib.cornell.edu/ reports/ nassr/ livestock/php-bb/>.

USDA (1999f). *Livestock Slaughter*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 22 – December 23. Data also available from <http://www.usda.gov/nass/pubs/reportname.htm#livestock-slaughter>.

USDA (1999g). *Milk Cows and Milk Production – Final Estimates 1993-1997*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 1999. Data also available from <http://www.nass.usda.gov:81/ipedb/>.

USDA (1999h). *Sheep and Goats, Final Estimates 1994-98*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC, 1999. Data also available from <http://usda.mannlib.cornell.edu/ reports/ general/sb/>.

USDA (1998a). *Cattle on Feed*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January. Data also available from <http://www.nass.usda.gov:81/ipedb/>.

USDA (1998b, 1998c). *Hogs and Pigs*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. September 25, December 29. Data also available from <http://jan.mannlib.cornell.edu/reports / nassr/livestock/php-bb/>.

USDA:APHIS:VS (1998) *Beef '97*, National Animal Health Monitoring System, Fort Collins, CO. 1998. Data also available from <http://www.aphis.usda.gov/vs/ceah/cahm>.

USDA (1997). *Cattle on Feed*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January. Data also available from <http://www.nass.usda.gov:81/ipedb/>.

USDA (1996a). *Beef Cow/Calf Health and Productivity Audit (CHAPA): Forage Analyses from Cow/Calf Herds in 18 States*, National Animal Health Monitoring System, Washington DC. March 1996. Data also available from <http://www.aphis.usda.gov/vs/ceah/cahm>.

USDA (1996b). *Cattle on Feed*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January. Data also available from <http://www.nass.usda.gov:81/ipedb/>.

USDA (1995a). *Cattle on Feed*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January. Data also available from <http://www.nass.usda.gov:81/ipedb/>.

USDA (1995b). *Cattle, Final Estimates 1989-93*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January. Data also available from <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1995c). *Cattle Highlights*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. February 3. Data also available from <http://jan.mannlib.cornell.edu/reports/nassr/livestock/pct-bb/>.

USDA (1995d). *Dairy Outlook*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. February 27. Data also available from <http://usda.mannlib.cornell.edu/reports/nassr/dairy/pdp-bb/1995/>.

USDA (1994a). *Hogs and Pigs, Final Estimates 1988-92*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. December. Data also available from <http://jan.mannlib.cornell.edu/reports/ nassr/livestock/php-bb/>.

USDA (1994b). *Sheep and Goats, Final Estimates 1988-93*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 31. Data also available from <http://usda.mannlib.cornell.edu/reports/ general/sb/>.

USDA:APHIS:VS (1994) *Beef Cow/Calf Health and Productivity Audit.* National Animal Health Monitoring System, Fort Collins, CO. Data also available from <http://www.aphis.usda.gov/vs/ceah/cahm>.

USDA:APHIS:VS (1993) *Beef Cow/Calf Health and Productivity Audit.* National Animal Health Monitoring System, Fort Collins, CO. August. Data also available from <http://www.aphis.usda.gov/vs/ceah/cahm>.

Western Dairyman (1998). "How Big Should Heifers Be at Calving?" The Western Dairyman, Sept. 1998, p. 12.

## Manure Management

Anderson, S. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Steve Anderson, Agricultural Statistician, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. 31 May.

ASAE (1999) *ASAE Standards 1999*, 46th Edition, American Society of Agricultural Engineers, St. Joseph, MI.

Bryant, M.P., V.H. Varel, R.A. Frobish, and H.R. Isaacson (1976) In: H.G. Schlegel (ed.). *Seminar on Microbial Energy Conversion*. E. Goltz KG. Gottingen, Germany. 347 pp.

Deal, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Peter B. Deal, Rangeland Management Specialist, Florida Natural Resource Conservation Service, 21 June.

EPA (2001a) Cost Methodology Report for Beef and Dairy Animal Feeding Operations. EPA-821-R-01-019, January.

EPA (2001b) Development Document for the Proposed Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations EPA-821-R-01-003, January.

EPA (2000) *AgSTAR Digest*, U.S. Environmental Protection Agency, Office of Air and Radiation. Spring.

EPA (1993) *Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to Congres*, U.S. Environmental Protection Agency, Office of Air and Radiation. April.

EPA (1992) *Global Methane Emissions from Livestock and Poultry Manure*, U.S. Environmental Protection Agency, Office of Air and Radiation, February.

ERG (2001) Summary of development of MDP Factor for methane conversion factor calculations. September.

ERG (2000a) Calculations: Percent Distribution of Manure for Waste Management Systems. August.

ERG (2000b) Summary of $B_o$ Literature Review. June.

FAO (2001) Yearly US total horse population data from the Food and Agriculture Organization of the United Nations database, <http://apps.fao.org> (Accessed July 11, 2001).

Groffman, P.M., Brumme, R., Butterbach-Bahl, K., Dobbie, K.E., Mosier, A.R., Ojima, D. Papen, H. Parton, W.J., Smith, K.A., Wagner-Riddle, C. (2000) "Evaluating annual nitrous oxide fluxes at the ecosystem scale." *Global Biogeochemcial Cycles,* 14(4): 1061-1070.

Hashimoto, A.G. (1984) "Methane from Swine Manure: Effect of Temperature and Influent Substrate Composition on Kinetic Parameter (k)." *Agricultural Wastes.* 9:299-308.

Hashimoto, A.G., V.H. Varel, and Y.R. Chen (1981) "Ultimate Methane Yield from Beef Cattle Manure; Effect of Temperature, Ration Constituents, Antibiotics and Manure Age." *Agricultural Wastes.* 3:241-256.

Hill, D.T. (1984) "Methane Productivity of the Major Animal Types." *Transactions of the ASAE.* 27(2):530-540.

Hill, D.T. (1982) "Design of Digestion Systems for Maximum Methane Production." *Transactions of the ASAE.* 25(1):226-230.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, NGGIP. Chapter 4, Agriculture.

Johnson, D. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Dan Johnson, State Water Management Engineer, California Natural Resource Conservation Service, 23 June.

Lange, J. (2000) Telephone conversation between Lee-Ann Tracy of ERG and John Lange, Agricultural Statistician, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. 8 May.

Martin, J. (2000) "A Comparison of the Performance of Three Swine Waste Stabilization Systems," paper submitted to Eastern Research Group, Inc. October, 2000.

Miller, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Paul Miller, Iowa Natural Resource Conservation Service, 12 June.

Milton, B. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Bob Milton, Chief of Livestock Branch, U.S. Department of Agriculture, National Agriculture Statistics Service, 1 May.

Morris, G.R. (1976) Anaerobic Fermentation of Animal Wastes: A Kinetic and Empirical Design Fermentation. M.S. Thesis. Cornell University.

NOAA (2001) National Oceanic and Atmospheric Administration (NOAA), National Climate Data Center (NCDC) Downloaded "0106.tmp" on July 27, 2001 from <ftp://ftp.ncdc.noaa.gov/pub/data/cirs/> (for all states except Alaska and Hawaii); downloaded "all-1994.tar", "all-1995.tar", "all-1996.tar", "all-1997.tar", "all-1998.tar", and "all-1999.tar" in April 2000 and "all-2000.tar" in July 2001 from <ftp://ftp.ncdc.noaa.gov/pub/data/globalsod/> (for Alaska and Hawaii). Documentation for Dataset: "Time Bias Corrected Divisional Temperature-Precipitation-Drought Index"; TD-9640; March, 1994. <http://www.ncdc.noaa.gov/onlineprod/drought/ftppage.html>.

Poe, G., N. Bills, B. Bellows, P. Crosscombe, R. Koelsch, M. Kreher, and P. Wright (1999) Staff Paper *Documenting the Status of Dairy Manure Management in New York: Current Practices and Willingness to Participate in Voluntary Programs*, Department of Agricultural, Resource, and Managerial Economics, Cornell University, Ithaca, New York, September.

Safley, L.M., Jr. and P.W. Westerman (1992) "Performance of a Low Temperature Lagoon Digester." *Biological Wastes.* 9060-8524/92/S05.00.

Safley, L.M., Jr. and P.W. Westerman (1990) "Psychrophilic Anaerobic Digestion of Animal Manure: Proposed Design Methodology." *Biological Wastes.* 34:133-148.

Safley, L.M., Jr. and P.W. Westerman (1989) "Anaerobic Lagoon Biogas Recovery Systems." *Biological Wastes.* 27:43-62.

Safley, L.M., Jr. (2000) Telephone conversation between Deb Bartram of ERG and L.M. Safley, President, Agri-Waste Technology, June and October.

Stettler, D. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Don Stettler, Environmental Engineer, National Climate Center, Oregon Natural Resource Conservation Service, 27 June.

Summers, R. and S. Bousfield (1980) "A Detailed Study of Piggery-waste Anaerobic Digestion." *Agricultural Wastes.* 2:61-78.

Sweeten, J. (2000) Telephone conversation between Indra Mitra of ERG and John Sweeten, Texas A&M University, June 2000.

UEP (1999) Voluntary Survey Results - Estimated Percentage Participation/Activity, Caged Layer Environmental Management Practices, Industry data submissions for EPA profile development, United Egg Producers and National Chicken Council. Received from John Thorne, Capitolink. June 2000.

USDA (2001a) *Cattle*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 26. (Data also available from <http://www.nass.usda.gov:81/ipedb/>).

USDA (2001b) *Cattle on Feed Cattle*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 19. (Data also available from <http://www.nass.usda.gov:81/ipedb/>).

USDA (2001c) *Hogs and Pig*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. March 30. (Data also available from <http://www.nass.usda.gov:81/ipedb/>).

USDA (2001d) *Chicken and Eggs - 1999 Summary Cattle*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January.

USDA (2001e) *Poultry Production and Value - 1999 Summary*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. April.

USDA (2001f) *Sheep and Goats*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January. (Data also available from <http://www.usda.gov/nass/pubs/reportname.htm>).

USDA (2001g) Published Estimates Database, U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC. Downloaded from <http://www.nass.usda.gov:81/ipedb/>. September 26.

USDA (2000a) *Cattle*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 28. (Data also available from <http://www.nass.usda.gov:81/ipedb/>).

USDA (2000b) *Cattle on Feed Cattle*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. April 14. (Data also available from <http://www.nass.usda.gov:81/ipedb/>).

USDA (2000c) *Hogs and Pig*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. March 24. (Data also available from <http://www.nass.usda.gov:81/ipedb/>).

USDA (2000d) *Chicken and Eggs - 1999 Summary Cattle*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January.

USDA (2000e) *Poultry Production and Value - 1999 Summary*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. April.

USDA (2000f) *Sheep and Goats*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January. (Data also available from <http://www.usda.gov/nass/pubs/reportname.htm>).

USDA (2000g) *Chicken and Eggs - Final Estimates 1988-1993*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. Downloaded from http://usda.mannlib.cornell.edu/data-sets/livestock/95908/sb908.txt. May 3.

USDA (2000h) Re-aggregated data from the National Animal Health Monitoring System's (NAHMS) Dairy '96 study provided by Stephen L. Ott of the U.S. Department of Agriculture, Animal and Plant Health Inspection Service. June 19.

USDA (2000i) *Layers '99 – Part II: References of 1999 Table Egg Layer Management in the U.S.*, U.S. Department of Agriculture, Animal and Plant Health Inspection Service (APHIS), National Animal Health Monitoring System (NAHMS). January.

USDA (1999a) *Cattle - Final Estimates 1994-98*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January. (Data also available from <http://www.nass.usda.gov:81/ipedb/>).

USDA (1999b) *Poultry Production and Value - Final Estimates 1994-97*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. March.

USDA (1999c) *Sheep and Goats - Final Estimates 1994-1998,* U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January.

USDA (1999d) <http://www.nass.usda.gov/census/census97/volume1/us-51/us2_25.pdf>, Table 25. Miscellaneous Livestock and Animal Specialties Inventory and Sales: 1997 and 1992, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. (Accessed May 2000).

USDA (1999e) 1992 and 1997 Census of Agriculture (CD-ROM), U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC.

USDA (1998a) *Hogs and Pigs - Final Estimates 1993-97,* U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. December. (Data also available from <http://www.nass.usda.gov:81/ipedb/>).

USDA (1998b) *Chicken and Eggs - Final Estimates 1994-97*, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. December.

USDA (1998c) *Nutrients Available from Livestock Manure Relative to Crop Growth Requirements*, Resource Assessment and Strategic Planning Working Paper 98-1, U.S. Department of Agriculture, Natural Resources Conservation Service. February.

USDA (1998d) Re-aggregated data from the National Animal Health Monitoring System's (NAHMS) Swine '95 study aggregated by Eric Bush of the U.S. Department of Agriculture, Centers for Epidemiology and Animal Health.

USDA (1996a) *Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH)*, Part 651, U.S. Department of Agriculture, Natural Resources Conservation Service. July.

USDA (1996b) *Swine '95: Grower/Finisher Part II: Reference of 1995 U.S. Grower/Finisher Health & Management Practices*, U.S. Department of Agriculture, Animal Plant Health and Inspection Service, Washington, DC. June.

USDA (1995a) *Cattle - Final Estimates 1989-93,* U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January. (Data also available from <http://www.nass.usda.gov:81/ipedb/>).

USDA (1995b) *Poultry Production and Value - Final Estimates 1989-1993,* U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January.

USDA (1994a) *Hogs and Pigs - Final Estimates 1988-92,* U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. December. (Data also available from <http://www.nass.usda.gov:81/ipedb/>).

USDA (1994b) *Sheep and Goats - Final Estimates 1989-1993,* U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. January 31.

Wright, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Peter Wright, Cornell University, College of Agriculture and Life Sciences, 23 June.

## Rice Cultivation

Bollich, P. (2000) Telephone conversation between Payton Deeks of ICF Consulting and Pat Bollich, Professor with Louisiana State University Agriculture Center, 17 May.

Bossio, Deborah A., Horwath, William, Mutters, Randall G. and van Kessel, Chris (1999) "Methane pool and flux dynamics in a rice field following straw incorporation." *Soil Biology and Biochemistry* 31:1313-1322.

Cicerone R.J., Delwiche, C.C., Tyler, S.C., and Zimmerman, P.R. (1992) "Methane Emissions from California Rice Paddies with Varied Treatments." *Global Biogeochemical Cycles* 6:233-248.

Guethle, D. (2001) Telephone conversation between Caren Mintz of ICF Consulting and David Guethle, Agronomy Specialist at Missouri Cooperative Extension Service, 4 September.

Holzapfel-Pschorn, A., Conrad, R., and Seiler, W. (1985) "Production, Oxidation, and Emissions of Methane in Rice Paddies." *FEMS Microbiology Ecology* 31:343-351.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.* IPCC National Greenhouse Gas Inventories Programme Technical Support Unit, Kanagawa, Japan. Available at <http://www.ipcc-nggip.iges.or.jp/gp/report.htm>.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Klosterboer, A. (2001a) Telephone conversation between Caren Mintz of ICF Consulting and Arlen Klosterboer, Extension Agronomist, Texas A & M University, 6 August.

Klosterboer, A. (2001b) Telephone conversation between Caren Mintz of ICF Consulting and Arlen Klosterboer, Extension Agronomist, Texas A & M University, 8 October.

Klosterboer, A. (2000) Telephone conversation between Payton Deeks of ICF Consulting and Arlen Klosterboer, Extension Agronomist, Texas A & M University, 18 May.

Klosterboer, A. (1999) Telephone conversation between Catherine Leining of ICF Consulting and Arlen Klosterboer, Extension Agronomist, Texas A & M University, 10 June.

Klosterboer, A. (1997) Telephone conversation between Holly Simpkins of ICF Incorporated and Arlen Klosterboer, Texas A & M University. 1 December.

Lindau, C.W. and Bollich, P.K. (1993) "Methane Emissions from Louisiana First and Ratoon Crop Rice." *Soil Science* 156:42-48.

Lindau, C.W., Bollich, P.K., and DeLaune, R.D. (1995) "Effect of Rice Variety on Methane Emission from Louisiana Rice." *Agriculture, Ecosystems and Environment* 54:109-114.

Linscombe, S. (2001a) Telephone conversation between Caren Mintz of ICF Consulting and Steve Linscombe, Research Agronomist, Rice Research Station in Crowley, LA, 30 July – 1 August.

Linscombe, S. (2001b) Email correspondence between Caren Mintz of ICF Consulting and Steve Linscombe, Research Agronomist, Rice Research Station in Crowley, LA, 4 October.

Linscombe, S. (1999a) Telephone conversation between Catherine Leining of ICF Consulting and Steve Linscombe, Research Agronomist, Rice Research Station in Crowley, LA, 3 June.

Linscombe, S. (1999b) Telephone conversation between Payton Deeks of ICF Consulting and Steve Linscombe, Research Agronomist, Rice Research Station in Crowley, LA, 9 August.

Mayhew, W. (1997) Telephone conversation between Holly Simpkins of ICF Incorporated and Walter Mayhew, University of Arkansas, Little Rock, 24 November.

Mutters, C. (2001) Telephone conversation between Caren Mintz of ICF Consulting and Cass Mutters, Rice Farm Advisor for Butte, Glen, and Tehama Counties, University of California Cooperative Extension Service, 5 September.

Saichuk, J. (1997) Telephone conversation between Holly Simpkins of ICF Incorporated and John Saichuk, Louisiana State University, 24 November.

Sass, R.L., Fisher, F.M., Harcombe, P.A., and Turner, F.T. (1991a) "Mitigation of Methane Emissions from Rice Fields: Possible Adverse Effects of Incorporated Rice Straw." *Global Biogeochemical Cycles* 5:275-287.

Sass, R.L., Fisher, F.M., Turner, F.T., and Jund, M.F. (1991b) "Methane Emissions from Rice Fields as Influenced by Solar Radiation, Temperature, and Straw Incorporation." *Global Biogeochemical Cycles* 5:335-350.

Sass, R.L., Fisher, F.M., Harcombe, P.A., and Turner, F.T. (1990) "Methane Production and Emissions in a Texas Rice Field." *Global Biogeochemical Cycles* 4:47-68.

Sass, R.L., Fisher, F.M., and Wang, Y.B. (1992) "Methane Emission from Rice Fields: The Effect of Floodwater Management." *Global Biogeochemical Cycles* 6:249-262.

Schueneman, T. (2001a) Telephone conversation between Caren Mintz of ICF Consulting and Tom Schueneman, Palm Beach County Agricultural Extension Agent, Florida, 30 July.

Schueneman, T. (2001b) Telephone conversation between Caren Mintz of ICF Consulting and Tom Schueneman, Palm Beach County Agricultural Extension Agent, Florida, 9 October.

Schueneman, T. (2000) Telephone conversation between Payton Deeks of ICF Consulting and Tom Schueneman, Palm Beach County Agricultural Extension Agent, Florida, 16 May.

Schueneman, T. (1999a) Telephone conversation between Catherine Leining of ICF Consulting and Tom Schueneman, Palm Beach County Agricultural Extension Agent, Florida, 7 June.

Schueneman, T. (1999b) Telephone conversation between Payton Deeks of ICF Consulting and Tom Schueneman, Palm Beach County Agricultural Extension Agent, Florida, 10 August.

Schueneman, T. (1999c) Telephone conversation between John Venezia of ICF Consulting and Tom Schueneman, Palm Beach County Agricultural Extension Agent, Florida, 27 August.

Schueneman, T. (1997) Telephone conversation between Barbara Braatz of ICF Incorporated and Tom Schueneman, County Extension Agent, Florida. 7 November.

Slaton, N. (2001a) Telephone conversation between Caren Mintz of ICF Consulting and Nathan Slaton, Extension Agronomist - Rice, University of Arkansas Division of Agriculture Cooperative Extension Service, 23 August.

Slaton, N. (2001b) Telephone conversation between Caren Mintz of ICF Consulting and Nathan Slaton, Extension Agronomist - Rice, University of Arkansas Division of Agriculture Cooperative Extension Service, 3 October.

Slaton, N. (2000) Telephone conversation between Payton Deeks of ICF Consulting and Nathan Slaton, Extension Agronomist - Rice, University of Arkansas Division of Agriculture Cooperative Extension Service, 20 May.

Slaton, N. (1999) Telephone conversation between Catherine Leining of ICF Consulting and Nathan Slaton, Extension Agronomist - Rice, University of Arkansas Division of Agriculture Cooperative Extension Service, 3 June.

Stevens, G. (1997) Telephone conversation between Holly Simpkins of ICF Incorporated and Gene Stevens, Extension Specialist, Missouri Commercial Agriculture Program, Delta Research Center, 17 December.

Street, J. (2001) Telephone conversation between Caren Mintz of ICF Consulting and Dr. Joe Street, Mississippi State University, Delta Research and Extension Center and Delta Branch Station, 3 October.

Street, J. (1997) Telephone conversation between Holly Simpkins of ICF Incorporated and Dr. Joe Street, Mississippi State University, Delta Research and Extension Center and Delta Branch Station, 1 December.

USDA (2001) *Crop Production 2000 Summary.* National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/>. Accessed July 2001.

USDA (2000) *Crop Production 1999 Summary.* National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/>. Accessed July 2001.

USDA (1998) *Field Crops Final Estimates 1992-97.* Statistical Bulletin Number 947 a. National Agricultural Statistics Service, U.S. Department of Agriculture. Available at <http://usda.mannlib.cornell.edu/>. Accessed July 2001.

USDA (1994) *Field Crops Final Estimates 1987-1992.* Statistical Bulletin Number 896. National Agricultural Statistics Service, U.S. Department of Agriculture. Available at <http://usda.mannlib.cornell.edu/>. Accessed July 2001.

## Agricultural Soil Management

AAPFCO (2000a) *1999-2000 Commercial Fertilizers Data.* ASCII files. Available: David Terry, Secretary, AAPFCO.

AAPFCO (2000b) *Commercial Fertilizers 2000.* Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1999) *Commercial Fertilizers 1999.* Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1998) *Commercial Fertilizers 1998.* Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1997) *Commercial Fertilizers 1997*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1996) *Commercial Fertilizers 1996*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

AAPFCO (1995) *Commercial Fertilizers 1995*. Association of American Plant Food Control Officials, University of Kentucky, Lexington, KY.

Anderson, S. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Steve Anderson, Agricultural Statistician, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. 31 May.

ASAE (1999) *ASAE Standards 1999*. 46th Edition, American Society of Agricultural Engineers, St. Joseph, MI.

Barnard, G.W. and L.A. Kristoferson (1985) *Agricultural Residues as Fuel in the Third World*. Technical Report No. 5. Earthscan, London, UK.

Bastian, R. (2001) Telephone conversation between Caren Mintz of ICF Consulting and Robert Bastian, Office of Water, U.S. Environmental Protection Agency, Washington, DC, September-October.

Bastian, R. (1999) Telephone conversation between Marco Alcaraz of ICF Consulting and Robert Bastian, Office of Water, U.S. Environmental Protection Agency, Washington, DC, August.

Beuselinck, P.R. and Grant, W.F. (1995) "Birdsfoot Trefoil." In: *Forages, Volume I: An Introduction to Grassland Agriculture*, Barnes, R.F., Miller, D.A., and Nelson, C.J. (eds.), pp. 237-248, Iowa State University Press, Ames, IA.

Brady, N.C. and Weil, R.R. (1999) *The Nature and Properties of Soils*. Prentice Hall, Upper Saddle River, New Jersey, 881 pp.

Carpenter, G.H. (1992) "Current Litter Practices and Future Needs." In: *1992 National Poultry Waste Management Symposium Proceedings*, Blake, J.P., Donald, J.O., and Patterson, P.H. (eds.), pp. 268-273, Auburn University Printing Service, Auburn, AL.

Cropper, J. (2000) Telephone Conversation between Payton Deeks of ICF Consulting and Jim Cropper, Natural Resource Conservation Service, Pennsylvania, 24 May, 6 June and 13 June.

Daly, C., G.H. Taylor, W.P. Gibson, T. Parzybok, G.L. Johnson, and P.A. Pasteris. (1998) "Development of high-quality spatial datasets for the United States." in: *Proc., 1st International Conference on Geospatial Information in Agriculture and Forestry*, Lake Buena Vista, FL. June 1-3, 1998, pp.I-512-I-519.

Daly, C., R.P. Neilson, and D.L. Phillips (1994) "A statistical-topographic model for mapping climatological precipitation over mountainous terrain." *Journal of Applied Meteorology*, 33:140-158.

Deal, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Peter B. Deal, Rangeland Management Specialist, Florida Natural Resource Conservation Service, 21 June.

EPA (1999) *Biosolids Generation, Use and Disposal in the United States*. Office of Solid Waste, U.S. Environmental Protection Agency. Available online at <http://biosolids.policy.net/relatives/18941.PDF>.

EPA (1993) Federal Register. Part II. Standards for the Use and Disposal of Sewage Sludge; Final Rules. U.S. Environmental Protection Agency, 40 CFR Parts 257, 403 and 503.

Eve, M. (2001) E-mail from Marlen Eve of the Natural Resources Ecology Laboratory to Barbara Braatz and Caren Mintz of ICF Consulting, containing statistics on U.S. histosol areas cultivated in 1982, 1992, and 1997, which were extracted from the *1997 National Resources Inventory*, 21 September.

Evers, G.W. (2000) Telephone and E-mail Conversation between Barbara Braatz of ICF Consulting and Gerald W. Evers, Texas Agricultural Experiment Center, Texas A&M University, 7 July and 10 July.

FAO (2001) Yearly U.S. total horse population data from the Food and Agriculture Organization of the United Nations database, <http://apps.fao.org>, last updated May 2, 2001 (Accessed July 30, 2001).

Gerrish, J. (2000) Telephone Conversation between Barbara Braatz of ICF Consulting and Dr. Jim Gerrish, Forage Systems Research Center, University of Missouri, 7 July.

Hoveland, C.S. (2000) Telephone Conversation between Barbara Braatz of ICF Consulting and Carl S. Hoveland, Department of Agronomy, University of Georgia, 7 July.

Hoveland, C.S. and Evers, G.W. (1995) "Arrowleaf, Crimson, and Other Annual Clovers." In: *Forages, Volume I: An Introduction to Grassland Agriculture*, Barnes, R.F., Miller, D.A., and Nelson, C.J. (eds.), pp. 249-260, Iowa State University Press, Ames, IA.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. IPCC National Greenhouse Gas Inventories Programme Technical Support Unit, Kanagawa, Japan. Available online at <http://www.ipcc-nggip.iges.or.jp/gp/report.htm>.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Johnson, D. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Dan Johnson, State Water Management Engineer, California Natural Resource Conservation Service, 23 June.

Karkosh, R. (2000) Telephone conversation between Barbara Braatz of ICF Consulting and Roy Karkosh, Crops Branch, National Agricultural Statistics Service, U.S. Department of Agriculture, 17 July.

Ketzis, J. (1999) Telephone and Email conversations between Marco Alcaraz of ICF Consulting and Jen Ketzis regarding the Animal Science Department Computer Model (Cornell Net Carbohydrate and Protein System), Cornell University, June/July.

Lange, J. (2000) Telephone conversation between Lee-Ann Tracy of ERG and John Lange, Agricultural Statistician, U. S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC, 8 May.

Metcalf and Eddy, Inc. (1991) *Wastewater Engineering: Treatment, Disposal, and Reuse*, Third Edition, McGraw-Hill Publishing Company, NY.

Miller, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Paul Miller, Iowa Natural Resource Conservation Service, 12 June.

Milton, B. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Bob Milton, Chief of Livestock Branch, U.S. Department of Agriculture, National Agriculture Statistics Service, 1 May.

Nevison, C. (2000) "Review of the IPCC methodology for estimating nitrous oxide emissions associated with agricultural leaching and runoff." *Chemosphere-Global Change Science* 2:493-500.

Ogle, Stephen (2002) E-mail from Stephen Ogle of the Natural Resources Ecology Laboratory to Barbara Braatz of ICF Consulting, containing revised statistics on U.S. histosol areas cultivated in 1982, 1992, and 1997, which were extracted from the *1997 National Resources Inventory* by Marlen Eve, 9 January.

Pederson, G.A. (2000) Telephone conversation between Barbara Braatz of ICF Consulting and Dr. Gary A. Pederson, Department of Agronomy, Mississippi State University, 24 July and 25 July.

Pederson, G.A. (1995) "White Clover and Other Perennial Clovers." In: *Forages, Volume I: An Introduction to Grassland Agriculture*, Barnes, R.F., Miller, D.A., and Nelson, C.J. (eds.), pp. 227-236, Iowa State University Press, Ames, IA.

Poe, G., Bills, N., Bellows, B., Crosscombe, P., Koelsch, R., Kreher, M., and Wright, P. (1999) *Documenting the Status of Dairy Manure Management in New York: Current Practices and Willingness to Participate in Voluntary Programs*. Staff Paper, Dept. of Agricultural, Resource, and Managerial Economics, Cornell University, Ithaca, NY, September.

Safley, L.M. (2000) Telephone conversation between Deb Bartram of ERG and L.M. Safley, President, Agri-Waste Technology, June.

Safley, L.M., Casada, M.E., Woodbury, J.W., Roos, J.F. (1992) *Global Methane Emissions from Livestock and Poultry Manure*. EPA/400/1-91/048, Office of Air and Radiation, U.S. Environmental Protection Agency. February.

Schueneman, T. (2001) Telephone conversation between Caren Mintz of ICF Consulting and Tom Schueneman, Palm Beach County Agricultural Extension Agent, Florida, 30 July.

Smith, T. (2001) Telephone conversation between Caren Mintz of ICF Consulting and Terrie Smith, Sem-Chi Rice Company, Florida, 31 August.

Stettler, D. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Don Stettler, Environmental Engineer, National Climate Center, Oregon Natural Resource Conservation Service, 27 June.

Schueneman, T. (1999) Telephone conversation between Payton Deeks of ICF Consulting and Tom Schueneman, Palm Beach County Agricultural Extension Agent, Florida, 10 August.

Strehler, A. and Stützle, W. (1987) "Biomass Residues". In: *Biomass*, Hall, D.O. and Overend, R.P. (eds.), pp. 75-102, John Wiley and Sons, Ltd. Chichester, UK.

Sweeten, J. (2000) Telephone conversation between Indra Mitra of ERG and John Sweeten, Texas A&M University, June.

Taylor, N.L. and Smith, R.R. (1995) "Red Clover." In: *Forages, Volume I: An Introduction to Grassland Agriculture*, Barnes, R.F., Miller, D.A., and Nelson, C.J. (eds.), pp. 217-226, Iowa State University Press, Ames, IA.

Turn, S.Q., Jenkins, B.M., Chow, J.C., Pritchett, L.C., Campbell, D., Cahill, T., and Whalen, S.A. (1997) "Elemental characterization of particulate matter emitted from biomass burning: Wind tunnel derived source profiles for herbaceous and wood fuels." Journal of Geophysical Research 102 (D3): 3683-3699.

TVA (1994) *Commercial Fertilizers 1994*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1993) *Commercial Fertilizers 1993*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1992a) *Commercial Fertilizers 1992*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1992b) *Fertilizer Summary Data 1992*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1991) *Commercial Fertilizers 1991*. Tennessee Valley Authority, Muscle Shoals, AL.

USDA (2001a) *Crop Production 2000 Summary*. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu>. Accessed July 2001.

USDA (2001b) *Cattle*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 26. (Data also available online at <http://www.nass.usda.gov:81/ipedb/>).

USDA (2001c) *Cattle on Feed Cattle*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January 19. (Data also available online at <http://www.nass.usda.gov:81/ipedb/>).

USDA (2001d) *Hogs and Pigs*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. March 30. (Data also available online at <http://www.nass.usda.gov:81/ipedb/>).

USDA (2001e) *Chicken and Eggs - 1999 Summary Cattle*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January.

USDA (2001f) *Poultry Production and Value - 1999 Summary*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. April.

USDA (2001g) *Sheep and Goats*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January. (Data also available online at <http://www.usda.gov/nass/pubs/reportname.htm>).

USDA (2000a) *Cattle on Feed Cattle*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. 14 April (data also available online at <http://www.nass.usda.gov:81/ipedb/>).

USDA (2000b) *Cattle*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. 28 January (data also available online at <http://www.nass.usda.gov:81/ipedb/>).

USDA (2000c) *Chicken and Eggs - 1999 Summary Cattle*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January.

USDA (2000d) *Chicken and Eggs - Final Estimates 1988-1993*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. 3 May.

USDA (2000e) *Hogs and Pigs*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. 24 March (data also available online at <http://www.nass.usda.gov:81/ipedb/>).

USDA (2000f) *Poultry Production and Value - 1999 Summary*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. April.

USDA (2000g) *Sheep and Goats*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January.

USDA (2000h) *1997 National Resources Inventory*. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

USDA (2000i) *Crop Production 1999 Summary*. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/reports/nassr/field/pcp-bban/cropan00.pdf>. Accessed July 2001.

USDA (1999a) *Cattle - Final Estimates 1994-98*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January (data also available online at <http://www.nass.usda.gov:81/ipedb/>).

USDA (1999b) *Poultry Production and Value - Final Estimates 1994-97*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. March.

USDA (1999c) *Sheep and Goats - Final Estimates 1994-1998*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January.

USDA (1999d) <http://www.nass.usda.gov/census/census97/volume1/us-51/us2_25.pdf>, Table 25. Miscellaneous Livestock and Animal Specialties Inventory and Sales: 1997 and 1992, U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC. (Accessed May 2000).

USDA (1999e) *1992 and 1997 Census of Agriculture* (CD-ROM), National Agriculture Statistics Service, U.S. Department of Agriculture.

USDA (1998a) *Chicken and Eggs - Final Estimates 1994-97*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. December.

USDA (1998b) *Field Crops Final Estimates 1992-97*. Statistical Bulletin Number 947 a. National Agricultural Statistics Service, U.S. Department of Agriculture, GPO, Washington, DC. Available online at <http://usda.mannlib.cornell.edu>. Accessed July 2001.

USDA (1998c) *Hogs and Pigs - Final Estimates 1993-97*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. December (data also available online at <http://www.nass.usda.gov:81/ipedb/>).

USDA (1998d) *Nutrients Available from Livestock Manure Relative to Crop Growth Requirements*, Resource Assessment and Strategic Planning Working Paper 98-1, U.S. Department of Agriculture, Natural Resources Conservation Service. February.

USDA (1996) *Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH)*, Part 651, U.S. Department of Agriculture, Natural Resources Conservation Service. July.

USDA (1995a) *Cattle - Final Estimates 1989-93*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January (data also available online at <http://www.nass.usda.gov:81/ipedb/>).

USDA (1995b) *Poultry Production and Value - Final Estimates 1989-1993*, National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC.

USDA (1994a) *Field Crops: Final Estimates, 1987-1992.* Statistical Bulletin Number 896. National Agriculture Statistics Service, U.S. Department of Agriculture, GPO, Washington, DC. Available online at http://usda.mannlib.cornell.edu/data-sets/crops/94896/sb896.txt.

USDA (1994b) *Hogs and Pigs - Final Estimates 1988-92,* National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. December (data also available online at <http://www.nass.usda.gov:81/ipedb/>).

USDA (1994c) *Sheep and Goats - Final Estimates 1989-1993,* National Agriculture Statistics Service, U.S. Department of Agriculture, Washington, DC. January.

Wright, P. (2000) Telephone conversation between Lee-Ann Tracy of ERG and Peter Wright, Cornell University, College of Agriculture and Life Sciences, 23 June.

## Agricultural Residue Burning

Barnard, G., and Kristoferson, L. (1985) *Agricultural Residues as Fuel in the Third World.* Earthscan Energy Information Programme and the Beijer Institute of the Royal Swedish Academy of Sciences. London, England.

Bollich, P. (2000) Telephone conversation between Payton Deeks of ICF Consulting and Pat Bollich, Professor with Louisiana State University Agriculture Center, 17 May.

California Air Resources Board (2001) *Progress Report on the Phase Down and the 1998-2000 Pause in the Phase Down of Rice Straw Burning in the Sacramento Valley Air Basin,* Proposed 2001 Report to the Legislature, June.

California Air Resources Board (1999) *Progress Report on the Phase Down of Rice Straw Burning in the Sacramento Valley Air Basin,* Proposed 1999 Report to the Legislature, December.

Cibrowski, P. (1996) Telephone conversation between Heike Mainhardt of ICF Incorporated and Peter Cibrowski, Minnesota Pollution Control Agency, 29 July.

EPA (1994) *International Anthropogenic Methane Emissions: Estimates for 1990, Report to Congress.* EPA 230-R-93-010. Office of Policy Planning and Evaluation, U.S. Environmental Protection Agency. Washington, DC.

EPA (1992) *Prescribed Burning Background Document and Technical Information Document for Prescribed Burning Best Available Control Measures.* EPA-450/2-92-003. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC.

Fife, L. (1999) Telephone conversation between Catherine Leining of ICF Consulting and Les Fife, President and General Manager, Fife Environmental, 9 June.

Guethle, D. (2001) Telephone conversation between Caren Mintz of ICF Consulting and David Guethle, Agronomy Specialist, Missouri Cooperative Extension Service, 31 July.

Guethle, D. (2000) Telephone conversation between Payton Deeks of ICF Consulting and David Guethle, Agronomy Specialist, Missouri Cooperative Extension Service, 17 May.

Guethle, D. (1999) Telephone conversation between Payton Deeks of ICF Consulting and David Guethle, Agronomy Specialist, Missouri Cooperative Extension Service, 6 August.

ILENR (1993) *Illinois Inventory of Greenhouse Gas Emissions and Sinks: 1990.* Office of Research and Planning, Illinois Department of Energy and Natural Resources. Springfield, IL.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Jenkins, B.M., Turn, S.Q., and Williams, R.B. (1992) Atmospheric emissions from agricultural burning in California: determination of burn fractions, distribution factors, and crop specific contributions. *Agriculture, Ecosystems and Environment* 38:313-330.

Ketzis, J. (1999) Telephone conversation between Marco Alcaraz of ICF Consulting and Jen Ketzis of Cornell University, June/July.

Klosterboer, A. (2001) Telephone conversation between Caren Mintz of ICF Consulting and Arlen Klosterboer, Extension Agronomist, Texas A & M University, 6 August.

Klosterboer, A. (2000) Telephone conversation between Payton Deeks of ICF Consulting and Arlen Klosterboer, Extension Agronomist, Texas A & M University, 18 May.

Klosterboer, A. (1999a) Telephone conversation between Catherine Leining of ICF Consulting and Arlen Klosterboer, Extension Agronomist, Texas A & M University, 10 June.

Klosterboer, A. (1999b) Telephone conversation between Payton Deeks of ICF Consulting and Arlen Klosterboer, Extension Agronomist, Texas A & M University, 12 August.

Linscombe, S. (2001) Email Correspondence between Caren Mintz of ICF Consulting and Steve Linscombe, Research Agronomist, Rice Research Station in Crowley, LA, 30 July – 1 August.

Linscombe, S. (1999a) Telephone conversation between Catherine Leining of ICF Consulting and Steve Linscombe, Research Agronomist, Rice Research Station in Crowley, LA, 3 June.

Linscombe, S. (1999b) Telephone conversation between Payton Deeks of ICF Consulting and Steve Linscombe, Research Agronomist, Rice Research Station in Crowley, LA, 9 August.

Najita, T. (2001) Telephone conversation between Caren Mintz of ICF Consulting and Theresa Najita, Air Pollution Specialist, California Air Resources Board, 31 July.

Najita, T. (2000) Telephone conversation between Payton Deeks of ICF Consulting and Theresa Najita, Air Pollution Specialist, California Air Resources Board, 17 August.

Noller, J. (1996) Telephone conversation between Heike Mainhardt of ICF Incorporated and John Noller, Missouri Department of Natural Resources, 30 July.

Oregon Department of Energy (1995) *Report on Reducing Oregon's Greenhouse Gas Emissions: Appendix D Inventory and Technical Discussion.* Oregon Department of Energy. Salem, OR.

Schueneman, T. (2001) Telephone conversation between Caren Mintz of ICF Consulting and Tom Schueneman, Palm Beach County Agricultural Extension Agent, Florida, 30 July.

Schueneman, T. (1999a) Telephone conversation between Catherine Leining of ICF Consulting and Tom Schueneman, Palm Beach County Agricultural Extension Agent, Florida, 7 June.

Schueneman, T. (1999b) Telephone conversation between Payton Deeks of ICF Consulting and Tom Schueneman, Palm Beach County Agricultural Extension Agent, Florida, 10 August.

Slaton, N. (2000) Telephone conversation between Payton Deeks of ICF Consulting and Nathan Slaton, Extension Agronomist - Rice, University of Arkansas Division of Agriculture Cooperative Extension Service, 20 May.

Slaton, N. (1999a) Telephone conversation between Catherine Leining of ICF Consulting and Dr. Nathan Slaton, Extension Agronomist - Rice, University of Arkansas Division of Agriculture Cooperative Extension Service, 3 June.

Slaton, N. (1999b) Telephone conversation between Payton Deeks of ICF Consulting and Dr. Nathan Slaton, Extension Agronomist - Rice, University of Arkansas Division of Agriculture Cooperative Extension Service, 6 August.

Smith, T. (2001) Telephone conversation between Caren Mintz of ICF Consulting and Terrie Smith, Sem-Chi Rice Company, Florida, 31 August.

Street, J. (2001) Telephone conversation and email correspondence between Caren Mintz of ICF Consulting and Joe Street, Mississippi State University, Delta Research Center, 1 August.

Street, J. (2000) Telephone conversation between Payton Deeks of ICF Consulting and Joe Street, Mississippi State University, Delta Research Center, 17 May.

Street, J. (1999a) Telephone conversation between Catherine Leining of ICF Consulting and Joe Street, Mississippi State University, Delta Research Center, 8 June.

Street, J. (1999b) Telephone conversation between Payton Deeks of ICF Consulting and Joe Street, Mississippi State University, Delta Research Center, 6 August.

Strehler, A. and Stützle, W. (1987) "Biomass Residues." In: Hall, D.O. and Overend, R.P. (eds.) *Biomass*. John Wiley and Sons, Ltd. Chichester, UK.

Turn, S.Q., Jenkins, B.M., Chow, J.C., Pritchett, L.C., Campbell, D., Cahill, T., and Whalen, S.A. (1997) "Elemental characterization of particulate matter emitted from biomass burning: Wind tunnel derived source profiles for herbaceous and wood fuels." *Journal of Geophysical Research* 102(D3):3683-3699.

University of California (1977) *Emission Factors From Burning of Agricultural Waste Collected in California.* University of California, Davis.

USDA (2001) *Crop Production 2000 Summary*. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/reports/nassr/field/pcp-bban/cropan01.pdf>.

USDA (2000) *Crop Production 1999 Summary*. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/reports/nassr/field/pcp-bban/cropan00.pdf>.

USDA (1998) *Field Crops, Final Estimates 1992-1997*. Statistical Bulletin No. 947a. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/usda/reports/general/sb/b9471298.pdf>.

USDA (1994) *Field Crops, Final Estimates 1987-1992*. Statistical Bulletin No. 896. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/data-sets/crops/94896/sb896.txt.>

Wilson, C. (2001) Telephone conversation between Caren Mintz of ICF Consulting and Dr. Chuck Wilson, Rice Specialist, University of Arkansas Division of Agriculture Cooperative Extension Service, 1 August.

Wisconsin Department of Natural Resources (1993) *Wisconsin Greenhouse Gas Emissions: Estimates for 1990*. Bureau of Air Management, Wisconsin Department of Natural Resources, Madison, WI.

## Land-Use Change and Forestry


Adams, D.M., and Haynes, R.W. (1980) "The Timber Assessment Market Model: Structure, Projections, and Policy Simulations." *Forest Science Monograph* 22, Society of American Foresters, Bethesda, MD, 64 pp.

Alig, R.J. (1985) "Econometric Analysis of Forest Acreage Trends in the Southeast." *Forest Science* 32: 119-134.

Armentano, T.V. and Verhoeven, J.T.A. (1990) "Biogeochemical Cycles: Global." In: *Wetlands and Shallow Continental Water Bodies*. Patten, B.C., et al. (eds.) SPB Academic Publishing, The Hague, Netherlands, Volume I, pp. 281-311.

Barlaz, M.A. (1998) "Carbon Storage During Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills." *Global Biogeochemical Cycles* 12: 373-380.

Birdsey, R.A. (1992) *Carbon Storage and Accumulation in United States Forest Ecosystems*. USDA Forest Service, Gen. Tech. Rep. WO-59, Washington, DC.

Birdsey, R.A. and Heath, L.S. (2001) "Forest Inventory Data, Models, and Assumptions for Monitoring Carbon Flux." p. 125-135. In: Lal, R., ed. *Soil Carbon Sequestration and the Greenhouse Effect*. SSSA Special publication No. 57. Soil Science Society of America, Inc. Madison, WI, 236 p.

Birdsey, R.A. and Heath, L.S. (1995) "Carbon Changes in U.S. Forests." In: *Productivity of America's Forests and Climate Change*. Gen. Tech. Rep. RM-271. Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Fort Collins, CO, pp. 56-70.

Brady, N.C. and Weil, R.R. (1999) *The Nature and Properties of Soils*. Prentice Hall, Upper Saddle River, New Jersey, 881 pp.

Cairns, M.A., Brown, S., Helmer, E.H., Baumgardner, G.A., (1997) "Root Biomass Allocation in the World's Upland Forests." *Oceologia* 111: 1-11.

CTIC (1998) *Crop Residue Management Executive Summary*. Conservation Technology Information Center, West Lafayette, Indiana.

Daly, C., Neilson, R.P. and Phillips, D.L. (1994) "A Statistical-Topographic Model for Mapping Climatological Precipitation over Mountainous Terrain." *Journal of Applied Meteorology* 33:140-158.

deVries, R.E. (1987) *A Preliminary Investigation of the Growth and Longevity of Trees in Central Park*. New Brunswick, NJ: Rutgers University, M.S. thesis.

Dwyer, J.F., Nowak, D.J., Noble, M.H., and Sisinni, S.M. (2000) *Connecting People with Ecosystems in the 21st Century: An Assessment of Our Nation's Urban Forests*. General Technical Report PNW-GTR-490, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

EPA (1998) *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. EPA530-R-98-013.

Eve, M., Ogle, S., Sperow, M., and Paustian, K. (2001) *Agricultural Soil C Emissions, 1990-2000: Documentation to Accompany EPA Inventory Tables*. Natural Resource Ecology Laboratory, Fort Collins, CO, Provided in 9 January 2002 e-mail from M.D. Eve to B.V. Braatz at ICF Consulting.

Fleming, L.E. (1988) *Growth Estimation of Street Trees in Central New Jersey*. New Brunswick, NJ: Rutgers University, M.S. thesis.

Follett, R.F., Kimble, J.M., and Lal, R. (2001) "The Potential of U.S. Grazing Lands to Sequester Soil Carbon." In: Follett, R.F., Kimble, J.M., and Lal, R. (eds.) *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect*. Lewis Publishers, Boca Raton, FL, pp. 401-430.

Franklin Associates (1999) *Characterization of Municipal Solid Waste in the United States: 1998 Update*. Prepared for U.S. Environmental Protection Agency. Prairie Village, KS.

Frayer, W.E., and Furnival, G.M. (1999) "Forest Survey Sampling Designs: A History." *Journal of Forestry* 97(12): 4-10.

Gebhart, D.L., Johnson, H.B., Mayeux, H.S., and Polley, H.W. (1994) "The CRP Increases Soil Organic Carbon." *J. Soil and Water Conservation,* 49:488-492.

Gillespie, A.J.R. (1999) "Rationale for a National Annual Forest Inventory Program." *Journal of Forestry* 97(12): 16-20.

Haynes, R.W. (technical coordinator) (2001a) *RPA 2000 Timber Assessment Draft Review*. Pacific Northwest Research Station, Forest Service, U. S. Department of Agriculture, Portland, OR. Downloaded from <http:www.fs.fed.us/pnw/sev/rpa/>.

Haynes, R.W. et al. (2001b) *The 2000 RPA Timber Assessment*. Gen. Tech. Rep. Portland, OR: Forest Service, U. S. Department of Agriculture. In preparation, draft available online: <http:www.fs.fed.us/pnw/sev/rpa/>.

Heath, L.S. and Smith, J.E. (2000a) "An Assessment of Uncertainty in Forest Carbon Budget Projections." *Environmental Science & Policy* 3:73-82.

Heath, L. S. and Smith, J.E. (2000b) "Soil Carbon Accounting and Assumptions for Forestry and Forest-related Land Use Change." In: *The Impact of Climate Change on America's Forests*. Joyce, L.A., and Birdsey, R.A. Gen. Tech. Rep. RMRS-59. Rocky Mountain Research Station, Forest Service, U.S. Department of Agriculture, Fort Collins, CO, pp. 89-101.

Heath, L.S., Birdsey, R.A., Row, C., and Plantinga, A.J. (1996) "Carbon Pools and Fluxes in U.S. Forest Products." In: Apps, M.J. and Price, D.T. (eds.) *Forest Ecosystems, Forest Management and the Global Carbon Cycle*. Springer-Verlag, Berlin, pp. 271-278.

Heath, L.S., and Birdsey, R.A. (1993) "Carbon Trends of Productive Temperate Forests of the Coterminous United States." *Water, Air, and Soil Pollution* 70: 279-293.

Howard, J.L. (2001) *U.S. Timber Production, Trade, Consumption, and Price Statistics 1965-1999*. Res. Pap. RP-595. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 90 p.

Huggins, D.R., Allan, D.L., Gradner, J.C., Karlen, D.L., Bezdicek, D.F., Rosek, M.J., Alms, M.J., Flock, M., Miller, B.S, and Staben, M.L. (1998) "Enhancing Carbon Sequestration in CRP-managed Land. In: Lal, R., Kimble, J.M., Follett, R.F. and Stewart, B.A. (eds) *Management of Carbon Sequestration in Soil*. pp. 323-350. CRC Press, Boca Raton, FL, USA.

Ince, P. J. (1994) *Recycling and Long-Range Timber Outlook*. Gen. Tech. Rep. RM-242. Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. Fort Collins, CO, 66 p.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

Johnson, D.W., and Curtis, P.S. (2001) "Effects of Forest Management on Soil C and N Storage: Meta-analysis." *Forest Ecology and Management*, 140(2): 227-238.

May, D.M. (1998) *The North Central Forest Inventory & Analysis Timber Product Output Database—A regional composite approach*. General Technical Report NC-200, U.S. Department of Agriculture, Forest Service, North Central Research Station, St. Paul, MN, 16 pp.

Metherell, A. K., Harding, L.A., Cole, C.V. and Parton, W.J. (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Mills, J.R., and Kincaid, J.C. (1992) *The Aggregate Timberland Assessment System-ATLAS: A Comprehensive Timber Projection Model*. Gen. Tech. Rep. PNW-281. Pacific Northwest Research Station, Forest Service, U.S. Department of Agriculture, Portland, OR, 160 pp.

Nowak, D.J. (2002) E-mail from David Nowak of the USDA Forest Service to Barbara Braatz at ICF Consulting, containing information on possible urban tree carbon and forest carbon overlap, 10 January.

Nowak, D.J. (1994) "Atmospheric Carbon Dioxide Reduction by Chicago's Urban Forest." In: McPherson, E.G., Nowak, D. J., and Rowntree, R.A. (eds.) *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project*. USDA Forest Service General Technical Report NE-186, Radnor, PA, pp. 83-94.

Nowak, D.J., (1986) "Silvics of an Urban Tree Species: Norway Maple (Acer platanoides L.)." Syracuse, NY: State University of New York, College of Environmental Science and Forestry, M.S. thesis.

Nowak, D.J. and Crane, D.E. (2001) "Carbon Storage and Sequestration by Urban Trees in the United States." *Environmental Pollution* 116(3): 381-389.

Nowak, D.J., Crane, D.E., Stevens, J.C., Ibarra, M. (in press) *Brooklyn's Urban Forest*, USDA Forest Service General Technical Report, Newtown Square, PA.

Nowak, D.J., Noble, M.H., Sisinni, S.M., Dwyer, J.F. (2001) "Assessing the U.S. Urban Forest Resource." *Journal of Forestry*. 99(3): 37-42.

NRCS (2000) "Digital Data and Summary Report: 1997 National Resources Inventory." Revised December 2000. United States Department of Agriculture, Natural Resources Conservation Service, Resources Inventory Division, Beltsville, MD.

NRCS (1997) "National Soil Survey Laboratory Characterization Data." *Digital Data*. USDA - NRCS, Lincoln, NE.

NRCS (1981) "Land Resource Regions and Major Land Resource Areas of the United States." *USDA Agriculture Handbook 296*. United States Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE, 156 pp.

Ogle, S.M., Breidt, F.J., Eve, M.D. and Paustian, K. (in prep.) *Uncertainty Analysis for Soil Organic Carbon Storage in U.S. Agricultural Lands Using the IPCC Approach*.

Parton, W.J., Ojima, D.S., Cole, C.V., and Schimel, D.S. (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management." In: *Quantitative Modeling of Soil Forming Processes*. Special Publication 39, Soil Science Society of America, Madison, WI, pp. 147-167.

Paustian, K., Killian, K., Cipra, J., Elliott, E.T., Bluhm, G, and Smith, J.L. (2001) "Modeling and Regional Assessment of Soil Carbon: A case study of the Conservation Reserve Program." In: Lal, R. and McSweeney, K. (Eds). *Soil Carbon Sequestration and the Greenhouse Effect*. Soil Science Society of America Special Publication Number 57, Madison WI, pp 207-225.

Plantinga, A.J., and Birdsey, R.A. (1993) "Carbon Fluxes Resulting from U.S. Private Timberland Management." *Climatic Change* 23:37-53.

Powell, D.S., Faulkner, J.L., Darr, D.R., Zhu, Z., and MacCleery, D.W. (1993) *Forest Resources of the United States, 1992*. Gen. Tech. Rep. RM-234. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, 132 pp.

Skog, K.E. and Nicholson, G.A. (1998) "Carbon Cycling Through Wood Products: The Role of Wood and Paper Products in Carbon Sequestration." *Forest Products Journal* 48:75-83.

Smith, J.E., Heath, L.S., Jenkins, J.C., and Chojnacky, D.C. (In review) "Forest Tree Volume-to-biomass Models and Estimates for Live and Standing Dead Trees of U.S. Forests."

Smith, W.B., Vissage, J.S., Darr, D.R., and Sheffield, R.M. (2001) *Forest Resources of the United States, 1997*. Gen. Tech. Rep. NC-219. North Central Research Station, Forest Service, U.S. Department of Agriculture, St. Paul, MN, 191 pp.

Smith, J.E. and Heath, L.S. (In review) "Estimators of Forest Floor Carbon for United States Forests."

Smith, J.E., and Heath, L.S. (2001) "Identifying Influences on Model Uncertainty: An Application Using a Forest Carbon Budget Model." *Environmental Management* 27:253-267.

Smith, J.E., and Heath, L.S. (2000) "Considerations for Interpreting Probabilistic Estimates of Uncertainty of Forest Carbon." In: *The Impact of Climate Change on America's Forests*. Gen. Tech. Rep. RMRS-59. Rocky Mountain Research Station, Forest Service, U.S. Department of Agriculture, Fort Collins, CO, pp. 102-111.

Smith, W.B. and Sheffield, R.M. (2000) *1997 RPA Assessment: The United States Forest Resource Current Situation (Final Statistics)*. Forest Service, U.S. Department of Agriculture. July 2000 Review Draft. Downloaded from <http://www.srsfia.usfs.msstate.edu/wo/review.htm>.

Smith, W.B. and Shifley, S.R. (1984) *Diameter Growth, Survival, and Volume Estimates for Trees in Indiana and Illinois*. Res. Pap. NC-257. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station.

Tepordei, V. V. (2001) "Crushed Stone," In: *Minerals Yearbook 1999*. U.S. Department of the Interior/U.S. Geological Survey, Washington, DC. (Available at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/630499.pdf>) Accessed August 2001.

Tepordei, V. V. (2000) "Crushed Stone," In: *Minerals Yearbook 1998*. U.S. Department of the Interior/U.S. Geological Survey, Washington, DC. (Available at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/630498.pdf>) Accessed August 2000.

Tepordei, V. V. (1999) "Crushed Stone," In: *Minerals Yearbook 1997*. U.S. Department of the Interior/U.S. Geological Survey, Washington, DC. (Available at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/630497.pdf>) Accessed August 2000.

Tepordei, V. V. (1998) "Crushed Stone," In: *Minerals Yearbook 1996*. U.S. Department of the Interior/U.S. Geological Survey, Washington, DC. (Available at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/630496.pdf>). Accessed August 2000.

Tepordei, V. V. (1997) "Crushed Stone," In: *Minerals Yearbook 1995*. U.S. Department of the Interior/U.S. Geological Survey, Washington, DC. pp. 783-809.

Tepordei, V. V. (1996) "Crushed Stone," In: *Minerals Yearbook 1994*. U.S. Department of the Interior/Bureau of Mines, Washington, DC. (Available at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/630494.pdf>). Accessed August 2000.

Tepordei, V. V. (1995) "Crushed Stone," In: *Minerals Yearbook 1993*. U.S. Department of the Interior/Bureau of Mines, Washington, DC, pp. 1107–1147.

Tepordei, V. V. (1994) "Crushed Stone," In: *Minerals Yearbook 1992*. U.S. Department of the Interior/Bureau of Mines, Washington, DC, pp. 1279-1303.

Tepordei, V. V. (1993) "Crushed Stone," In: *Minerals Yearbook 1991*. U.S. Department of the Interior/Bureau of Mines, Washington, DC, pp. 1469-1511.

Towery, D. (2001) Adjustments to the CTIC (1998) tillage data to reflect long-term trends provided by Dan Towery of the Conservation Technology Information Center, West Lafayette, Indiana, to Marlen Eve of the National Resource Ecology Laboratory, Fort Collins, Colorado. February.

Ulrich, A.H. (1989) *U.S. Timber Production, Trade, Consumption, and Price Statistics, 1950-1987*. USDA Miscellaneous Publication No. 1471, U.S. Department of Agriculture, Forest Service, Washington, DC, 77 pp.

USDA (2000a) *1997 National Resources Inventory*. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

USDA (2000b) *USDA Agricultural Baseline Projections to 2009*. Staff Report WAOB-2000-1. U.S. Department of Agriculture, Washington, DC.

USDA (1991) *State Soil Geographic Data Base (STATSGO): Data Users Guide*. U.S. Department of Agriculture, Soil Conservation Service, National Resource Conservation Service. Miscellaneous Publication Number 1492, U.S. Government Printing Office.

USDA Forest Service (1964) *The Demand and Price Situation for Forest Products, 1964*. Misc. Pub. 983, Washington, DC.

USGS (2001) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2001.* U.S. Geological Survey, Reston, VA.

Waddell, K.L., Oswald, D.D. and Powell, D.S. (1989) *Forest Statistics of the United States, 1987.* Resource Bulletin PNW-RB-168. Pacific Northwest Research Station, Forest Service, U.S. Department of Agriculture, Portland, OR, 106 pp.

# Waste

## Landfills

40 CFR Part 60, Subparts Cc (1999) and WWW. Available online at < http://www.access.gpo.gov/cfr >.

Barlaz, M. A. (1997) *Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale Landfills*, U.S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC. EPA 600/R-97-071.

Bingemer, H. and J. Crutzen (1987) "The Production of Methane from Solid Wastes," *Journal of Geophysical Research*, 92:2181-2187.EPA (1998) *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste.* U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. EPA530-R-98-013.

BioCycle (2001) "13th Annual BioCycle Nationwide Survey: The State of Garbage in America," N. Goldstein, BioCycle, December.

BioCycle (2000) "BioCycle Nationwide Survey: The State of Garbage in America," N. Goldstein, *BioCycle,* November.

EPA (2000) *Characterization of Municipal Solid Waste in the United States: 1999 Factsheet*, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. EPA530-F-00-024.

EPA (1998) *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste.* U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. EPA530-R-98-013.

EPA (1993) *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress*, U.S. Environmental Protection Agency, Office of Air and Radiation, Washington, DC. EPA/430-R-93-003. April.

EPA (1988) *National Survey of Solid Waste (Municipal) Landfill Facilities*, U.S. Environmental Protection Agency, Washington, DC. EPA/530-SW-88-011. September.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Liptay, K., et al. (1998) "Use of Stable Isotopes to Determine Methane Oxidation in Landfill Cover Soils," *JGR Atmospheres*, 103D, 8243-8250 pp.

## Wastewater Treatment

EPA (1999) *Kraft Pulp Mill Compliance Assessment Guide (CAA, CWA, RCRA, and EPCRA).* EPA/310-B-99-001. United States Environmental Protection Agency, Office of Compliance, Washington, DC. May, 1999.

EPA (1997a) *Supplemental Technical Development Document for Effluent Limitations Guidelines and Standards for the Pulp, Paper, and Paperboard Category.* United States Environmental Protection Agency, Office of Water. EPA/821-R-97-011, Washington, DC, October, 1997.

EPA (1997b) *Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment.* United States Environmental Protection Agency, Office of Policy, Planning, and Evaluation. EPA-600/R-97-091, Washington, DC, September, 1997.

EPA (1993) *Development Document for the Proposed Effluent Limitations Guidelines and Standards for the Pulp, Paper and Paperboard Point Source Category.* EPA-821-R-93-019. United States Environmental Protection Agency, Office of Water, Washington, DC, October, 1993.

IPCC (2000) *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, May, 2000.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Lockwood-Post (1992-2001) *Lockwood-Post's Directory of Pulp, Paper and Allied Trades,* Miller-Freeman Publications, San Francisco, CA.

Metcalf & Eddy, Inc. (1991) *Wastewater Engineering: Treatment, Disposal, Reuse.* McGraw-Hill: New York.

Nemerow, Nelson Leonard and Avijit Dasgupta. 1991. Industrial and Hazardous Waste Treatment. Van Nostrand Reinhold. NY. ISBN 0-442-31934-7.

U.S. Census Bureau (2001) Statistical Abstract of the United States. Washington, DC. (Available on the Internet at <http://www.census.gov/prod/www/statistical-abstract-us.html>.)

USDA National Agricultural Statistics Service (2001). Washington, DC. (Available on the Internet at <http://www.usda.gov/nass/>.)

WORLDBANK (1999) Pollution Prevention and Abatement Handbook 1998, Toward Cleaner Production. The International Bank for Reconstruction and Development/The WORLDBANK. 1818 H Street, N.W. Washington, DC. 20433, USA. ISBN 0-8213-3638-X.

## Human Sewage

FAO (2001) *FAOSTAT Statistical Database*, United Nations Food and Agriculture Organization. (Available on the Internet at <http://apps.fao.org/lim500/nph-wrap.pl?FoodBalanceSheet&Domain=FoodBalanceSheet> (Accessed August 17, 2001)).

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

U.S. Census Bureau (2001) *Monthly Estimates of the United States Population: April 1, 1980 to July 1, 2001*, Population Estimates Program, Population Division, U.S. Census Bureau, Washington, DC. (Available on the Internet at <http://www.census.gov/population/estimates/nation/intfile1-1.txt> (Accessed September 7, 2001).

## Waste Sources of Ambient Air Pollutants

EPA (2001) Unpublished data provided by U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, October.

# Annexes

The following twenty-six annexes provide additional information to the material presented in the main body of this report. Annexes A through O discuss methodologies for individual source categories in greater detail than was presented in the main body of the report and include explicit activity data and emission factor tables. Annex P analyzies the key sources in this report. Annex Q presents a summary of Global Warming Potential values. Annexes R and S summarize U.S. emissions of ozone depleting substances (e.g., CFCs and HCFCs) and sulfur dioxide ($SO_2$), respectively. Annex T provides a complete list of emission sources assessed in this report. Annex U presents the IPCC reference approach for estimating $CO_2$ emissions from fossil fuel combustion. Annex V addresses the criteria for the inclusion of an emission source category and some of the sources that meet the criteria but are nonetheless excluded from U.S. estimates. Annex W provides some useful constants, unit definitions, and conversions. Annexes X and Y provide a listing of abbreviations and chemical symbols used. Finally, Annex Z contains a glossary of terms related to greenhouse gas emissions and inventories.

**List of Annexes**


| | |
|---|---|
| ANNEX A | Methodology for Estimating Emissions of $CO_2$ from Fossil Fuel Combustion |
| ANNEX B | Methodology for Estimating Carbon Stored in Products from Non-Energy Uses of Fossil Fuels |
| ANNEX C | Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Ambient Air Pollutants from Stationary Combustion |
| ANNEX D | Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Ambient Air Pollutants from Mobile Combustion |
| ANNEX E | Methodology for Estimating $CH_4$ Emissions from Coal Mining |
| ANNEX F | Methodology for Estimating $CH_4$ Emissions from Natural Gas Systems |
| ANNEX G | Methodology for Estimating $CH_4$ Emissions from Petroleum Systems |
| ANNEX H | Methodology for Estimating $CO_2$ Emissions from Municipal Solid Waste Combustion |
| ANNEX I | Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military |
| ANNEX J | Methodology for Estimating HFC, PFC, and $SF_6$ Emissions from Substitution of Ozone Depleting Substances |
| ANNEX K | Methodology for Estimating $CH_4$ Emissions from Enteric Fermentation |
| ANNEX L | Methodology for Estimating $CH_4$ and $N_2O$ Emissions from Manure Management |
| ANNEX M | Methodology for Estimating $N_2O$ Emissions from Agricultural Soil Management |
| ANNEX N | Methodology for Estimating $CO_2$ Emissions and Sinks from Forest Carbon Stocks |
| ANNEX O | Methodology for Estimating $CH_4$ Emissions from Landfills |
| ANNEX P | Key Source Analysis |
| ANNEX Q | Global Warming Potential Values |
| ANNEX R | Ozone Depleting Substance Emissions |
| ANNEX S | Sulfur Dioxide Emissions |
| ANNEX T | Complete List of Source Categories |
| ANNEX U | IPCC Reference Approach for Estimating $CO_2$ Emissions from Fossil Fuel Combustion |
| ANNEX V | Sources of Greenhouse Gas Emissions Excluded |
| ANNEX W | Constants, Units, and Conversions |
| ANNEX X | Abbreviations |
| ANNEX Y | Chemical Formulas |
| ANNEX Z | Glossary |

# ANNEX A

## Methodology for Estimating Emissions of $CO_2$ from Fossil Fuel Combustion

Carbon dioxide ($CO_2$) emissions from fossil fuel combustion were estimated using a "bottom-up" methodology characterized by six steps. These steps are described below.

### Step 1: Determine Energy Consumption by Fuel Type and Sector

The bottom-up methodology used by the United States for estimating $CO_2$ emissions from fossil fuel combustion is conceptually similar to the approach recommended by the Intergovernmental Panel on Climate Change (IPCC) for countries that intend to develop detailed, sectoral-based emission estimates (IPCC/UNEP/OECD/IEA 1997). Basic consumption data are presented in Columns 2-8 of Table A-1 through Table A- 11, with totals by fuel type in Column 8 and totals by end-use sector in the last rows. Fuel consumption data for the bottom-up approach were obtained directly from the Energy Information Administration (EIA) of the U.S. Department of Energy. These data were first gathered in physical units, and then converted to their energy equivalents (see "Converting Physical Units to Energy Units" in Annex W). The EIA data were collected through a variety of consumption surveys at the point of delivery or use and qualified with survey data on fuel production, imports, exports, and stock changes. Individual data elements were supplied by a variety of sources within EIA. Most information was taken from published reports, although some data were drawn from unpublished energy studies and databases maintained by EIA.

Energy consumption data were aggregated by sector (i.e., residential, commercial, industrial, transportation, electricity generation, and U.S. territories), primary fuel type (e.g., coal, natural gas, and petroleum), and secondary fuel type (e.g., motor gasoline, distillate fuel, etc.). The 2000 total energy consumption across all sectors, including territories, and energy types was 83,610 trillion British thermal units (TBtu), as indicated in the last entry of Column 8 in Table A-1. This total includes fuel used for non-energy purposes and fuel consumed as international bunkers, both of which are deducted in later steps.

Fuel consumption data for electricity generation data by nonutility power producers are initially categorized by the EIA as part of the industrial sector. These data are then combined with fuel consumption by electric utilities to form the electricity generation sector. The method for this reallocation is described in detail in EIA's report on U.S. GHG emissions, *Emissions of Greenhouse Gases in the United States, 2000* (EIA 2001c).

There were a number of modifications made in this report that may cause consumption information herein to differ from figures given in the cited literature. These are 1) the reallocation of some coking coal, petroleum coke, and natural gas consumption for ammonia production to the Industrial Processes chapter, 2) corrections for synthetic natural gas production, 3) corrections for ethanol added to motor gasoline, and 4) corrections for biogas in natural gas.

First, portions of the fuel consumption data for three fuel categories—coking coal, petroleum coke, and natural gas—were reallocated to the Industrial Processes chapter, as these portions were actually consumed as raw material during non-energy related industrial processes. Coking coal, also called "coal coke," is used as a raw material (specifically as a reducing agent) in the blast furnace process to produce iron and steel, and therefore is not used as a fuel for this process. Similarly, petroleum coke is used in multiple processes as a raw material, and is thus not used as a fuel in those applications. The processes in which petroleum coke is used include 1) ferroalloy production, 2) aluminum production (for the production of carbon anodes and cathodes), and 3) titanium dioxide production (in the chloride process). Finally, natural gas consumption is used for the production of ammonia. Consumption of these fuels for non-energy purposes is presented in the Industrial Processes chapter, and is removed from the energy and non-energy consumption estimates within the Energy chapter.

Second, a portion of industrial coal accounted for in EIA combustion figures is actually used to make "synthetic natural gas" via coal gasification. The energy in this gas enters the natural gas stream, and is accounted for in natural gas consumption statistics. Because this energy is already accounted for as natural gas, it is deducted from industrial coal consumption to avoid double counting. This makes the figure for other industrial coal consumption in this report slightly lower than most EIA sources.

Third, ethanol has been added to the motor gasoline stream for several years, but prior to 1993 this addition was not captured in EIA motor gasoline statistics. Starting in 1993, ethanol was included in gasoline statistics. However, because ethanol is a biofuel, which is assumed to result in no net $CO_2$ emissions, the amount of ethanol added is subtracted from total gasoline consumption. Thus, motor gasoline consumption statistics given in this report may be slightly lower than in EIA sources.

Fourth, EIA natural gas consumption statistics include "biomass gas," which is upgraded landfill methane that is sold to pipelines. However, because this gas is biogenic, the biomass gas total is deducted from natural gas consumption. The subtraction is done only from natural gas in the industrial sector, as opposed to all end-sectors, because the biogas amount is small. Due to this adjustment–and the ammonia adjustment mentioned previously–industrial natural gas consumption in this report is slightly lower than in EIA sources.

There are also three basic differences between the consumption figures presented in Table A-1 through Table A-11 and those recommended in the IPCC emission inventory methodology.

First, consumption data in the U.S. inventory are presented using higher heating values (HHV)[1] rather than the lower heating values (LHV)[2] reflected in the IPCC emission inventory methodology. This convention is followed because data obtained from EIA are based on HHV. Of note, however, is that EIA renewable energy statistics are often published using LHV. The difference between the two conventions relates to the treatment of the heat energy that is consumed in the process of evaporating the water contained in the fuel. The simplified convention used by the International Energy Agency for converting from HHV to LHV is to multiply the energy content by 0.95 for petroleum and coal and by 0.9 for natural gas.

Second, while EIA's energy use data for the United States includes only the 50 U.S. states and the District of Columbia, the data reported to the Framework Convention on Climate Change are to include energy consumption within territories. Therefore, consumption estimates for U.S. territories were added to domestic consumption of fossil fuels. Energy consumption data from U.S. territories are presented in Column 7 of Table A-1 through Table A- 11. It is reported separately from domestic sectoral consumption, because it is collected separately by EIA with no sectoral disaggregation.

Third, the domestic sectoral consumption data in Table A-1 through Table A- 11 include bunker fuels used for international transport activities and non-energy uses of fossil fuels. The IPCC requires countries to estimate emissions from international bunker fuels separately and exclude these emissions from national totals, so international bunker fuel emissions have been estimated in Table A-12 and deducted from national estimates (see Step 4). Similarly, fossil fuels used to produce non-energy products that store carbon rather than release it to the atmosphere are provided in Table A- 13 and deducted from national emission estimates (see Step 3). The final fate of these fossil fuel based products is dealt with under the waste combustion source category in cases where the products are combusted through waste management practices.

### Step 2: Determine the Carbon Content of All Fuels

The carbon content of combusted fossil fuels was estimated by multiplying energy consumption (Columns 2 through 8 of Table A-1 through Table A- 11) by fuel-specific carbon content coefficients (see Table A-14 and Table A-15) that reflect the amount of carbon per unit of energy in each fuel. The resulting carbon contents are sometimes referred to as potential emissions, or the maximum amount of carbon that could potentially be released to the atmosphere if all carbon in the fuels were oxidized. The carbon content coefficients used in the U.S. inventory were derived by EIA from detailed fuel information and are similar to the carbon content coefficients contained in the IPCC's default methodology (IPCC/UNEP/OECD/IEA 1997), with modifications reflecting fuel qualities specific to the United States.

### Step 3: Adjust for the amount of Carbon Stored in Products

Depending on the end-use, non-energy uses of fossil fuels can result in long term storage of some or all of the carbon contained in the fuel. For example, asphalt made from petroleum can sequester up to 100 percent of the

[1] Also referred to as Gross Calorific Values (GCV).

[2] Also referred to as Net Calorific Values (NCV).

carbon contained in the petroleum feedstock for extended periods of time. Other non-energy fossil fuel products, such as lubricants or plastics also store carbon, but can lose or emit some of this carbon when they are used and/or burned as waste.[3]

The amount of carbon in non-energy fossil fuel products was based upon data that addressed the fraction of carbon that remains in products after they are manufactured, with all non-energy use attributed to the industrial, transportation, and territories end-use sectors. This non-energy consumption is presented in Table A- 13. This data were then multiplied by fuel-specific carbon content coefficients (Table A-14 and Table A-15) to obtain the carbon content of the fuel, or the maximum amount of carbon that could remain in non-energy products (Column 4 of Table A- 13). This carbon content was then multiplied by the fraction of carbon assumed to actually have remained in products (Column 5 of Table A- 13), resulting in the final estimates by sector and fuel type, which are presented in Column 6 of Table A- 13. A detailed discussion of carbon stored in products is provided in the Energy chapter and in Annex B.

### Step 4: Subtract Carbon in International Bunker Fuels

Emissions from international transport activities, or international bunker fuel consumption, are not included in national totals, as required by the IPCC (IPCC/UNEP/OECD/IEA 1997). There is currently disagreement internationally as to how these emissions should be allocated, and until this issue is resolved, countries are asked to report them separately. EIA energy statistics, however, include these bunker fuels—jet fuel for aircraft, and distillate fuel oil and residual fuel oil for marine shipping—as part of fuel consumption by the transportation end-use sector. To compensate for this inclusion, international bunker fuel emissions[4] were calculated separately (see Table A-12) and the carbon content of these fuels was subtracted from the transportation end-use sector. International bunker fuel emissions from military activities were developed using data provided by the Department of Defense as described in the International Bunker Fuels section of the Energy chapter and in Annex I. The calculations of international bunker fuel emissions followed the same procedures used for other fuel emissions (i.e., estimation of consumption, determination of carbon content, and adjustment for the fraction of carbon not oxidized).

### Step 5: Account for Carbon that Does Not Oxidize During Combustion

Because combustion processes are not 100 percent efficient, some of the carbon contained in fuels is not emitted in a gaseous form to the atmosphere. Rather, it remains behind as soot, particulate matter and ash. The estimated fraction of carbon not oxidized in U.S. energy conversion processes due to inefficiencies during combustion ranges from 0.5 percent for natural gas to 1 percent for petroleum and coal. Except for coal these assumptions are consistent with the default values recommended by the IPCC (IPCC/UNEP/OECD/IEA 1997). In the United States, unoxidized carbon from coal combustion was estimated to be no more than one percent (Bechtel 1993).

Table A-14 presents fractions oxidized by fuel type, which are multiplied by the net carbon content of the combusted energy to give final emissions estimates.

Of the fraction of carbon that is oxidized (e.g., 99 to 99.5 percent), the vast majority is emitted in its fully oxidized form as carbon dioxide ($CO_2$). A much smaller portion of this "oxidized" carbon is also emitted as carbon monoxide (CO), methane ($CH_4$), and non-methane volatile organic compounds (NMVOCs). These partially oxidized or unoxidized carbon compounds when in the atmosphere, though, are generally oxidized to $CO_2$ through atmospheric processes (e.g., reaction with hydroxyl (OH)).[5]

---

[3] See Waste Combustion section of the Energy chapter for a discussion of emissions from the combustion of plastics in the municipal solid waste stream.

[4] Refer to the International Bunker Fuels section of the Energy chapter for a description of the methodology for distinguishing between bunker and non-bunker fuel consumption.

[5] See indirect $CO_2$ from $CH_4$ oxidation section in Energy chapter for a discussion of proper accounting of carbon from hydrocarbon and CO emissions.

### Step 6: Summarize Emission Estimates

Actual $CO_2$ emissions in the United States were summarized by major fuel (i.e., coal, petroleum, natural gas, geothermal) and consuming sector (i.e., residential, commercial, industrial, transportation, electricity generation, and U.S. territories). Adjustments for international bunker fuels and carbon in non-energy products were made. Emission estimates are expressed in teragrams of carbon dioxide equivalents (Tg $CO_2$ Eq.).

To determine total emissions by final end-use sector, emissions from electricity generation were distributed to each end-use sector according to its share of aggregate electricity consumption (see Table A-16). This pro-rated approach to allocating emissions from electricity generation may overestimate or underestimate emissions for particular sectors due to differences in the average carbon content of fuel mixes burned to generate electricity.

## Table A-1: 2000 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Consumption (TBtu)[a] | | | | | | | Emissions (Tg $CO_2$ Eq.) including Adjustments[b] and Fraction Oxidized | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **46.6** | **69.9** | **1,119.2** | **NE** | **20,486.7** | **9.8** | **21,732.3** | **4.4** | **6.6** | **102.8** | **NE** | **1,915.4** | **0.9** | **2,030.1** |
| Residential Coal | 46.6 | | | | | | 46.6 | 4.4 | | | | | | 4.4 |
| Commercial Coal | | 69.9 | | | | | 69.9 | | 6.6 | | | | | 6.6 |
| Industrial Coking Coal | | | 43.7 | | | | 43.7 | | | 2.2 | | | | 2.2 |
| Industrial Other Coal | | | 1,010.2 | | | | 1,010.2 | | | 94.0 | | | | 94.0 |
| Coke Imports | | | 65.4 | | | | 65.4 | | | 6.6 | | | | 6.6 |
| Transportation Coal | | | | NE | | | NE | | | | | NE | | NE |
| Utility Coal | | | | | 20,486.7 | | 20,486.7 | | | | | 1,915.4 | | 1,915.4 |
| US Territory Coal (bit) | | | | | | 9.8 | 9.8 | | | | | | 0.9 | 0.9 |
| **Natural Gas** | **5,081.5** | **3,425.4** | **7,249.8** | **793.2** | **6,476.7** | **11.7** | **23,038.3** | **268.3** | **180.8** | **371.3** | **41.9** | **341.9** | **0.6** | **1,204.8** |
| **Total Petroleum** | **1,492.3** | **722.5** | **8,657.4** | **26,043.6** | **1,194.8** | **725.3** | **38,836.0** | **102.2** | **51.8** | **355.1** | **1,747.6** | **95.2** | **36.3** | **2,388.2** |
| Asphalt & Road Oil | | | 1,275.7 | | | | 1,275.7 | | | + | | | | + |
| Aviation Gasoline | | | | 36.3 | | | 36.3 | | | | 2.5 | | | 2.5 |
| Distillate Fuel Oil | 846.7 | 434.5 | 1,055.4 | 5,399.4 | 199.4 | 125.8 | 8,061.2 | 61.3 | 31.5 | 76.2 | 382.7 | 14.4 | 9.1 | 575.2 |
| Jet Fuel | | | | 3,580.4 | | 73.7 | 3,654.0 | | | | 194.0 | | 5.2 | 199.1 |
| Kerosene | 103.0 | 25.0 | 11.9 | | | 6.5 | 146.4 | 7.4 | 1.8 | 0.9 | | | 0.5 | 10.5 |
| LPG | 542.6 | 95.7 | 2,293.1 | 13.7 | | 8.5 | 2,953.5 | 33.5 | 5.9 | 75.2 | 0.8 | | 0.5 | 116.0 |
| Lubricants | | | 189.9 | 179.4 | | 1.4 | 370.6 | | | 12.7 | 12.0 | | 0.1 | 24.7 |
| Motor Gasoline | | 46.2 | 152.7 | 15,749.1 | | 186.0 | 16,134.0 | | 3.2 | 10.7 | 1,105.7 | | 13.1 | 1,132.7 |
| Residual Fuel | | 121.1 | 48.9 | 1,085.4 | 835.1 | 101.0 | 2,191.6 | | 9.5 | 1.9 | 50.0 | 64.5 | 7.9 | 133.8 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 3.8 | | | | 3.8 | | | 0.3 | | | | 0.3 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | 119.2 | | | 222.5 | 341.7 | | | | | | | |
| Naphtha (<401 deg. F) | | | 613.5 | | | | 613.5 | | | 16.9 | | | | 16.9 |
| Other Oil (>401 deg. F) | | | 722.2 | | | | 722.2 | | | 21.9 | | | | 21.9 |
| Pentanes Plus | | | 343.2 | | | | 343.2 | | | 10.7 | | | | 10.7 |
| Petroleum Coke | | | 650.5 | | 160.2 | | 810.7 | | | 58.6 | | 16.2 | | 74.8 |
| Still Gas | | | 1,448.2 | | | | 1,448.2 | | | 91.7 | | | | 91.7 |
| Special Naphtha | | | 97.4 | | | | 97.4 | | | 7.0 | | | | 7.0 |
| Unfinished Oils | | | (401.2) | | | | (401.2) | | | (29.5) | | | | (29.5) |
| Waxes | | | 33.1 | | | | 33.1 | | | | | | | |
| **Geothermal** | | | | | **3.2** | | **3.2** | | | | | + | | + |
| **TOTAL (All Fuels)** | **6,620.4** | **4,217.8** | **17,026.5** | **26,836.9** | **28,161.3** | **746.8** | **83,609.8** | **374.8** | **239.3** | **829.2** | **1,789.5** | **2,352.5** | **37.8** | **5,623.1** |

[a] Expressed as gross calorific values (i.e., higher heating values).

[b] Adjustments include: international bunker fuel consumption (see Table A-12) and carbon in non-energy products (see Table A-13).

+ Does not exceed 0.05 Tg $CO_2$ Eq.

NE (Not Estimated)

## Table A-2: 1999 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Consumption (TBtu)[a] | | | | | | | Emissions (Tg $CO_2$ Eq.) including Adjustments[b] and Fraction Oxidized | | | | | | |
| Fuel Type | Res. | Comm. | Ind. | Trans. | Elec. | Terr. | Total | Res. | Comm. | Ind. | Trans. | Elec. | Terr. | Total |
| **Total Coal** | 46.6 | 69.9 | 1,270.9 | NE | 19,552.7 | 9.8 | 20,949.9 | 4.4 | 6.6 | 117.0 | NE | 1,828.0 | 0.9 | 1,956.9 |
| Residential Coal | 46.6 | | | | | | 46.6 | 4.4 | | | | | | 4.4 |
| Commercial Coal | | 69.9 | | | | | 69.9 | | 6.6 | | | | | 6.6 |
| Industrial Coking Coal | | | 34.4 | | | | 34.4 | | | 1.5 | | | | 1.5 |
| Industrial Other Coal | | | 1,178.8 | | | | 1,178.8 | | | 109.7 | | | | 109.7 |
| Coke Imports | | | 57.7 | | | | 57.7 | | | 5.8 | | | | 5.8 |
| Transportation Coal | | | | NE | | | NE | | | | NE | | | NE |
| Utility Coal | | | | | 19,552.7 | | 19,552.7 | | | | | 1,828.0 | | 1,828.0 |
| US Territory Coal (bit) | | | | | | 9.8 | 9.8 | | | | | | 0.9 | 0.9 |
| **Natural Gas** | 4,858.0 | 3,129.9 | 7,278.8 | 761.5 | 5,879.7 | | 21,907.9 | 256.5 | 165.2 | 372.9 | 40.2 | 310.4 | | 1,145.2 |
| **Total Petroleum** | 1,456.1 | 671.6 | 8,895.4 | 25,315.0 | 1,352.4 | 694.4 | 38,384.9 | 99.6 | 48.0 | 368.2 | 1,688.0 | 107.7 | 34.8 | 2,346.3 |
| Asphalt & Road Oil | | | 1,324.4 | | | | 1,324.4 | | | | | | | |
| Aviation Gasoline | | | | 39.2 | | | 39.2 | | | | 2.7 | | | 2.7 |
| Distillate Fuel Oil | 811.2 | 416.6 | 1,014.6 | 5,160.9 | 191.1 | 121.2 | 7,715.7 | 58.7 | 30.2 | 73.2 | 365.5 | 13.8 | 8.8 | 550.3 |
| Jet Fuel | | | | 3,461.8 | | 71.4 | 3,533.1 | | | | 184.0 | | 5.0 | 189.0 |
| Kerosene | 111.2 | 26.9 | 12.8 | | | 6.5 | 157.4 | 8.0 | 1.9 | 0.9 | | | 0.5 | 11.3 |
| LPG | 533.8 | 94.2 | 2,255.7 | 13.4 | | 7.6 | 2,904.7 | 32.9 | 5.8 | 74.7 | 0.8 | | 0.5 | 114.7 |
| Lubricants | | | 192.8 | 182.1 | | 1.3 | 376.2 | | | 12.9 | 12.1 | | 0.1 | 25.1 |
| Motor Gasoline | | 45.9 | 151.5 | 15,658.6 | | 177.6 | 16,033.6 | | 3.2 | 10.6 | 1,098.7 | | 12.5 | 1,125.0 |
| Residual Fuel | | 88.0 | 29.3 | 798.9 | 988.6 | 96.0 | 2,001.0 | | 6.9 | 0.3 | 24.1 | 76.4 | 7.5 | 115.2 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 6.4 | | | | 6.4 | | | 0.4 | | | | 0.4 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | 111.9 | | | 212.8 | 324.7 | | | | | | | |
| Naphtha (<401 deg. F) | | | 502.1 | | | | 502.1 | | | 13.8 | | | | 13.8 |
| Other Oil (>401 deg. F) | | | 811.1 | | | | 811.1 | | | 24.6 | | | | 24.6 |
| Pentanes Plus | | | 365.0 | | | | 365.0 | | | 11.4 | | | | 11.4 |
| Petroleum Coke | | | 785.7 | | 172.7 | | 958.3 | | | 65.3 | | 17.5 | | 82.7 |
| Still Gas | | | 1,437.1 | | | | 1,437.1 | | | 90.7 | | | | 90.7 |
| Special Naphtha | | | 145.4 | | | | 145.4 | | | 10.5 | | | | 10.5 |
| Unfinished Oils | | | (287.9) | | | | (287.9) | | | (21.1) | | | | (21.1) |
| Waxes | | | 37.4 | | | | 37.4 | | | | | | | |
| **Geothermal** | | | | | 5.8 | | 5.8 | | | | | + | | + |
| **TOTAL (All Fuels)** | 6,360.7 | 3,871.4 | 17,445.1 | 26,076.5 | 26,790.6 | 704.2 | 81,248.5 | 360.5 | 219.8 | 858.1 | 1,728.2 | 2,246.2 | 35.7 | 5,448.4 |

[a] Expressed as gross calorific values (i.e., higher heating values).

[b] Adjustments include: international bunker fuel consumption (see Table A-12) and carbon in non-energy products (seeTable A-13).

+ Does not exceed 0.05 Tg $CO_2$ Eq.

NE (Not Estimated)

## Table A-3: 1998 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Consumption (TBtu)[a] | | | | | | | Emissions (Tg $CO_2$ Eq.) including Adjustments[b] and Fraction Oxidized | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **44.3** | **66.4** | **1,317.3** | **NE** | **19,434.2** | **9.8** | **20,872.0** | **4.2** | **6.3** | **121.4** | **NE** | **1,817.0** | **0.9** | **1,949.7** |
| Residential Coal | 44.3 | | | | | | 44.3 | 4.2 | | | | | | 4.2 |
| Commercial Coal | | 66.4 | | | | | 66.4 | | 6.3 | | | | | 6.3 |
| Industrial Coking Coal | | | 25.9 | | | | 25.9 | | | 0.7 | | | | 0.7 |
| Industrial Other Coal | | | 1,224.3 | | | | 1,224.3 | | | 113.9 | | | | 113.9 |
| Coke Imports | | | 67.1 | | | | 67.1 | | | 6.8 | | | | 6.8 |
| Transportation Coal | | | | NE | | | NE | | | | NE | | | NE |
| Utility Coal | | | | | 19,434.2 | | 19,434.2 | | | | | 1,817.0 | | 1,817.0 |
| US Territory Coal (bit) | | | | | | 9.8 | 9.8 | | | | | | 0.9 | 0.9 |
| **Natural Gas** | **4,669.4** | **3,098.5** | **7,366.0** | **661.7** | **5,736.8** | | **21,532.4** | **246.5** | **163.6** | **378.0** | **34.9** | **302.9** | | **1,125.8** |
| **Total Petroleum** | **1,323.8** | **664.7** | **8,857.0** | **24,472.5** | **1,353.7** | **668.2** | **37,339.8** | **91.1** | **47.7** | **381.7** | **1,620.1** | **106.5** | **33.3** | **2,280.3** |
| Asphalt & Road Oil | | | 1,262.6 | | | | 1,262.6 | | | | | | | |
| Aviation Gasoline | | | | 35.5 | | | 35.5 | | | | 2.4 | | | 2.4 |
| Distillate Fuel Oil | 781.9 | 422.5 | 1,114.7 | 4,881.8 | 158.5 | 116.5 | 7,476.0 | 56.6 | 30.6 | 80.5 | 342.0 | 11.5 | 8.4 | 529.6 |
| Jet Fuel | | | | 3,356.8 | | 67.9 | 3,424.7 | | | | 180.5 | | 4.8 | 185.3 |
| Kerosene | 108.3 | 31.2 | 22.1 | | | 6.3 | 167.8 | 7.8 | 2.2 | 1.6 | | | 0.4 | 12.0 |
| LPG | 433.6 | 76.5 | 2,048.3 | 16.6 | | 7.2 | 2,582.2 | 26.7 | 4.7 | 69.3 | 1.0 | | 0.4 | 102.2 |
| Lubricants | | | 190.8 | 180.2 | | 1.3 | 372.3 | | | 12.7 | 12.0 | | 0.1 | 24.8 |
| Motor Gasoline | | 43.8 | 199.4 | 15,285.1 | | 170.0 | 15,698.4 | | 3.1 | 14.0 | 1,072.5 | | 11.9 | 1,101.5 |
| Residual Fuel | | 90.7 | 143.7 | 716.4 | 1,085.0 | 91.9 | 2,127.6 | | 7.1 | 9.2 | 9.5 | 83.9 | 7.2 | 116.8 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 4.0 | | | | 4.0 | | | 0.3 | | | | 0.3 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | 119.0 | | | 207.1 | 326.1 | | | | | | | |
| Naphtha (<401 deg. F) | | | 584.0 | | | | 584.0 | | | 16.1 | | | | 16.1 |
| Other Oil (>401 deg. F) | | | 818.7 | | | | 818.7 | | | 24.8 | | | | 24.8 |
| Pentanes Plus | | | 294.0 | | | | 294.0 | | | 9.2 | | | | 9.2 |
| Petroleum Coke | | | 782.9 | | 110.2 | | 893.1 | | | 68.1 | | 11.1 | | 79.2 |
| Still Gas | | | 1,437.2 | | | | 1,437.2 | | | 91.4 | | | | 91.4 |
| Special Naphtha | | | 107.3 | | | | 107.3 | | | 7.7 | | | | 7.7 |
| Unfinished Oils | | | (313.9) | | | | (313.9) | | | (23.1) | | | | (23.1) |
| Waxes | | | 42.4 | | | | 42.4 | | | | | | | |
| **Geothermal** | | | | | **17.7** | | **17.7** | | | | | **0.1** | | **0.1** |
| **TOTAL (All Fuels)** | **6,037.5** | **3,829.5** | **17,540.3** | **25,134.1** | **26,542.3** | **678.0** | **79,761.8** | **341.8** | **217.5** | **881.1** | **1,655.0** | **2,226.4** | **34.2** | **5,356.0** |

[a] Expressed as gross calorific values (i.e., higher heating values).

[b] Adjustments include: international bunker fuel consumption (see Table A-12) and carbon in non-energy products (seeTable A-13).

+ Does not exceed 0.05 Tg $CO_2$ Eq.

NE (Not Estimated)

## Table A-4: 1997 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Consumption (TBtu)[a] | | | | | | | Emissions (Tg $CO_2$ Eq.) including Adjustments[b] and Fraction Oxidized | | | | | | |
| Fuel Type | Res. | Comm. | Ind. | Trans. | Elec. | Terr. | Total | Res. | Comm. | Ind. | Trans. | Elec. | Terr. | Total |
| **Total Coal** | **57.8** | **86.8** | **1,380.8** | **NE** | **19,134.9** | **10.4** | **20,670.7** | **5.5** | **8.2** | **126.9** | **NE** | **1,789.0** | **0.9** | **1,930.5** |
| Residential Coal | 57.8 | | | | | | 57.8 | 5.5 | | | | | | 5.5 |
| Commercial Coal | | 86.8 | | | | | 86.8 | | 8.2 | | | | | 8.2 |
| Industrial Coking Coal | | | 36.1 | | | | 36.1 | | | 1.4 | | | | 1.4 |
| Industrial Other Coal | | | 1,298.3 | | | | 1,298.3 | | | 120.8 | | | | 120.8 |
| Coke Imports | | | 46.4 | | | | 46.4 | | | 4.7 | | | | 4.7 |
| Transportation Coal | | | | NE | | | NE | | | | NE | | | NE |
| Utility Coal | | | | | 19,134.9 | | 19,134.9 | | | | | 1,789.0 | | 1,789.0 |
| US Territory Coal (bit) | | | | | | 10.4 | 10.4 | | | | | | 0.9 | 0.9 |
| **Natural Gas** | **5,124.6** | **3,309.7** | **7,965.7** | **785.7** | **5,122.2** | | **22,307.8** | **270.5** | **174.7** | **409.6** | **41.5** | **270.4** | | **1,166.7** |
| **Total Petroleum** | **1,431.9** | **705.2** | **9,056.4** | **23,950.5** | **992.8** | **598.4** | **36,735.2** | **98.9** | **50.8** | **398.7** | **1,587.3** | **78.4** | **27.9** | **2,242.0** |
| Asphalt & Road Oil | | | 1,223.6 | | | | 1,223.6 | | | | | | | |
| Aviation Gasoline | | | | 39.7 | | | 39.7 | | | | 2.7 | | | 2.7 |
| Distillate Fuel Oil | 900.0 | 446.5 | 1,108.1 | 4,733.9 | 115.7 | 107.1 | 7,411.3 | 65.2 | 32.3 | 80.0 | 333.7 | 8.4 | 7.8 | 527.4 |
| Jet Fuel | | | | 3,308.2 | | 64.0 | 3,372.1 | | | | 176.2 | | 4.5 | 180.7 |
| Kerosene | 92.9 | 24.6 | 18.8 | | | 4.0 | 140.3 | 6.6 | 1.8 | 1.3 | | | 0.3 | 10.0 |
| LPG | 439.1 | 77.5 | 2,159.6 | 13.4 | | 7.9 | 2,697.5 | 27.1 | 4.8 | 73.6 | 0.8 | | 0.5 | 106.8 |
| Lubricants | | | 182.3 | 172.1 | | 2.5 | 356.9 | | | 12.2 | 11.5 | | 0.2 | 23.8 |
| Motor Gasoline | | 43.1 | 213.5 | 14,956.7 | | 143.6 | 15,356.8 | | 3.0 | 15.0 | 1,050.6 | | 10.1 | 1,078.7 |
| Residual Fuel | | 113.6 | 205.1 | 726.5 | 783.1 | 60.0 | 1,888.2 | | 8.9 | 14.0 | 11.8 | 60.5 | 4.7 | 99.9 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 9.1 | | | | 9.1 | | | 0.6 | | | | 0.6 |
| Crude Oil | | | 4.6 | | | | 4.6 | | | 0.3 | | | | 0.3 |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | 97.7 | | | 209.4 | 307.2 | | | | | | | |
| Naphtha (<401 deg. F) | | | 536.4 | | | | 536.4 | | | 14.8 | | | | 14.8 |
| Other Oil (>401 deg. F) | | | 861.2 | | | | 861.2 | | | 26.1 | | | | 26.1 |
| Pentanes Plus | | | 328.9 | | | | 328.9 | | | 10.3 | | | | 10.3 |
| Petroleum Coke | | | 647.2 | | 94.0 | | 741.2 | | | 60.9 | | 9.5 | | 70.4 |
| Still Gas | | | 1,447.1 | | | | 1,447.1 | | | 91.9 | | | | 91.9 |
| Special Naphtha | | | 72.3 | | | | 72.3 | | | 5.2 | | | | 5.2 |
| Unfinished Oils | | | (102.9) | | | | (102.9) | | | (7.6) | | | | (7.6) |
| Waxes | | | 43.7 | | | | 43.7 | | | | | | | |
| **Geothermal** | | | | | **18.7** | | **18.7** | | | | | **0.1** | | **0.1** |
| **TOTAL (All Fuels)** | **6,614.4** | **4,101.7** | **18,402.9** | **24,736.2** | **25,268.5** | **608.8** | **79,732.5** | **374.9** | **233.7** | **935.2** | **1,628.8** | **2,137.9** | **28.9** | **5,339.4** |

[a] Expressed as gross calorific values (i.e., higher heating values).

[b] Adjustments include: international bunker fuel consumption (see Table A-12) and carbon in non-energy products (see Table A-13).

+ Does not exceed 0.05 Tg $CO_2$ Eq.

NE (Not Estimated)

## Table A-5: 1996 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Consumption (TBtu)[a] | | | | | | | Emissions (Tg $CO_2$ Eq.) including Adjustments[b] and Fraction Oxidized | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **54.5** | **81.9** | **1,369.7** | **NE** | **18,610.4** | **10.3** | **20,126.9** | **5.1** | **7.7** | **125.5** | **NE** | **1,739.1** | **0.9** | **1,878.4** |
| Residential Coal | 54.5 | | | | | | 54.5 | 5.1 | | | | | | 5.1 |
| Commercial Coal | | 81.9 | | | | | 81.9 | | 7.7 | | | | | 7.7 |
| Industrial Coking Coal | | | 59.7 | | | | 59.7 | | | 3.5 | | | | 3.5 |
| Industrial Other Coal | | | 1,287.2 | | | | 1,287.2 | | | 119.6 | | | | 119.6 |
| Coke Imports | | | 22.8 | | | | 22.8 | | | 2.3 | | | | 2.3 |
| Transportation Coal | | | | NE | | | NE | | | | NE | | | NE |
| Utility Coal | | | | | 18,610.4 | | 18,610.4 | | | | | 1,739.1 | | 1,739.1 |
| US Territory Coal (bit) | | | | | | 10.3 | 10.3 | | | | | | 0.9 | 0.9 |
| **Natural Gas** | **5,390.2** | **3,250.4** | **8,052.1** | **737.1** | **4,782.8** | | **22,212.5** | **284.6** | **171.6** | **414.8** | **38.9** | **252.5** | | **1,162.4** |
| **Total Petroleum** | **1,457.3** | **740.7** | **8,857.6** | **23,716.8** | **885.2** | **560.0** | **36,217.6** | **100.7** | **53.5** | **396.2** | **1,579.8** | **69.5** | **25.8** | **2,225.6** |
| Asphalt & Road Oil | | | 1,175.9 | | | | 1,175.9 | | | | | | | |
| Aviation Gasoline | | | | 37.4 | | | 37.4 | | | | 2.6 | | | 2.6 |
| Distillate Fuel Oil | 929.8 | 476.0 | 1,101.4 | 4,543.2 | 124.1 | 106.3 | 7,280.8 | 67.3 | 34.5 | 79.5 | 320.7 | 9.0 | 7.7 | 518.7 |
| Jet Fuel | | | | 3,274.2 | | 66.1 | 3,340.3 | | | | 177.6 | | 4.6 | 182.2 |
| Kerosene | 88.8 | 21.0 | 18.3 | | | 3.0 | 131.1 | 6.4 | 1.5 | 1.3 | | | 0.2 | 9.4 |
| LPG | 438.7 | 77.4 | 2,129.5 | 14.7 | | 7.3 | 2,667.8 | 27.1 | 4.8 | 72.5 | 0.9 | | 0.5 | 105.7 |
| Lubricants | | | 172.5 | 163.0 | | 0.8 | 336.3 | | | 11.5 | 10.9 | | 0.1 | 22.4 |
| Motor Gasoline | | 26.7 | 201.3 | 14,818.6 | | 118.6 | 15,165.3 | | 1.9 | 14.1 | 1,041.4 | | 8.3 | 1,065.8 |
| Residual Fuel | | 139.5 | 254.9 | 865.7 | 692.0 | 57.2 | 2,009.3 | | 10.9 | 17.9 | 25.7 | 53.5 | 4.5 | 112.4 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 7.0 | | | | 7.0 | | | 0.5 | | | | 0.5 |
| Crude Oil | | | 13.7 | | | | 13.7 | | | 1.0 | | | | 1.0 |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | 89.0 | | | 200.7 | 289.8 | | | | | | | |
| Naphtha (<401 deg. F) | | | 479.3 | | | | 479.3 | | | 13.2 | | | | 13.2 |
| Other Oil (>401 deg. F) | | | 729.6 | | | | 729.6 | | | 22.1 | | | | 22.1 |
| Pentanes Plus | | | 355.0 | | | | 355.0 | | | 11.3 | | | | 11.3 |
| Petroleum Coke | | | 682.5 | | 69.1 | | 751.6 | | | 62.8 | | 7.0 | | 69.8 |
| Still Gas | | | 1,437.1 | | | | 1,437.1 | | | 91.3 | | | | 91.3 |
| Special Naphtha | | | 74.5 | | | | 74.5 | | | 5.4 | | | | 5.4 |
| Unfinished Oils | | | (112.8) | | | | (112.8) | | | (8.3) | | | | (8.3) |
| Waxes | | | 48.7 | | | | 48.7 | | | | | | | |
| **Geothermal** | | | | | **17.9** | | **17.9** | | | | | **0.1** | | **0.1** |
| **TOTAL (All Fuels)** | **6,902.0** | **4,073.0** | **18,279.4** | **24,453.8** | **24,296.3** | **570.3** | **78,574.8** | **390.4** | **232.8** | **936.5** | **1,618.7** | **2,061.2** | **26.8** | **5,266.4** |

[a] Expressed as gross calorific values (i.e., higher heating values).

[b] Adjustments include: international bunker fuel consumption (see Table A-12) and carbon in non-energy products (seeTable A-13).

+ Does not exceed 0.05 Tg $CO_2$ Eq.

NE (Not Estimated)

## Table A-6: 1995 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Consumption (TBtu)[a] | | | | | | | Emissions (Tg $CO_2$ Eq.) including Adjustments[b] and Fraction Oxidized | | | | | | |
| Fuel Type | Res. | Comm. | Ind. | Trans. | Elec. | Terr. | Total | Res. | Comm. | Ind. | Trans. | Elec. | Terr. | Total |
| **Total Coal** | **53.3** | **80.4** | **1,427.3** | **NE** | **17,634.6** | **10.2** | **19,205.8** | **5.0** | **7.6** | **131.2** | **NE** | **1,647.9** | **0.9** | **1,792.7** |
| Residential Coal | 53.3 | | | | | | 53.3 | 5.0 | | | | | | 5.0 |
| Commercial Coal | | 80.4 | | | | | 80.4 | | 7.6 | | | | | 7.6 |
| Industrial Coking Coal | | | 50.6 | | | | 50.6 | | | 2.6 | | | | 2.6 |
| Industrial Other Coal | | | 1,315.6 | | | | 1,315.6 | | | 122.4 | | | | 122.4 |
| Coke Imports | | | 61.1 | | | | 61.1 | | | 6.2 | | | | 6.2 |
| Transportation Coal | | | | NE | | | NE | | | | NE | | | NE |
| Utility Coal | | | | | 17,634.6 | | 17,634.6 | | | | | 1,647.9 | | 1,647.9 |
| US Territory Coal (bit) | | | | | | 10.2 | 10.2 | | | | | | 0.9 | 0.9 |
| **Natural Gas** | **4,984.4** | **3,116.9** | **7,743.5** | **725.8** | **5,242.5** | | **21,813.1** | **263.1** | **164.5** | **398.5** | **38.3** | **276.8** | | **1,141.3** |
| **Total Petroleum** | **1,361.1** | **715.2** | **8,381.7** | **23,133.1** | **819.2** | **605.5** | **35,015.8** | **94.2** | **51.8** | **365.1** | **1,541.0** | **64.5** | **34.3** | **2,150.9** |
| Asphalt & Road Oil | | | 1,178.2 | | | | 1,178.2 | | | | | | | |
| Aviation Gasoline | | | | 39.6 | | | 39.6 | | | | 2.7 | | | 2.7 |
| Distillate Fuel Oil | 882.6 | 459.8 | 1,048.3 | 4,310.5 | 116.5 | 125.6 | 6,943.3 | 63.9 | 33.3 | 75.7 | 303.1 | 8.4 | 9.1 | 493.5 |
| Jet Fuel | | | | 3,132.2 | | 75.5 | 3,207.7 | | | | 168.7 | | 5.3 | 174.0 |
| Kerosene | 74.3 | 22.1 | 15.4 | | | 3.6 | 115.4 | 5.3 | 1.6 | 1.1 | | | 0.3 | 8.3 |
| LPG | 404.2 | 71.3 | 2,019.4 | 16.7 | | 5.6 | 2,517.3 | 24.9 | 4.4 | 68.0 | 1.0 | | 0.3 | 98.8 |
| Lubricants | | | 177.8 | 167.9 | | 2.0 | 347.7 | | | 11.9 | 11.2 | | 0.1 | 23.2 |
| Motor Gasoline | | 18.2 | 201.6 | 14,541.5 | | 148.1 | 14,909.5 | | 1.3 | 14.2 | 1,023.0 | | 10.4 | 1,048.9 |
| Residual Fuel | | 143.7 | 255.5 | 924.7 | 630.8 | 111.9 | 2,066.6 | | 11.2 | 18.0 | 31.3 | 48.8 | 8.7 | 118.0 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 5.3 | | | | 5.3 | | | 0.4 | | | | 0.4 |
| Crude Oil | | | 14.5 | | | | 14.5 | | | 1.1 | | | | 1.1 |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | 97.1 | | | 133.2 | 230.3 | | | | | | | |
| Naphtha (<401 deg. F) | | | 373.0 | | | | 373.0 | | | 10.3 | | | | 10.3 |
| Other Oil (>401 deg. F) | | | 801.0 | | | | 801.0 | | | 24.3 | | | | 24.3 |
| Pentanes Plus | | | 337.9 | | | | 337.9 | | | 10.7 | | | | 10.7 |
| Petroleum Coke | | | 648.8 | | 71.8 | | 720.6 | | | 60.1 | | 7.3 | | 67.3 |
| Still Gas | | | 1,417.5 | | | | 1,417.5 | | | 88.1 | | | | 88.1 |
| Special Naphtha | | | 70.8 | | | | 70.8 | | | 5.1 | | | | 5.1 |
| Unfinished Oils | | | (320.9) | | | | (320.9) | | | (23.6) | | | | (23.6) |
| Waxes | | | 40.6 | | | | 40.6 | | | | | | | |
| **Geothermal** | | | | | **16.2** | | **16.2** | | | | | **0.1** | | **0.1** |
| **TOTAL (All Fuels)** | **6,398.8** | **3,912.5** | **17,552.5** | **23,858.9** | **23,712.5** | **615.7** | **76,050.9** | **362.3** | **223.9** | **894.9** | **1,579.4** | **1,989.3** | **35.2** | **5,084.9** |

[a] Expressed as gross calorific values (i.e., higher heating values).

[b] Adjustments include: international bunker fuel consumption (see Table A-12) and carbon in non-energy products (seeTable A-13).

+ Does not exceed 0.05 Tg $CO_2$ Eq.

NE (Not Estimated)

## Table A-7: 1994 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Consumption (TBtu)[a] | | | | | | | Emissions (Tg $CO_2$ Eq.) including Adjustments[b] and Fraction Oxidized | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **55.1** | **82.7** | **1,436.5** | **NE** | **17,529.3** | **10.0** | **19,113.6** | **5.2** | **7.8** | **132.1** | **NE** | **1,636.5** | **0.9** | **1,782.6** |
| Residential Coal | 55.1 | | | | | | 55.1 | 5.2 | | | | | | 5.2 |
| Commercial Coal | | 82.7 | | | | | 82.7 | | 7.8 | | | | | 7.8 |
| Industrial Coking Coal | | | 37.0 | | | | 37.0 | | | 1.5 | | | | 1.5 |
| Industrial Other Coal | | | 1,341.2 | | | | 1,341.2 | | | 124.8 | | | | 124.8 |
| Coke Imports | | | 58.3 | | | | 58.3 | | | 5.9 | | | | 5.9 |
| Transportation Coal | | | | NE | | | NE | | | | NE | | | NE |
| Utility Coal | | | | | 17,529.3 | | 17,529.3 | | | | | 1,636.5 | | 1,636.5 |
| US Territory Coal (bit) | | | | | | 10.0 | 10.0 | | | | | | 0.9 | 0.9 |
| **Natural Gas** | **4,980.3** | **2,977.6** | **7,380.3** | **708.0** | **4,875.3** | | **20,921.5** | **262.9** | **157.2** | **378.7** | **37.4** | **257.4** | | **1,093.6** |
| **Total Petroleum** | **1,340.3** | **753.5** | **8,607.5** | **22,661.6** | **1,129.9** | **561.8** | **35,054.6** | **92.8** | **54.7** | **383.5** | **1,514.0** | **88.5** | **37.3** | **2,170.8** |
| Asphalt & Road Oil | | | 1,172.9 | | | | 1,172.9 | | | | | | | |
| Aviation Gasoline | | | | 38.1 | | | 38.1 | | | | 2.6 | | | 2.6 |
| Distillate Fuel Oil | 880.0 | 464.3 | 1,082.9 | 4,175.0 | 121.1 | 118.8 | 6,842.1 | 63.7 | 33.6 | 78.2 | 293.6 | 8.8 | 8.6 | 486.5 |
| Jet Fuel | | | | 3,154.5 | | 65.8 | 3,220.3 | | | | 173.2 | | 4.6 | 177.9 |
| Kerosene | 64.9 | 19.5 | 16.9 | | | 3.0 | 104.3 | 4.6 | 1.4 | 1.2 | | | 0.2 | 7.5 |
| LPG | 395.4 | 69.8 | 1,996.5 | 32.2 | | 7.3 | 2,501.2 | 24.4 | 4.3 | 68.2 | 2.0 | | 0.4 | 99.3 |
| Lubricants | | | 180.9 | 170.8 | | 1.9 | 353.6 | | | 12.1 | 11.4 | | 0.1 | 23.6 |
| Motor Gasoline | | 25.3 | 193.3 | 14,194.9 | | 148.0 | 14,561.6 | | 1.8 | 13.6 | 1,002.2 | | 10.5 | 1,028.1 |
| Residual Fuel | | 174.6 | 338.5 | 896.0 | 933.4 | 164.1 | 2,506.5 | | 13.6 | 24.4 | 29.0 | 72.1 | 12.8 | 152.0 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 6.1 | | | | 6.1 | | | 0.4 | | | | 0.4 |
| Crude Oil | | | 18.7 | | | | 18.7 | | | 1.4 | | | | 1.4 |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | 105.9 | | | 53.0 | 158.8 | | | | | | | |
| Naphtha (<401 deg. F) | | | 398.3 | | | | 398.3 | | | 11.0 | | | | 11.0 |
| Other Oil (>401 deg. F) | | | 838.6 | | | | 838.6 | | | 25.4 | | | | 25.4 |
| Pentanes Plus | | | 338.7 | | | | 338.7 | | | 12.5 | | | | 12.5 |
| Petroleum Coke | | | 637.4 | | 75.4 | | 712.8 | | | 59.4 | | 7.6 | | 67.0 |
| Still Gas | | | 1,439.4 | | | | 1,439.4 | | | 90.4 | | | | 90.4 |
| Special Naphtha | | | 81.1 | | | | 81.1 | | | 5.8 | | | | 5.8 |
| Unfinished Oils | | | (279.2) | | | | (279.2) | | | (20.5) | | | | (20.5) |
| Waxes | | | 40.6 | | | | 40.6 | | | | | | | |
| **Geothermal** | | | | | **23.7** | | **23.7** | | | | | **0.2** | | **0.2** |
| **TOTAL (All Fuels)** | **6,375.7** | **3,813.7** | **17,424.3** | **23,369.6** | **23,558.2** | **571.8** | **75,113.4** | **360.9** | **219.7** | **894.4** | **1,551.4** | **1,982.6** | **38.2** | **5,047.1** |

[a] Expressed as gross calorific values (i.e., higher heating values).

[b] Adjustments include: international bunker fuel consumption (see Table A-12) and carbon in non-energy products (seeTable A-13).

+ Does not exceed 0.05 Tg $CO_2$ Eq.

NE (Not Estimated)

## Table A-8: 1993 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Consumption (TBtu)[a] | | | | | | | Emissions (Tg $CO_2$ Eq.) including Adjustments[b] and Fraction Oxidized | | | | | | |
| Fuel Type | Res. | Comm. | Ind. | Trans. | Elec. | Terr. | Total | Res. | Comm. | Ind. | Trans. | Elec. | Terr. | Total |
| **Total Coal** | **56.6** | **85.5** | **1,413.3** | **NE** | **17,364.1** | **9.6** | **18,929.1** | **5.3** | **8.1** | **129.6** | **NE** | **1,620.3** | **0.9** | **1,764.1** |
| Residential Coal | 56.6 | | | | | | 56.6 | 5.3 | | | | | | 5.3 |
| Commercial Coal | | 85.5 | | | | | 85.5 | | 8.1 | | | | | 8.1 |
| Industrial Coking Coal | | | 38.3 | | | | 38.3 | | | 1.5 | | | | 1.5 |
| Industrial Other Coal | | | 1,347.9 | | | | 1,347.9 | | | 125.3 | | | | 125.3 |
| Coke Imports | | | 27.1 | | | | 27.1 | | | 2.7 | | | | 2.7 |
| Transportation Coal | | | | NE | | | NE | | | | NE | | | NE |
| Utility Coal | | | | | 17,364.1 | | 17,364.1 | | | | | 1,620.3 | | 1,620.3 |
| US Territory Coal (bit) | | | | | | 9.6 | 9.6 | | | | | | 0.9 | 0.9 |
| **Natural Gas** | **5,097.5** | **2,943.7** | **7,244.6** | **644.1** | **4,507.2** | | **20,437.1** | **269.1** | **155.4** | **373.8** | **34.0** | **237.9** | | **1,070.3** |
| **Total Petroleum** | **1,387.0** | **752.8** | **8,220.6** | **22,056.6** | **1,195.3** | **534.1** | **34,146.6** | **96.1** | **54.7** | **369.2** | **1,468.6** | **93.8** | **34.0** | **2,116.3** |
| Asphalt & Road Oil | | | 1,149.0 | | | | 1,149.0 | | | | | | | |
| Aviation Gasoline | | | | 38.4 | | | 38.4 | | | | 2.6 | | | 2.6 |
| Distillate Fuel Oil | 912.9 | 463.9 | 1,076.7 | 3,912.9 | 99.7 | 104.9 | 6,570.9 | 66.1 | 33.6 | 77.7 | 272.7 | 7.2 | 7.6 | 465.0 |
| Jet Fuel | | | | 3,028.0 | | 62.1 | 3,090.1 | | | | 165.4 | | 4.4 | 169.8 |
| Kerosene | 75.6 | 14.0 | 13.1 | | | 3.8 | 106.5 | 5.4 | 1.0 | 0.9 | | | 0.3 | 7.6 |
| LPG | 398.6 | 70.3 | 1,794.4 | 19.0 | | 4.9 | 2,287.3 | 24.6 | 4.3 | 62.6 | 1.2 | | 0.3 | 93.0 |
| Lubricants | | | 173.1 | 163.5 | | 3.3 | 339.8 | | | 11.5 | 10.9 | | 0.2 | 22.7 |
| Motor Gasoline | | 29.6 | 179.4 | 13,981.5 | | 128.3 | 14,318.8 | | 2.1 | 12.7 | 986.1 | | 9.0 | 1,009.9 |
| Residual Fuel | | 175.0 | 374.9 | 913.4 | 1,015.4 | 155.9 | 2,634.6 | | 13.7 | 27.1 | 29.6 | 78.5 | 12.2 | 161.0 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 0.1 | | | | 0.1 | | | + | | | | + |
| Crude Oil | | | 21.2 | | | | 21.2 | | | 1.6 | | | | 1.6 |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | 94.7 | | | 71.0 | 165.7 | | | | | | | |
| Naphtha (<401 deg. F) | | | 350.6 | | | | 350.6 | | | 9.7 | | | | 9.7 |
| Other Oil (>401 deg. F) | | | 844.1 | | | | 844.1 | | | 25.6 | | | | 25.6 |
| Pentanes Plus | | | 332.3 | | | | 332.3 | | | 11.4 | | | | 11.4 |
| Petroleum Coke | | | 638.2 | | 80.2 | | 718.4 | | | 60.5 | | 8.1 | | 68.6 |
| Still Gas | | | 1,430.2 | | | | 1,430.2 | | | 89.5 | | | | 89.5 |
| Special Naphtha | | | 104.6 | | | | 104.6 | | | 7.5 | | | | 7.5 |
| Unfinished Oils | | | (396.0) | | | | (396.0) | | | (29.1) | | | | (29.1) |
| Waxes | | | 40.0 | | | | 40.0 | | | | | | | |
| **Geothermal** | | | | | **25.8** | | **25.8** | | | | | **0.2** | | **0.2** |
| **TOTAL (All Fuels)** | **6,541.1** | **3,782.0** | **16,878.5** | **22,700.7** | **23,092.5** | **543.7** | **73,538.5** | **370.5** | **218.1** | **872.6** | **1,502.5** | **1,952.3** | **34.8** | **4,950.9** |

[a] Expressed as gross calorific values (i.e., higher heating values).

[b] Adjustments include: international bunker fuel consumption (see Table A-12) and carbon in non-energy products (seeTable A-13).

+ Does not exceed 0.05 Tg $CO_2$ Eq.

NE (Not Estimated)

## Table A-9: 1992 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Consumption (TBtu)[a] | | | | | | | Emissions (Tg $CO_2$ Eq.) including Adjustments[b] and Fraction Oxidized | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **56.7** | **85.7** | **1,408.3** | **NE** | **16,719.4** | **8.8** | **18,278.9** | **5.4** | **8.1** | **128.5** | **NE** | **1,559.4** | **0.8** | **1,702.2** |
| Residential Coal | 56.7 | | | | | | 56.7 | 5.4 | | | | | | 5.4 |
| Commercial Coal | | 85.7 | | | | | 85.7 | | 8.1 | | | | | 8.1 |
| Industrial Coking Coal | | | 24.9 | | | | 24.9 | | | (0.5) | | | | (0.5) |
| Industrial Other Coal | | | 1,348.7 | | | | 1,348.7 | | | 125.4 | | | | 125.4 |
| Coke Imports | | | 34.6 | | | | 34.6 | | | 3.5 | | | | 3.5 |
| Transportation Coal | | | | NE | | | NE | | | | NE | | | NE |
| Utility Coal | | | | | 16,719.4 | | 16,719.4 | | | | | 1,559.4 | | 1,559.4 |
| US Territory Coal (bit) | | | | | | 8.8 | 8.8 | | | | | | 0.8 | 0.8 |
| **Natural Gas** | **4,821.1** | **2,884.2** | **7,006.4** | **609.0** | **4,434.8** | | **19,755.5** | **254.5** | **152.3** | **361.9** | **32.1** | **234.1** | | **1,035.0** |
| **Total Petroleum** | **1,312.4** | **813.5** | **8,428.3** | **21,795.0** | **1,068.6** | **507.5** | **33,925.2** | **90.9** | **59.1** | **391.4** | **1,440.8** | **83.7** | **32.7** | **2,098.6** |
| Asphalt & Road Oil | | | 1,102.2 | | | | 1,102.2 | | | | | | | |
| Aviation Gasoline | | | | 41.1 | | | 41.1 | | | | 2.8 | | | 2.8 |
| Distillate Fuel Oil | 864.9 | 464.0 | 1,125.6 | 3,810.2 | 86.2 | 91.8 | 6,442.7 | 62.6 | 33.6 | 81.3 | 265.4 | 6.2 | 6.6 | 455.7 |
| Jet Fuel | | | | 3,001.3 | | 61.3 | 3,062.6 | | | | 164.2 | | 4.3 | 168.5 |
| Kerosene | 65.0 | 11.1 | 9.8 | | | 3.3 | 89.2 | 4.7 | 0.8 | 0.7 | | | 0.2 | 6.4 |
| LPG | 382.5 | 67.5 | 1,859.8 | 18.4 | | 11.9 | 2,340.1 | 23.6 | 4.2 | 65.3 | 1.1 | | 0.7 | 94.9 |
| Lubricants | | | 170.0 | 160.5 | | 1.5 | 332.0 | | | 11.3 | 10.7 | | 0.1 | 22.1 |
| Motor Gasoline | | 79.6 | 194.3 | 13,681.5 | | 122.1 | 14,077.5 | | 5.6 | 13.7 | 964.5 | | 8.6 | 992.4 |
| Residual Fuel | | 191.2 | 328.2 | 1,082.0 | 916.7 | 154.6 | 2,672.7 | | 14.9 | 23.3 | 32.2 | 70.8 | 12.1 | 153.3 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 0.2 | | | | 0.2 | | | + | | | | + |
| Crude Oil | | | 27.4 | | | | 27.4 | | | 2.0 | | | | 2.0 |
| MoGas Blend Components | | | 75.7 | | | | 75.7 | | | 5.3 | | | | 5.3 |
| Misc. Products | | | 100.1 | | | 61.2 | 161.2 | | | | | | | |
| Naphtha (<401 deg. F) | | | 377.1 | | | | 377.1 | | | 10.4 | | | | 10.4 |
| Other Oil (>401 deg. F) | | | 814.5 | | | | 814.5 | | | 24.7 | | | | 24.7 |
| Pentanes Plus | | | 322.5 | | | | 322.5 | | | 19.0 | | | | 19.0 |
| Petroleum Coke | | | 686.9 | | 65.7 | | 752.7 | | | 61.6 | | 6.6 | | 68.2 |
| Still Gas | | | 1,447.0 | | | | 1,447.0 | | | 91.4 | | | | 91.4 |
| Special Naphtha | | | 104.6 | | | | 104.6 | | | 7.5 | | | | 7.5 |
| Unfinished Oils | | | (354.8) | | | | (354.8) | | | (26.0) | | | | (26.0) |
| Waxes | | | 37.3 | | | | 37.3 | | | | | | | |
| **Geothermal** | | | | | **27.7** | | **27.7** | | | | | **0.2** | | **0.2** |
| **TOTAL (All Fuels)** | **6,190.2** | **3,783.3** | **16,843.0** | **22,403.9** | **22,250.4** | **516.4** | **71,987.2** | **350.8** | **219.5** | **881.8** | **1,473.0** | **1,877.5** | **33.5** | **4,836.0** |

[a] Expressed as gross calorific values (i.e., higher heating values).

[b] Adjustments include: international bunker fuel consumption (see Table A-12) and carbon in non-energy products (seeTable A-13).

+ Does not exceed 0.05 Tg $CO_2$ Eq.

NE (Not Estimated)

## Table A-10: 1991 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Consumption (TBtu)[a] | | | | | | | Emissions (Tg $CO_2$ Eq.) including Adjustments[b] and Fraction Oxidized | | | | | | |
| Fuel Type | Res. | Comm. | Ind. | Trans. | Elec. | Terr. | Total | Res. | Comm. | Ind. | Trans. | Elec. | Terr. | Total |
| **Total Coal** | **56.3** | **84.5** | **1,458.7** | **NE** | **16,465.7** | **7.7** | **18,072.9** | **5.3** | **8.0** | **134.3** | **NE** | **1,535.7** | **0.7** | **1,684.0** |
| Residential Coal | 56.3 | | | | | | 56.3 | 5.3 | | | | | | 5.3 |
| Commercial Coal | | 84.5 | | | | | 84.5 | | 8.0 | | | | | 8.0 |
| Industrial Coking Coal | | | 28.5 | | | | 28.5 | | | 1.4 | | | | 1.4 |
| Industrial Other Coal | | | 1,420.5 | | | | 1,420.5 | | | 132.0 | | | | 132.0 |
| Coke Imports | | | 9.7 | | | | 9.7 | | | 1.0 | | | | 1.0 |
| Transportation Coal | | | | NE | | | NE | | | | NE | | | NE |
| Utility Coal | | | | | 16,465.7 | | 16,465.7 | | | | | 1,535.7 | | 1,535.7 |
| US Territory Coal (bit) | | | | | | 7.7 | 7.7 | | | | | | 0.7 | 0.7 |
| **Natural Gas** | **4,685.0** | **2,807.7** | **6,929.7** | **621.9** | **4,189.4** | | **19,233.6** | **247.3** | **148.2** | **356.6** | **32.8** | **221.2** | | **1,006.1** |
| **Total Petroleum** | **1,293.3** | **860.7** | **7,884.8** | **21,441.9** | **1,261.6** | **539.8** | **33,282.0** | **89.4** | **62.6** | **356.5** | **1,404.9** | **98.2** | **31.1** | **2,042.6** |
| Asphalt & Road Oil | | | 1,076.5 | | | | 1,076.5 | | | | | | | |
| Aviation Gasoline | | | | 41.7 | | | 41.7 | | | | 2.9 | | | 2.9 |
| Distillate Fuel Oil | 831.5 | 481.6 | 1,125.8 | 3,677.6 | 93.4 | 71.4 | 6,281.3 | 60.2 | 34.9 | 81.3 | 255.5 | 6.8 | 5.2 | 443.8 |
| Jet Fuel | | | | 3,025.0 | | 78.2 | 3,103.2 | | | | 166.5 | | 5.5 | 172.0 |
| Kerosene | 72.3 | 12.1 | 11.4 | | | 2.8 | 98.6 | 5.2 | 0.9 | 0.8 | | | 0.2 | 7.1 |
| LPG | 389.5 | 68.7 | 1,749.3 | 19.9 | | 13.8 | 2,241.2 | 24.0 | 4.2 | 58.8 | 1.2 | | 0.8 | 89.2 |
| Lubricants | | | 166.7 | 157.5 | | 0.6 | 324.8 | | | 11.1 | 10.5 | | + | 21.7 |
| Motor Gasoline | | 85.0 | 193.3 | 13,488.3 | | 124.7 | 13,891.2 | | 6.0 | 13.6 | 950.4 | | 8.8 | 978.8 |
| Residual Fuel | | 213.2 | 290.9 | 1,031.9 | 1,121.0 | 134.6 | 2,791.7 | | 16.6 | 20.2 | 18.0 | 86.6 | 10.5 | 152.0 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | (0.1) | | | | (0.1) | | | + | | | | + |
| Crude Oil | | | 38.9 | | | | 38.9 | | | 2.9 | | | | 2.9 |
| MoGas Blend Components | | | (25.9) | | | | (25.9) | | | (1.8) | | | | (1.8) |
| Misc. Products | | | 152.6 | | | 113.8 | 266.4 | | | | | | | |
| Naphtha (<401 deg. F) | | | 298.9 | | | | 298.9 | | | 8.2 | | | | 8.2 |
| Other Oil (>401 deg. F) | | | 827.3 | | | | 827.3 | | | 25.1 | | | | 25.1 |
| Pentanes Plus | | | 294.0 | | | | 294.0 | | | 17.7 | | | | 17.7 |
| Petroleum Coke | | | 585.6 | | 47.2 | | 632.8 | | | 55.6 | | 4.8 | | 60.4 |
| Still Gas | | | 1,426.6 | | | | 1,426.6 | | | 89.6 | | | | 89.6 |
| Special Naphtha | | | 88.0 | | | | 88.0 | | | 6.3 | | | | 6.3 |
| Unfinished Oils | | | (450.2) | | | | (450.2) | | | (33.0) | | | | (33.0) |
| Waxes | | | 35.1 | | | | 35.1 | | | | | | | |
| **Geothermal** | | | | | **27.6** | | **27.6** | | | | | **0.2** | | **0.2** |
| **TOTAL (All Fuels)** | **6,034.6** | **3,752.8** | **16,273.1** | **22,063.8** | **21,944.2** | **547.5** | **70,616.1** | **342.0** | **218.8** | **847.4** | **1,437.7** | **1,855.3** | **31.8** | **4,733.0** |

[a] Expressed as gross calorific values (i.e., higher heating values).

[b] Adjustments include: international bunker fuel consumption (see Table A-12) and carbon in non-energy products (see Table A-13).

+ Does not exceed 0.05 Tg $CO_2$ Eq.

NE (Not Estimated)

## Table A-11: 1990 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Consumption (TBtu)[a] | | | | | | | Emissions (Tg $CO_2$ Eq.) including Adjustments[b] and Fraction Oxidized | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **61.9** | **92.9** | **1,478.0** | **NE** | **16,535.8** | **7.0** | **18,175.6** | **5.8** | **8.7** | **135.9** | **NE** | **1,541.5** | **0.6** | **1,692.6** |
| Residential Coal | 61.9 | | | | | | 61.9 | 5.8 | | | | | | 5.8 |
| Commercial Coal | | 92.9 | | | | | 92.9 | | 8.7 | | | | | 8.7 |
| Industrial Coking Coal | | | 21.0 | | | | 21.0 | | | 0.5 | | | | 0.5 |
| Industrial Other Coal | | | 1,452.2 | | | | 1,452.2 | | | 134.9 | | | | 134.9 |
| Coke Imports | | | 4.8 | | | | 4.8 | | | 0.5 | | | | 0.5 |
| Transportation Coal | | | | NE | | | NE | | | | NE | | | NE |
| Utility Coal | | | | | 16,535.8 | | 16,535.8 | | | | | 1,541.5 | | 1,541.5 |
| US Territory Coal (bit) | | | | | | 7.0 | 7.0 | | | | | | 0.6 | 0.6 |
| **Natural Gas** | **4,518.7** | **2,698.1** | **6,963.2** | **682.4** | **4,049.8** | | **18,912.2** | **238.5** | **142.4** | **358.0** | **36.0** | **213.8** | | **988.8** |
| **Total Petroleum** | **1,266.3** | **907.5** | **8,152.3** | **21,791.8** | **1,329.1** | **461.5** | **33,908.4** | **87.7** | **66.1** | **377.8** | **1,435.8** | **103.4** | **27.4** | **2,098.2** |
| Asphalt & Road Oil | | | 1,170.2 | | | | 1,170.2 | | | | | | | |
| Aviation Gasoline | | | | 45.0 | | | 45.0 | | | | 3.1 | | | 3.1 |
| Distillate Fuel Oil | 837.4 | 487.0 | 1,168.3 | 3,830.5 | 99.0 | 74.0 | 6,496.1 | 60.6 | 35.3 | 84.3 | 266.0 | 7.2 | 5.4 | 458.7 |
| Jet Fuel | | | | 3,129.5 | | 61.0 | 3,190.5 | | | | 173.8 | | 4.3 | 178.1 |
| Kerosene | 63.9 | 11.8 | 12.3 | | | 2.6 | 90.6 | 4.6 | 0.8 | 0.9 | | | 0.2 | 6.5 |
| LPG | 365.0 | 64.4 | 1,607.7 | 21.6 | | 14.4 | 2,073.1 | 22.5 | 4.0 | 56.4 | 1.3 | | 0.9 | 85.2 |
| Lubricants | | | 186.3 | 176.0 | | 0.7 | 363.1 | | | 12.4 | 11.7 | | + | 24.2 |
| Motor Gasoline | | 111.2 | 185.2 | 13,559.0 | | 101.0 | 13,956.4 | | 7.8 | 13.0 | 955.3 | | 7.1 | 983.3 |
| Residual Fuel | | 233.1 | 375.0 | 1,030.2 | 1,181.6 | 121.8 | 2,941.7 | | 18.2 | 27.4 | 24.5 | 91.3 | 9.5 | 170.9 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 0.2 | | | | 0.2 | | | + | | | | + |
| Crude Oil | | | 50.9 | | | | 50.9 | | | 3.7 | | | | 3.7 |
| MoGas Blend Components | | | 53.7 | | | | 53.7 | | | 3.8 | | | | 3.8 |
| Misc. Products | | | 137.8 | | | 86.0 | 223.8 | | | | | | | |
| Naphtha (<401 deg. F) | | | 347.8 | | | | 347.8 | | | 9.6 | | | | 9.6 |
| Other Oil (>401 deg. F) | | | 753.9 | | | | 753.9 | | | 22.8 | | | | 22.8 |
| Pentanes Plus | | | 250.3 | | | | 250.3 | | | 13.4 | | | | 13.4 |
| Petroleum Coke | | | 608.0 | | 48.5 | | 656.5 | | | 56.6 | | 4.9 | | 61.5 |
| Still Gas | | | 1,473.2 | | | | 1,473.2 | | | 92.6 | | | | 92.6 |
| Special Naphtha | | | 107.1 | | | | 107.1 | | | 7.7 | | | | 7.7 |
| Unfinished Oils | | | (369.0) | | | | (369.0) | | | (27.0) | | | | (27.0) |
| Waxes | | | 33.3 | | | | 33.3 | | | | | | | |
| **Geothermal** | | | | | **29.3** | | **29.3** | | | | | **0.2** | | **0.2** |
| **TOTAL (All Fuels)** | **5,846.9** | **3,698.5** | **16,593.5** | **22,474.1** | **21,944.0** | **468.6** | **71,025.5** | **332.1** | **217.3** | **871.6** | **1,471.8** | **1,858.9** | **28.0** | **4,779.8** |

[a] Expressed as gross calorific values (i.e., higher heating values).

[b] Adjustments include: international bunker fuel consumption (see Table A-12) and carbon in non-energy products (see Table A-13).

+ Does not exceed 0.05 Tg $CO_2$ Eq.

NE (Not Estimated)

## Table A-12: 2000 $CO_2$ Emissions From International Bunker Fuel Consumption

| Fuel Type | Bunker Fuel Consumption (TBtu) | Carbon Content Coefficient (Tg Carbon/QBtu)[1] | Potential Emissions (Tg Carbon) | Fraction Oxidized | Emissions (Tg $CO_2$ Eq.) |
|---|---|---|---|---|---|
| Distillate Fuel Oil | 115 | 19.95 | 2.3 | 0.99 | 8.3 |
| Jet Fuel | 816 | 19.33 | 15.8 | 0.99 | 57.3 |
| Residual Fuel Oil | 444 | 21.49 | 9.5 | 0.99 | 34.6 |
| **Total** | **1,375** | | **27.6** | | **100.2** |

Note: See Annex I for additional information on military bunkers.

## Table A-13: 2000 Carbon In Non-Energy Products

| *1* | *2* | *3* | *4* | *5* | *6* |
|---|---|---|---|---|---|
| Fuel Type | Non-energy Use (TBtu) | Carbon Content Coefficient (Tg Carbon/QBtu) | Potential Emissions (Tg Carbon) | Fraction Sequestered[a] | Carbon Stored (Tg $CO_2$ Eq.) |
| **Industry** | **5,512.4** | | **103.6** | | **265.6** |
| Industrial Coking Coal | 26.4 | 25.56 | 0.7 | 0.75 | 1.9 |
| Natural Gas | 342.4 | 14.47 | 5.0 | 0.63 | 11.5 |
| Asphalt & Road Oil | 1,275.7 | 20.62 | 26.3 | 1.00 | 96.4 |
| LPG | 1,707.3 | 16.87 | 28.8 | 0.63 | 66.8 |
| Lubricants | 189.9 | 20.24 | 3.8 | 0.09 | 1.3 |
| Pentanes Plus | 286.8 | 18.24 | 5.2 | 0.63 | 12.1 |
| Petrochemical Feedstocks | | | | | |
| Naphtha (<401 deg. F) | 564.2 | 18.14 | 10.2 | 0.63 | 23.7 |
| Other Oil (>401 deg. F) | 664.1 | 19.95 | 13.2 | 0.63 | 30.7 |
| Still Gas | 7.4 | 17.51 | 0.1 | 0.80 | 0.4 |
| Petroleum Coke | 141.4 | 27.85 | 3.9 | 0.50 | 7.2 |
| Special Naphtha | 97.4 | 19.86 | 1.9 | 0.00 | 0.0 |
| Other (Wax/Misc.) | | | | | |
| Distillate Fuel Oil | 7.0 | 19.95 | 0.1 | 0.50 | 0.3 |
| Residual Fuel | 50.3 | 21.49 | 1.1 | 0.50 | 2.0 |
| Waxes | 33.1 | 19.81 | 0.7 | 1.00 | 2.4 |
| Miscellaneous | 119.2 | 20.23 | 2.4 | 1.00 | 8.8 |
| **Transportation** | **179.4** | | **3.6** | | **1.2** |
| Lubricants | 179.4 | 20.24 | 3.6 | 0.09 | 1.2 |
| **U.S. Territories** | **223.8** | | **4.5** | | **16.5** |
| Lubricants | 1.4 | 20.24 | 0.0 | 0.09 | 0.0 |
| Other Petroleum (Misc.) | 222.5 | variable | 4.5 | 1.00 | 16.5 |
| **Total** | **5,915.6** | | **111.7** | | **283.4** |

[a] See Annex B for additional information.

[1] One QBtu is one quadrillion Btu, or $10^{15}$ Btu. This unit is commonly referred to as a "Quad."

## Table A-14: Key Assumptions for Estimating Carbon Dioxide Emissions

| Fuel Type | Carbon Content Coefficient (Tg Carbon/QBtu) | Fraction Oxidized |
|---|---|---|
| **Coal** | | |
| Residential Coal | [a] | 0.99 |
| Commercial Coal | [a] | 0.99 |
| Industrial Coking Coal | [a] | 0.99 |
| Industrial Other Coal | [a] | 0.99 |
| Coke Imports | 27.85 | 0.99 |
| Transportation Coal | NC | NC |
| Utility Coal | [a] | 0.99 |
| U.S. Territory Coal (bit) | 25.14 | 0.99 |
| **Natural Gas** | **14.47** | **0.995** |
| **Petroleum** | | |
| Asphalt & Road Oil | 20.62 | 0.99 |
| Aviation Gasoline | 18.87 | 0.99 |
| Distillate Fuel Oil | 19.95 | 0.99 |
| Jet Fuel | [a] | 0.99 |
| Kerosene | 19.72 | 0.99 |
| LPG | [a] | 0.99 |
| LPG (energy use/Territories) | [a] | 0.99 |
| LPG (non-energy use) | [a] | - |
| Lubricants | 20.24 | 0.99 |
| Motor Gasoline | [a] | 0.99 |
| Residual Fuel | 21.49 | 0.99 |
| **Other Petroleum** | | |
| AvGas Blend Components | 18.87 | 0.99 |
| Crude Oil | [a] | 0.99 |
| MoGas Blend Components | [a] | 0.99 |
| Misc. Products | [a] | 0.99 |
| Misc. Products (Territories) | variable | 0.99 |
| Naphtha (<401 deg. F) | 18.14 | 0.99 |
| Other Oil (>401 deg. F) | 19.95 | 0.99 |
| Pentanes Plus | 18.24 | 0.99 |
| Petrochemical Feedstocks | 19.37 | 0.99 |
| Petroleum Coke | 27.85 | 0.99 |
| Still Gas | 17.51 | 0.99 |
| Special Naphtha | 19.86 | 0.99 |
| Unfinished Oils | [a] | 0.99 |
| Waxes | 19.81 | 0.99 |
| Other Wax & Misc. | 19.81 | 0.99 |
| **Geothermal** | **2.05** | **1.00** |

Sources: Carbon coefficients from EIA. Combustion efficiency for coal from Bechtel (1993) and for petroleum and natural gas from IPCC (IPCC/UNEP/OECD/IEA 1997).
- Not applicable
NC (Not Calculated)
[a] These coefficients vary annually due to fluctuations in fuel quality (seeTable A-15).

## Table A-15: Annually Variable Carbon Content Coefficients by Year (Tg Carbon/QBtu)

| Fuel Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Residential Coal | 25.92 | 26.00 | 26.13 | 25.97 | 25.95 | 26.00 | 25.92 | 26.00 | 26.00 | 26.00 | 26.00 |
| Commercial Coal | 25.92 | 26.00 | 26.13 | 25.97 | 25.95 | 26.00 | 25.92 | 26.00 | 26.00 | 26.00 | 26.00 |
| Industrial Coking Coal | 25.51 | 25.51 | 25.51 | 25.51 | 25.52 | 25.53 | 25.55 | 25.56 | 25.56 | 25.56 | 25.56 |
| Industrial Other Coal | 25.58 | 25.59 | 25.62 | 25.61 | 25.63 | 25.63 | 25.61 | 25.63 | 25.63 | 25.63 | 25.63 |
| Utility Coal | 25.68 | 25.69 | 25.69 | 25.71 | 25.72 | 25.74 | 25.74 | 25.76 | 25.76 | 25.76 | 25.76 |
| LPG | 16.99 | 16.98 | 16.99 | 16.97 | 17.01 | 17.00 | 16.99 | 16.99 | 16.99 | 16.99 | 16.99 |
| LPG (energy use/Territories) | 17.21 | 17.21 | 17.21 | 17.22 | 17.22 | 17.20 | 17.20 | 17.18 | 17.18 | 17.18 | 17.18 |
| LPG (non-energy use) | 16.83 | 16.84 | 16.84 | 16.80 | 16.88 | 16.87 | 16.86 | 16.88 | 16.87 | 16.88 | 16.87 |
| Motor Gasoline | 19.41 | 19.41 | 19.42 | 19.43 | 19.45 | 19.38 | 19.36 | 19.35 | 19.33 | 19.33 | 19.34 |
| Jet Fuel | 19.40 | 19.40 | 19.39 | 19.37 | 19.35 | 19.34 | 19.33 | 19.33 | 19.33 | 19.33 | 19.33 |
| MoGas Blend Components | 19.41 | 19.41 | 19.42 | 19.43 | 19.45 | 19.38 | 19.36 | 19.35 | 19.33 | 19.33 | 19.34 |
| Misc. Products | 20.16 | 20.18 | 20.22 | 20.22 | 20.21 | 20.23 | 20.25 | 20.24 | 20.24 | 20.19 | 20.23 |
| Unfinished Oils | 20.16 | 20.18 | 20.22 | 20.22 | 20.21 | 20.23 | 20.25 | 20.24 | 20.24 | 20.19 | 20.23 |
| Crude Oil | 20.16 | 20.18 | 20.22 | 20.22 | 20.21 | 20.23 | 20.25 | 20.24 | 20.24 | 20.19 | 20.23 |

Source: EIA (2001a) and EIA (2001c)

## Table A-16: Electricity Consumption by End-Use Sector (Billion Kilowatt-Hours)

| End-Use Sector | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Residential | 924 | 955 | 936 | 995 | 1,008 | 1,043 | 1,083 | 1,076 | 1,130 | 1,145 | 1,192 |
| Commercial | 839 | 856 | 851 | 886 | 914 | 954 | 981 | 1,028 | 1,079 | 1,105 | 1,135 |
| Industrial | 946 | 947 | 973 | 977 | 1,008 | 1,013 | 1,034 | 1,038 | 1,051 | 1,058 | 1,068 |
| Transportation | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| U.S. Territories* | - | - | - | - | - | - | - | - | - | - | - |
| Total | 2,713 | 2,762 | 2,763 | 2,861 | 2,935 | 3,013 | 3,101 | 3,146 | 3,264 | 3,312 | 3,398 |

*EIA data on fuel consumption for electricity generation does not include the U.S. territories.
- Not applicable
Source: EIA (2001a)

# ANNEX B

## Methodology for Estimating Carbon Stored in Products from Non-Energy Uses of Fossil Fuels

Carbon storage associated with the non-energy use of fossil fuels was calculated by multiplying each fuel's potential emissions (i.e., each fuel's total carbon content) by a fuel-specific storage factor. This Annex explains the methods and data sources employed in developing the storage factors for asphalt and road oil, lubricants, petrochemical feedstocks, liquefied petroleum gases (LPG), pentanes plus, and natural gas used for chemical manufacturing plant feedstocks (i.e., not used as fuel.) The storage factors for the remaining non-energy fuel uses are based on values reported by Marland and Rotty (1984).

**Table B-1: Fuel Types and Percent of Carbon Stored for Non-Energy Uses**

| Fuel Type | Storage Factor |
|---|---|
| Industrial Coking Coal[a] | 75% |
| Natural Gas to Chemical Plants | - |
| Nitrogenous Fertilizers | 0% |
| Other Uses | 63% |
| Asphalt & Road Oil | 100% |
| Liquefied Petroleum Gas (LPG) | 63% |
| Lubricants | 9% |
| Pentanes Plus | 63% |
| Petrochemical Feedstocks | - |
| Naphtha (b.p.<401° F) | 63% |
| Other Oil (b.p.>401° F) | 63% |
| Petroleum Coke[b] | 50% |
| Special Naphtha | 0% |
| Other | - |
| Distillate Fuel Oil | 50% |
| Residual Fuel | 50% |
| Waxes | 100% |
| Miscellaneous Products | 100% |

- Not applicable

[a] Includes processes for which specific coking coal consumption and emission factor data are not available. Consumption of coking coal for production of iron and steel is covered in the Industrial Processes chapter.

[b] Includes processes for which specific petroleum coke consumption and emission factor data are not available (e.g., carbon fibers and textiles, refractory, electric motor parts, brake parts, batteries). Consumption of petroleum coke for production of primary aluminum anodes, electric arc furnace anodes, titanium dioxide, and ferroalloys is covered in the Industrial Processes chapter.

The following sections describe the selected non-energy uses in greater detail, outlining the methods employed and data used in estimating each storage factor. Several of the fuel types tracked by EIA—petrochemical feedstocks, pentanes plus, LPG, and natural gas—are used in organic chemical synthesis and in other manufacturing processes. Because the methods and data used to analyze them overlap, they are handled as a group and are discussed first. Discussions of the storage factors for asphalt and road oil and lubricants follow.

## Petrochemical Feedstocks, Pentanes Plus, Liquefied Petroleum Gases, and Natural Gas

Petrochemical feedstocks, pentanes plus, liquefied petroleum gases (LPG) and natural gas[1] are used in the manufacture of a wide variety of man-made chemicals and products. Plastics, rubber, synthetic fibers, solvents, paints, fertilizers, pharmaceuticals, and food additives are just a few of the derivatives of these four fuel types. Chemically speaking, these fuels are diverse, ranging from simple natural gas (i.e., predominantly methane, $CH_4$) to heavier, more complex naphthas and other oils.[2] The storage factor for petrochemical feedstocks, pentanes plus, LPG, and natural gas used for purposes other than fuel is estimated based on data for the year 1998, which is the latest year for which data are available from several key data sources concerning consumption for non-fuel uses.

The four fuel categories constituted approximately 234.2 Tg $CO_2$ Eq., or 49 percent, of the 478.22 Tg $CO_2$ Eq. of non-energy fuel consumption in 1998 (including net exports of petrochemical feedstocks). Of this amount for the four fuels, 18.8 Tg $CO_2$ Eq. was exported, resulting in a net U.S. consumption of 215.4 Tg $CO_2$ Eq. in 1998. Of this net consumption, 136.3 Tg $CO_2$ Eq. ended up stored in products—including products subsequently combusted for waste disposal—while the remaining 79.1 Tg $CO_2$ Eq. was emitted to the atmosphere directly as $CO_2$ (e.g., through combustion of industrial byproducts) or indirectly as $CO_2$ precursors (e.g., through evaporative product use). The indirect emissions include a variety of organic gases such as volatile organic compounds (VOCs) and carbon monoxide (CO), which eventually oxidize into $CO_2$ in the atmosphere. For 1998 the storage factor for the four fuel categories was 63.3 percent; this factor was assumed to remain constant. The derivation of the storage factor is described in the following sections.

### Methodology and Data Sources

An empirically determined storage factor was developed for the carbon consumed for non-energy end uses of petrochemical feedstocks, pentanes plus, LPG, and natural gas (henceforth referred to as feedstocks). The storage factor is equal to the ratio of carbon stored in the final products to total carbon content for the non-energy fossil fuel feedstocks used in industrial processes, after adjusting for net exports of feedstocks. Only one aggregate storage factor was calculated for the four fuel feedstock types. The feedstocks were grouped because of the overlap of their derivative products. Due to the many reaction pathways involved in producing petrochemical products (or wastes), it becomes extraordinarily complex to link individual products (or wastes) to their parent fuel feedstocks.

Import and export data for feedstocks were obtained from the Energy Information Administration (EIA) and from the National Petroleum Refiners Association (NPRA) for the major categories of petrochemical feedstocks (EIA 2001a, NPRA 2001). The EIA tracks imports and exports of petrochemical feedstocks in its publication *Petroleum Supply Annual* (EIA 2001c), including butanes, butylenes, ethane, ethylene, propane, propylene, LPG, and naphthas (i.e., most of the large volume primary chemicals produced by petroleum refineries). These imports and exports are already factored into the U.S. fuel consumption statistics. However, EIA does not track imports and exports of chemical intermediates and products produced by the chemical industry (e.g., xylenes, vinyl chloride, and polypropylene resins), which were derived from the primary chemicals produced by the refineries. For these products, the NPRA data were used. NPRA notes that their data set does not cover all imports and exports, due to the extremely broad range of products and the large number of importers and exporters; they estimate that their data set accounts for roughly 75 percent of the total mass imports and exports of feedstocks. Therefore, after calculating the net carbon flows from the NPRA data, the estimate was adjusted (i.e., by 100/75, or 1.33) to account for 100 percent of the total. Overall, the United States is a net exporter of chemical intermediates and products. Net exports of these materials amounted to 18.8 Tg $CO_2$ in 1998, corresponding to 8 percent of the total domestic fuel feedstocks production of 234.2 Tg $CO_2$. Net domestic consumption of fuel feedstocks (i.e., adjusted for net exports of intermediates and products) amounted to 215.4 Tg $CO_2$ in 1998.

The overall storage factor for the feedstocks was determined by developing a mass balance on the carbon in feedstocks, and characterizing products, uses, and environmental releases as resulting in either storage or emissions.

---

[1] Natural gas has two categories of non-energy consumption: for fertilizer and for other chemical syntheses. Only natural gas that is supplied to chemical plants for other uses is included here. Natural gas used for fertilizer is not included because it covered in the Industrial Processes chapter.

[2] Naphthas are compounds distilled from petroleum containing 4 to 12 carbon atoms per molecule and having a boiling point less than 401° F. Other oils are distillates containing 12 to 25 carbon atoms per molecule and having a boiling point greater than 401° F.

The total carbon in the system is estimated by multiplying net domestic consumption—reported by EIA and then adjusted by assuming 8 percent net exports—by the carbon content of each of the feedstocks (i.e., petrochemical feedstocks-naptha, petrochemical feedstocks-other oils, LPG, pentanes plus, natural gas). Carbon content values for the fuel feedstocks are discussed in Annex A.

Next, carbon pools and releases in a variety of products and processes were characterized. Plastics, synthetic rubber, synthetic fibers, carbon black, industrial non-methane volatile organic compound (NMVOC) emissions, industrial toxic chemical (i.e., TRI) releases, pesticides, and organic solvents were identified as the major product categories.[3]

The carbon in each product or waste produced was categorized as either stored or emitted. The aggregate storage factor is the carbon-weighted average of storage across fuel types. As discussed later in the section on uncertainty, data were not available for all of the non-energy end uses of fuel feedstocks, so the uses analyzed represent a sample of the total carbon consumed. The sample accounts for 195.0 Tg $CO_2$ Eq., or 91 percent, of the 215.4 Tg $CO_2$ Eq. of carbon within these fuel feedstock types that is consumed for non-energy purposes. The remaining 9 percent (18.8 Tg $CO_2$ Eq.) that is "unaccounted for" is assumed to be emitted, not stored. The total amount of carbon that is stored in products, including the amount subsequently lost to waste disposal, corresponds to 136.3 Tg $CO_2$ Eq. Emissions of $CO_2$ from waste disposal are accounted for separately in the Inventory and are discussed in the Waste Combustion section of the Energy chapter.

The following sections provide details on the calculation steps, assumptions, and data sources employed in estimating and classifying the carbon in each product and waste. Summing the carbon stored and dividing it by the total fuel feedstock carbon used yields the overall storage factor, as shown in Table B-2 and the equation below. The major products and their carbon contents are also shown in the Table.

Overall Storage Factor = Carbon Stored / Total Carbon = 136.3 Tg $CO_2$ Eq. / 215.4 Tg $CO_2$ Eq. = 63.3%

**Table B-2: Carbon Stored and Emitted by Products from Petrochemical Feedstocks, Pentanes Plus, LPG, and Natural Gas in 1998 (Tg $CO_2$ Eq.)**

| Product/Waste Type | Carbon Stored | Carbon Emitted |
|---|---|---|
| Plastics | 110.4 | - |
| Synthetic Rubber | 7.7 | - |
| Synthetic Fiber | 11.8 | - |
| Carbon Black | 5.9 | - |
| Pesticides | 0.4 | 0.2 |
| Industrial Releases | - | - |
| Industrial VOCs | | 4.0 |
| TRI Releases | 0.1 | 1.0 |
| Non-Combustion CO | - | 1.3 |
| Solvent VOCs | - | 9.2 |
| Energy Recovery | - | 41.1 |
| Hazardous Waste Incin. | - | 1.9 |
| "Unaccounted for"* | | 20.4 |
| **Total** | **136.3** | **79.1** |

- Not applicable
* Unaccounted for carbon was assumed to be emitted.
Note: Totals may not sum due to independent rounding.

[3] For the most part, the releases covered by the U.S. Toxic Release Inventory (TRI) represent air emissions or water discharges associated with production facilities. Similarly, VOC emissions are generally associated with production facilities. These emissions could have been accounted for as part of the Waste chapter, but because they are not necessarily associated with waste management, they were included here. Toxic releases are not a "product" category, but they are referred to as such for ease of discussion.

### *Plastics*

Data on annual production of plastics were taken from the American Plastics Council, as published in *Chemical & Engineering News* and through direct communication with the APC (APC 2000, Eldredge-Roebuck 2000). These data were organized by year and resin type (see Table B-3). A carbon content was assigned for each resin. These contents were based on molecular formulas and are listed in Table B-4 and Table B-5. In cases where the resin type is generic, referring to a group of chemicals and not a single polymer (e.g., phenolic resins, other styrenic resins), a representative compound was chosen. For engineering resins and other resins, a weighted carbon content of 65 percent was assumed (i.e., it was assumed that these resins had the same content as those for which a representative compound could be assigned).

There were no emissive uses of plastics identified, so 100 percent of the carbon was considered stored in products. However, an estimate of emissions related to the combustion of these plastics in the municipal solid waste stream can be found in the Waste Combustion section of the Energy chapter.

**Table B-3: 1998 Plastic Resin Production (Tg dry weight) and Carbon Stored (Tg $CO_2$ Eq.)**

| Resin Type | 1998 Production [a] | Carbon Stored |
|---|---|---|
| Epoxy | 0.29 | 0.8 |
| Polyester (Unsaturated) | 0.78 | 1.8 |
| Urea | 1.17 | 1.5 |
| Melamine | 0.13 | 0.1 |
| Phenolic | 1.79 | 5.0 |
| Low-Density Polyethylene (LDPE) | 3.44 | 10.8 |
| Linear Low-Density Polyethylene (LLDPE) | 3.28 | 10.3 |
| High Density Polyethylene (HDPE) | 5.86 | 18.4 |
| Polypropylene (PP) | 6.27 | 19.7 |
| Acrylonitrile-butadiene-styrene (ABS) | 0.65 | 2.0 |
| Styrene-acrylonitrile (SAN) | 0.06 | 0.2 |
| Other Styrenics | 0.75 | 2.5 |
| Polystyrene (PS) | 2.83 | 9.6 |
| Nylon | 0.58 | 1.4 |
| Polyvinyl chloride (PVC) [b] | 6.58 | 9.3 |
| Thermoplastic Polyester | 2.01 | 4.6 |
| Engineering Resins | 1.25 | 3.0 |
| All Other | 3.88 | 9.4 |
| **Total** | **41.59** | **110.4** |

[a] Includes production from Canada for ABS, SAN, PVC, PP, Phenolic, Urea, Melamine, and Thermoplastic Polyester
[b] Includes copolymers
Note: Totals may not sum due to independent rounding.

**Table B-4: Assigned Carbon Contents of Plastic Resins (by weight)**

| Resin Type | Carbon Content | Source of Carbon Content Assumption |
|---|---|---|
| Epoxy | 76% | Typical epoxy resin made from epichlorhydrin and bisphenol A |
| Polyester (Unsaturated) | 63% | Poly (ethylene terepthalate) (PET) |
| Urea | 34% | 50% carbamal, 50% N-(hydroxymethyl) urea * |
| Melamine | 29% | Trimethylol melamine * |
| Phenolic | 77% | Phenol |
| Low-Density Polyethylene (LDPE) | 86% | Polyethylene |
| Linear Low-Density Polyethylene (LLDPE) | 86% | Polyethylene |
| High Density Polyethylene (HDPE) | 86% | Polyethylene |
| Polypropylene (PP) | 86% | Polypropylene |
| Acrylonitrile-Butadiene-Styrene (ABS) | 85% | 50% styrene, 25% acrylonitrile, 25% butadiene |
| Styrene-Acrylonitrile (SAN) | 80% | 50% styrene, 50% acrylonitrile |
| Other Styrenics | 92% | Polystyrene |
| Polystyrene (PS) | 92% | Polystyrene |
| Nylon | 65% | Average of nylon resins (see Table B-5) |
| Polyvinyl Chloride (PVC) | 38% | Polyvinyl chloride |
| Thermoplastic Polyester | 63% | Polyethylene terephthalate |
| Engineering Resins | 66% | Weighted average of other resin production |
| All Other | 66% | Weighted average of other resin production |

*Does not include alcoholic hydrogens.

**Table B-5: Major Nylon Resins and their Carbon Contents (by weight)**

| Resin | Carbon Content |
|---|---|
| Nylon 6 | 64% |
| Nylon 6,6 | 64% |
| Nylon 4 | 52% |
| Nylon 6,10 | 68% |
| Nylon 6,11 | 69% |
| Nylon 6,12 | 70% |
| Nylon 11 | 72% |

### *Synthetic Rubber*

Data on annual consumption of synthetic rubber were obtained from the International Institute of Synthetic Rubber Producers (IISRP) press release "Synthetic Rubber Use Growth to Continue Through 2004, Says IISRP and RMA" (IISRP 2000). Due to the fact that production data for synthetic rubber were unavailable, consumption was assumed to equal production. These data were organized by year and elastomer type. A carbon content was assigned for each elastomer type. These contents, based on stoichiometry, are listed in Table B-6. For the "Others" category, a weighted carbon content was calculated from total 1998 consumption data.

There were no emissive uses of rubber identified, so 100 percent of the carbon was assumed stored. However, emissions related to the combustion of scrap tires and rubber consumer goods can be found in the Waste Combustion section of the Energy chapter.

**Table B-6: 1998 Rubber Consumption, Carbon Content, and Carbon Stored**

| Elastomer Type | 1998 Consumption (Thousand Metric Tons) * | Carbon Content | Carbon Stored (Tg $CO_2$ Eq.) |
|---|---|---|---|
| SBR Solid | 908 | 91% | 3.0 |
| Polybutadiene | 561 | 89% | 1.8 |
| Ethylene Propylene | 320 | 86% | 1.0 |
| Polychloroprene | 69 | 59% | 0.1 |
| NBR Solid | 87 | 77% | 0.2 |
| Polyisoprene | 78 | 88% | 0.3 |
| Others | 369 | 88% | 1.2 |
| **Total** | **2,392** | - | **7.7** |

* Includes consumption in Canada.
- Not applicable
Note: Totals may not sum due to independent rounding.

### *Synthetic Fibers*

Annual synthetic fiber production data were obtained from the Fiber Economics Bureau, as published in *Chemical & Engineering News* and exhibited on the FiberSource website (FEB 2000). These data are organized by year and fiber type. For each fiber, a carbon content was assigned based on stoichiometry (see Table B-7). For polyester, the carbon content for poly(ethylene terephthalate) (PET) was used as a representative compound. For nylon, the average carbon content of nylon 6 and nylon 6,6 was used, since these are the most widely produced nylon fibers. Cellulosic fibers, such as acetate and rayon, have been omitted from the synthetic fibers' carbon accounting because much of their carbon is of biogenic origin. These fibers account for only 4 percent of overall fiber production by weight.

There were no emissive uses of fibers identified, so 100 percent of the carbon was considered stored. However, emissions related to the combustion of textiles in the municipal solid waste stream is accounted for under the Waste Combustion section of the Energy chapter.

**Table B-7: 1998 Fiber Production, Carbon Content, and Carbon Stored**

| Fiber Type | Production (Tg) | Carbon Content | Carbon Stored (Tg $CO_2$ Eq.) |
|---|---|---|---|
| Polyester | 1.8 | 63% | 4.1 |
| Nylon | 1.3 | 64% | 3.0 |
| Olefin | 1.3 | 86% | 4.1 |
| Acrylic | 0.2 | 68% | 0.5 |
| **Total** | **4.6** | - | **11.7** |

- Not applicable
Note: Totals may not sum due to independent rounding

### *Carbon Black*

Carbon black is a finely divided solid form of carbon produced from the partial oxidation of heavy oil fractions.[4] It is used primarily in manufacture of tire treads and other abrasion resistant rubber products, but can also be used in pigments for paints and inks. In 1998, carbon black ranked 35th in chemical production in the United States with 1,610,280 metric tons produced (CMA 1999). Since carbon black is essentially pure carbon, its carbon content was assumed to be 100 percent. Also, since it is used in solid products and resists degradation, it was considered 100 percent stored. For 1998, carbon stored as a result of carbon black production was estimated to be 5.9 Tg $CO_2$ Eq.

[4] Carbon black can also be produced from the cracking of natural gas, but this method is uncommon.

### *Energy Recovery*

The amount of fuel feedstocks that are combusted for energy recovery was estimated from data included in EIA's Manufacturers Energy Consumption Survey (MECS) for 1998 (EIA 2001b). Fuel feedstocks may be combusted for energy recovery because the chemical reactions in which fuel feedstocks are used are not 100 percent efficient. These chemical reactions may generate unreacted raw material feedstocks or generate byproducts that have a high energy content. The chemical industry and many downstream industries are energy-intensive, and therefore unreacted feedstocks or byproducts of production may be combusted for energy recovery in industrial boilers. Also, hazardous waste regulations provide a strong incentive—and in some cases require—burning of organic wastes generated from chemical production processes. Combustion of hazardous waste without energy recovery is referred to as "incineration," and is discussed separately in this Annex.

MECS data include data on the consumption for energy recovery of "other" fuels in the petroleum and coal products, chemicals, primary metals, nonmetallic minerals, and other manufacturing sectors. These "other" fuels include refinery still gas; waste gas; waste oils, tars, and related materials; petroleum coke, coke oven and blast furnace gases; and other uncharacterized fuels. Fuel use of petroleum coke is included separately in the fuel use data provided annually by EIA, and energy recovery of coke oven gas and blast furnace gas (i.e., byproducts of the iron and steel production process) is addressed in the Iron and Steel production section in the Industrial Processes chapter. Consumption of refinery still gas and "other" fuels in the refinery sector is also included separately in the fuel use data from EIA. Therefore these categories of "other" fuels are addressed elsewhere in the inventory and not considered as part of the petrochemical feedstocks energy recovery discussion. The remaining categories of fuels included in the 1998 MECS data (Table B-8) including waste gas; waste oils, tars, and related materials; and other uncharacterized fuels are assumed to be petrochemical feedstocks burned for energy recovery. The conversion factors listed in Annex A were used to convert the Btu values for each fuel feedstock to Tg $CO_2$. Petrochemical feedstocks combusted for energy recovery corresponded to 41.1 Tg $CO_2$ Eq. in 1998.

**Table B-8: Summary of 1998 MECS Data for Other Fuels used in Manufacturing/Energy Recovery (Trillion Btu)**

| Subsector and Industry | NAICS Code | Waste Gas[b] | Waste Oils/Tars[c] | Refinery Still Gas[d] | Net Steam[e] | Other Fuels[f,g] |
|---|---|---|---|---|---|---|
| Printing and Related Support | 323 | 0 | 1 | 0 | 0 | 0 |
| Petroleum and Coal Products | 324 | 0 | 1 | 1399 | 0 | 324[a] |
| Chemicals | 325 | 416 | 16 | 0 | 194 | 118[a] |
| Plastics and Rubber Products | 326 | 0 | 0 | 0 | 0 | 0 |
| Nonmetallic Mineral Products | 327 | 2 | 9 | 0 | 0 | 14 |
| Primary Metals | 331 | 2 | 2 | 0 | 0 | 22 |
| Fabricated Metal Products | 332 | 1 | 0 | 0 | 0 | 0 |
| Machinery | 333 | 0 | 1 | 0 | 0 | 0 |
| Computer and Electronic Products | 334 | 0 | 0 | 0 | 0 | 0 |
| Electrical Equipment, Appliances, Components | 335 | 1 | 1 | 0 | 0 | 0 |
| Transportation Equipment | 336 | 1 | 2 | 0 | 0 | 0 |
| **Total** | | **423** | **33** | **1399** | **194** | **478** |
| Carbon Content (Tg/QBTU) | | 18.1 | 20.6 | 17.5 | 0 | 19.4 |
| Fraction Oxidized | | 99% | 99% | 99% | 0% | 99% |
| **Total Carbon (Tg)** | | **7.6** | **0.7** | **24.2** | **0.0** | **9.2** |
| **Total Carbon (Non-Refining)** | | **7.6** | **0.7** | **0.0** | **0.0** | **3.0** |

[a] EIA personal communication, 2001.
[b] C content assumed to be naphtha <401F.
[c] C content assumed to be asphalt and road oil.
[d] Refinery "other" fuel consumption is reported elsewhere in the inventory and is excluded from the total carbon. The total non-refining total carbon excludes all "other" fuel consumption under NAICS Code 325 (Petroleum and Coal Products).
[e] Net steam is reported elsewhere in the inventory and is excluded from the total carbon content estimate.
[f] Assumed to be petrochemical feedstocks.
[g] Includes net steam, except for NAICS Code 325 (Chemicals). Net steam for other sectors assumed to be negligible.
Note: Totals may not sum due to independent rounding.

### *Industrial and Solvent Evaporation Volatile Organic Compound Emissions*

Data on annual non-methane volatile organic compound (NMVOC) emissions were obtained from the *National Air Quality and Emissions Trends Report* (EPA 2000b). NMVOC emissions were organized by end-use

category. NMVOC emissions from solvent utilization were considered to be a result of non-energy use of petrochemical feedstocks. The end-use categories that represent "Industrial NMVOC Emissions" include chemical and allied products, petroleum and related industries, and other industrial processes. These categories are non-energy uses of the four fuel types; other categories where VOCs could be emitted due to combustion of fossil fuels were excluded to avoid double counting.

Because solvent evaporation and industrial NMVOC emission data are provided in tons of total NMVOCs, assumptions were made concerning the average carbon content of the NMVOCs for each category of emissions. The assumptions for calculating the carbon fraction of industrial and solvent utilization emissions were made separately and differ significantly. For industrial NMVOC emissions, the carbon content of 85 percent was assumed. This value was chosen to reflect the carbon content of an average volatile organic compound based on the list of the most abundant, NMVOCs provided in the *Trends Report.* The list contains only pure hydrocarbons, including saturated alkanes (carbon contents ranging from 80 to 85 percent based upon carbon number), alkenes (carbon contents equal 85.7 percent), and some aromatics (carbon contents approximately 90 percent, depending upon substitution).

EPA (2000b) solvent evaporation emissions data were used directly to estimate the carbon content of solvent emissions. The EPA data identify solvent emissions by compound or compound category for six different solvent end-use categories: degreasing, graphic arts, dry cleaning, surface coating, other industrial processes, and non-industrial processes. The percent carbon of each compound identified in the EPA solvent evaporation emissions data was calculated based on the stoichiometry of the individual compound (e.g., the carbon content of methlyene chloride is 14 percent; the carbon content of toluene is 91 percent). For solvent emissions that are identified in the EPA data only by chemical category (e.g., butanediol derivatives) a single individual compound was selected to represent each category, and the carbon content of the category was estimated based on the carbon content of the representative compound. The overall carbon content of the solvent evaporation emissions is estimated to be 56 percent.

The results of the industrial and solvent NMVOC emissions analysis are provided in Table B-9.

**Table B-9: 1998 Industrial and Solvent NMVOC Emissions**

| Activity | Thousand short tons | Carbon Content | Carbon Emitted (Tg $CO_2$ Eq.) |
|---|---|---|---|
| Industrial NMVOCs[a] | 1,417 | 85% | 4.0 |
| Solvent Evaporation[b] | 4,950 | 56% | 9.3 |

[a] Includes emissions from chemical and allied products, petroleum and related industries, and other industrial processes categories.
[b] Includes solvent usage and solvent evaporation emissions from degreasing, graphic arts, dry cleaning, surface coating, other industrial processes, and non-industrial processes.

### *Hazardous Waste Incineration*

Hazardous wastes are defined by the EPA under the Resource Conservation and Recovery Act (RCRA).[5] Industrial wastes, such as rejected products, spent reagents, reaction by-products, and sludges from wastewater or air pollution control, are federally regulated as hazardous wastes if they are found to be ignitable, corrosive, reactive, or toxic according to standardized tests or studies conducted by the EPA.

Hazardous wastes must be treated prior to disposal according to the federal regulations established under the authority of RCRA. Combustion is one of the most common techniques for hazardous waste treatment, particularly for those wastes that are primarily organic in composition or contain primarily organic contaminants. Generally speaking, combustion devices fall into two categories: incinerators that burn waste solely for the purpose of waste management, and boilers and industrial furnaces (BIFs) that burn waste in part to recover energy from the waste. More than half of the hazardous waste combusted in the U.S. is burned in BIFs; these processes are included in the energy recovery calculations described above.

The EPA's Office of Solid Waste requires biennial reporting of hazardous waste management activities, and these reports provide estimates of the amount of hazardous waste burned for incineration or energy recovery.

[5] [42 U.S.C. §6924, SDWA §3004]

EPA stores this information in its Biennial Reporting System (BRS) database (EPA 2000a). Combusted hazardous wastes are identified based on EPA-defined management system types M041 through M049 (incineration). Combusted quantities are grouped into four representative waste form categories based on the form codes reported in the BRS: aqueous liquids, organic liquids and sludges, organic solids, and inorganic solids. To relate hazardous waste quantities to carbon emissions, "fuel equivalent" factors were derived for hazardous waste by assuming that the hazardous wastes are simple mixtures of a common fuel, water, and noncombustible ash. For liquids and sludges, crude oil is used as the fuel equivalent and coal is used to represent solids.

Fuel equivalent factors were multiplied by the tons of waste incinerated to obtain the tons of fuel equivalent. Multiplying the tons of fuel equivalent by the appropriate carbon content factors from Marland and Rotty (1984) yields tons of carbon emitted. Implied carbon content is calculated by dividing the tons of carbon emitted by the associated tons of waste incinerated.

Waste quantity data for hazardous wastes were obtained from the EPA's BRS database for reporting years 1989, 1991, 1993, 1995, and 1997 (EPA 2000a). Combusted waste quantities were obtained from Form GM (Generation and Management) for wastes burned on site and Form WR (Wastes Received) for waste received from off-site for combustion. For each of the waste types, assumptions were developed on average waste composition (see Table B-10). Carbon emission factors for equivalent fuels were obtained from Marland and Rotty (1984). Regulations require incinerators to achieve at least 99.99 percent destruction of organics; this formed the basis for assuming the fraction of carbon oxidized. A least-squares linear regression from the time series 1989 through 1997 was used to estimate emissions for 1998.

**Table B-10: Assumed Composition of Combusted Hazardous Waste by Weight (Percent)**

| Waste Type | Water | Noncombustibles | Fuel Equivalent |
|---|---|---|---|
| Aqueous Waste | 90 | 5 | 5 |
| Organic Liquids and Sludges | 40 | 20 | 40 |
| Organic Solids | 20 | 40 | 40 |
| Inorganic Solids | 20 | 70 | 10 |

### *Non-Combustion Carbon Monoxide Emissions*

Carbon monoxide (CO) emissions data were obtained from the National Air Quality and Emissions Trends Report (EPA 2000a). There are four categories of CO emissions in EPA (2000a) that are classified as process-related emissions not related to fuel combustion. These include chemical and allied products manufacturing, metals processing, petroleum and related industries, and other industrial processes. Some of these CO emissions are accounted for in the Industrial Processes section of this report, and are therefore not accounted for in this section, including total carbon emissions from the primary aluminum, titanium dioxide, iron and steel, and ferroalloys production processes. The total carbon (CO and $CO_2$) emissions from oil and gas production and asphalt manufacturing are also accounted for elsewhere in this Inventory. Sustainably harvested biogenic emissions (e.g., pulp and paper process emissions) are also excluded from calculation of CO emissions in this section. Those CO emissions that are not accounted for elsewhere are considered to be byproducts of non-fuel use of feedstocks and are included in the calculation of the petrochemical feedstocks storage factor. Table B-11 lists the industrial processes and CO emissions that remain after excluding those reported in the Industrial Processes chapter, or where the carbon originates from sustainably harvested biogenic sources.

**Table B-11: Carbon Monoxide Non-Combustion Emissions (Gg)**

| Source | 1998 |
|---|---|
| **Chemical and Allied Products** | |
| Organic Chemical Manufacture | 83.6 |
| Inorganic Chemical Manufacture, Other | 2.7 |
| Polymer and Resin Manufacture | 4.5 |
| Agricultural Chemical Manufacture | 11.8 |
| Paint, Varnish, Lacquer Manufacture | - |
| Pharmaceutical Manufacture | - |
| Other Chemical Manufacture | 23.6 |
| **Metals Processing** | |
| Nonferrous Metals Processing, Other | 145.5 |
| Metals Processing NEC | 40.0 |
| **Petroleum and Related Industries** | |
| Petroleum Refineries and Related Industry | 300.9 |
| **Other Industrial Processes** | |
| Rubber and Misc. Plastic Products | - |
| Mineral Products | 169.1 |
| Machinery Products | 0.91 |
| Electronic Equipment | - |
| Transportation Equipment | - |
| Misc. Industrial Processes | 18.2 |
| **Total** | **801.7** |
| **Total (Tg $CO_2$ Eq.)** | **1.3** |

### *Pesticides*

Pesticide consumption data were obtained from the *1996/1997 Pesticides Industry Sales and Usage* (EPA 1999) report. Although some production data were available, consumption data were used because these data provided information on active ingredients. Active ingredient compound names and consumption weights were available for the top 25 agriculturally-used pesticides and top 9 pesticides used in the home and garden and the industry/commercial/government categories. Since the report provides a range of consumption for each active ingredient, the midpoint was used to represent actual consumption. Each of these compounds was assigned a carbon content value based on stoichiometry. If the compound contained aromatic rings substituted with chlorine or other halogens, then the compound was considered persistent and assigned a 100 percent carbon storage factor. All other pesticides were assumed to release their carbon to the atmosphere. Nearly one-third of total pesticide active ingredient consumption was not specified by chemical type in the *Sales and Usage* report (EPA 1999). This unspecified portion of the active ingredient consumption was treated as a single chemical and assigned a carbon content and a storage factor based on the weighted average of the known chemicals' values.

**Table B-12: Active Ingredient Consumption in Pesticides (Million lbs.) and Carbon Emitted and Stored (Tg $CO_2$ Eq.)**

| Pesticide Use | Active Ingredient | Carbon Emitted | Carbon Stored |
|---|---|---|---|
| **Agricultural Uses [a]** | **551.0** | **0.1** | **0.2** |
| **Non-Agricultural Uses [b]** | **84.5** | **+** | **+** |
| Home & Garden | 34.0 | + | + |
| Industry/Gov't/Commercial | 50.5 | + | + |
| **Other** | **334.5** | **0.1** | **0.1** |
| **Total** | **970.0** | **0.2** | **0.4** |

+ Less than 0.05 Tg $CO_2$ Eq.
[a] 1997 estimate (EPA 1999).
[b] Approximate quantities, 1995/1996 estimates (EPA 1999).
Note: Totals may not sum due to independent rounding.

### *TRI Releases*

Carbon is also found in toxic substances released by industrial facilities. The Toxic Release Inventory (TRI), maintained by the EPA, tracks these releases by chemical and environmental release medium (i.e., land, air,

or water) on a biennial basis (EPA 2000b). By examining the carbon contents and receiving media for the top 35 toxic chemicals released, which account for 90 percent of the total mass of chemicals, the quantity of carbon stored and emitted in the form of toxic releases can be estimated.

The TRI specifies releases by chemical, so carbon contents were assigned to each chemical based on stoichiometry. The TRI also classifies releases by disposal location as either off-site or on-site. The on-site releases are further subdivided into air emissions, surface water discharges, underground injection, and releases to land; the latter is further broken down to disposal in a RCRA Subtitle C (i.e., hazardous waste) landfill or to "Other On-Site Land Disposal."[6] The carbon released in each disposal location is provided in Table B-13.

Each on-site classification was assigned a storage factor. A one hundred percent storage factor was applied to disposition of carbon to Underground Injection and to Disposal to RCRA-permitted Landfills, while the other disposition categories were assumed to result in an ultimate fate of emission as $CO_2$ (i.e., a storage factor of zero was applied to these categories.) The release allocation is not reported for off-site releases; therefore, the approach was to develop a carbon-weighted average storage factor for the on-site carbon and apply it to the off-site releases.

For the remaining 10 percent of the TRI releases, the weights of all chemicals were added and an average carbon content value, based upon the top 35 chemicals' carbon contents, was applied. The storage and emission allocation for the remaining 10 percent of the TRI releases was carried out in the same fashion as for the 35 major chemicals.

**Table B-13: 1998 TRI Releases by Disposal Location (Gg $CO_2$ Eq.)**

| Disposal Location | Carbon Stored | Carbon Emitted |
|---|---|---|
| Air Emissions | - | 924.0 |
| Surface Water Discharges | - | 6.7 |
| Underground Injection | 89.4 | - |
| RCRA Subtitle C Landfill Disposal | 1.4 | - |
| Other On-Site Land Releases | - | 15.9 |
| Off-site Releases | 6.4 | 36.0 |
| **Total** | **97.2** | **982.6** |

- Not applicable
Note: Totals may not sum due to independent rounding.

### Uncertainty

There are several cross-cutting sources of uncertainty that pervade the characterization of a storage factor for feedstocks. The aggregate storage factor for petrochemical feedstocks, pentanes plus, liquefied petroleum gases, and natural gas is based on only a partial sampling of the products derived from these fossil fuel feedstocks and imports and exports of petrochemical feedstocks. Including consideration of petrochemical feedstocks that are exported and feedstocks that are burned for energy recovery, approximately 91 percent of the carbon consumed across these four fuel types for non-energy uses is accounted for. The remaining "unaccounted-for" carbon could have a variety of fates. For the purposes of this inventory, all of the unaccounted for carbon was assumed to be emitted, and using this assumption the overall storage factor is 63.3 percent. If the assumption had been made that the products which contained the unaccounted for carbon would store and emit carbon in the same ratio as the investigated products, the overall storage factor would have been 69.9 percent, rather than 63.3 percent.

With respect to the "unaccounted for" carbon, there are uncertainties associated with the EIA and NPRA data for net imports and exports of feedstocks that could affect the calculation of the storage factor. To a lesser extent, there are uncertainties associated with the simplifying assumptions made for each end use category carbon estimate. Generally, the estimate for a product is subject to one or both of the following uncertainties:

- The value used for estimating the carbon content has been assumed or assigned based upon a representative compound.

[6] Only the top 9 chemicals had their land releases separated into RCRA Landfills and Other Land Disposal. For the remaining chemicals, it was assumed that the ratio of disposal in these two categories was equal to the carbon-weighted average of the land disposal fate of the top 9 chemicals (i.e., 8 percent attributed to RCRA Landfills and 92 percent in the "Other" category).

- The split between carbon storage and emission has been assumed based on an examination of the environmental fate of the products in each end use category.

Another cross-cutting source of uncertainty is that the estimate of the balance between storage and emissions is based on data for only for a single year, 1998. This specific year may not be representative of storage for the entire decade.

Sources of uncertainty associated with specific elements of the analysis are discussed below.

### *Imports/Exports*

Import and export data for petrochemical feedstocks were obtained from EIA and the National Petroleum Refiners Association for the major categories of petrochemical feedstocks (EIA 2001a, NPRA 2001). However, the NPRA believes that the import and export data that they provide account for only 75 percent of the total imports and exports of petrochemical feedstocks. The NPRA data provided were adjusted to account for 100 percent of the total, though this adjustment represents a source of uncertainty in the estimate of net exports. Net exports could be lower or higher than that estimated depending upon how comprehensive the combined EIA and NPRA data are in tracking total imports and exports of petrochemical feedstocks.

### *Oxidation Factors*

Oxidation factors have been applied to non-energy uses of petrochemical feedstocks in the same manner as for energy uses. However, this "oxidation factor" may be inherent in the storage factor applied when calculation emissions from non-energy consumption, which would result in a double-counting of the unoxidized carbon. Oxidation factors are small corrections, on the order of 1 percent, and therefore application of oxidation factors to non-energy uses may result in a slight underestimation of carbon emissions from non-energy uses.

### *Plastics*

Uncertainty in the carbon storage estimate for plastics arises primarily from three factors. First, the production data for acrylonitrile-butadiene-styrene, styrene-acrylonitrile, polyvinyl chloride, polypropylene, phenolic, urea, melamine, and thermoplastic polyester resins include Canadian production and may overestimate the amount of plastic produced from U.S. fuel feedstocks. Second, the assumed carbon content values are estimates for representative compounds, and thus do not account for the many formulations of resins available. This uncertainty is greater for resin categories that are generic (e.g., phenolics, other styrenics, nylon) than for resins with more specific formulations (e.g., polypropylene, polyethylene). Lastly, the assumption that all of the carbon contained in plastics is stored ignores certain end uses (e.g., adhesives and coatings) where the resin may be released to the atmosphere; however, these end uses are likely to be small relative to use in plastics.

### *Rubber*

Similar to plastics, uncertainty results from using consumption data for the United States and Canada, rather than just domestic consumption, which may overestimate the amount of rubber produced from U.S. fuel feedstocks. There are also uncertainties as to the assignment of carbon content values; however, they are much smaller than in the case of plastics. There are probably fewer variations in rubber formulations than in plastics, and the range of potential carbon content values is much narrower. Lastly, assuming that all of the carbon contained in rubber is stored ignores the possibility of volatilization or degradation during product lifetimes. However, the proportion of the total carbon that is released to the atmosphere during use is probably negligible.

### *Fiber*

A small degree of uncertainty arises from the assignment of carbon content values; however, the magnitude of this uncertainty is less than that for plastics or rubber. Although there is considerable variation in final textile products, the stock fiber formulations are standardized and proscribed explicitly by the Federal Trade Commission.

### *Energy Recovery*

The amount of feedstocks combusted for energy recovery was estimated from data included in the Manufacturers Energy Consumption Survey (MECS) for 1998 (EIA 2001b). MECS is a comprehensive survey intended to represent U.S. industry as a whole, but because EIA does not receive data from all manufacturers (i.e., it is a sample rather than a census), EIA must extrapolate from the sample. Also, the "other" fuels are identified in the 1998 MECS data in broad categories, including refinery still gas; waste gas; waste oils, tars, and related materials; petroleum coke, coke oven and blast furnace gases; and other uncharacterized fuels, and the industries using these "other" fuels are also identified only in broad categories, including the petroleum and coal products, chemicals, primary metals, nonmetallic minerals, and other manufacturing sectors. The "other" fuel consumption data are reported in BTUs (energy units) and there is uncertainty concerning the selection of a specific conversion factor for each broad "other" fuel category to convert energy units to mass units.

### *NMVOCs (Solvent Evaporation and Industry)*

The principal sources of uncertainty in estimating $CO_2$ emissions from solvent evaporation and industry are in the estimates of total NMVOC emissions and in the application of factors for the carbon content of these emissions. Solvent evaporation and industrial NMVOC emissions reported by EPA are based on a number of data sources and emission factors, and may underestimate or overestimate emissions. The carbon content for solvent evaporation emissions is calculated directly from the specific solvent compounds identified by EPA as being emitted, and is thought to have relatively low uncertainty. The carbon content for industrial emissions has more uncertainty, however, as it is calculated from the average carbon content of an average volatile organic compound based on the list of the most abundant measured NMVOCs provided in EPA (2000b).

### *Hazardous Waste*

The greatest uncertainty in the hazardous waste combustion analysis is introduced by the assumptions about the composition of combusted hazardous wastes, including the characterization that hazardous wastes are similar to mixtures of water, noncombustibles, and fuel equivalent materials. Another limitation is the assumption that all of the carbon that enters hazardous waste combustion is emitted—some small fraction is likely to be sequestered in combustion ash—but given that the destruction and removal efficiency for hazardous organics is required to meet or exceed 99.99 percent, this is a minor source of uncertainty. Carbon emission estimates from hazardous waste should be considered central value estimates that are likely to be accurate to within ±50 percent.

### *Pesticides*

The largest source of uncertainty involves the assumption that a pesticide's active ingredient carbon is either 0 percent stored or 100 percent stored. This split is a generalization of chemical behavior, based upon active-ingredient molecular structure, and not on compound-specific environmental data. The mechanism by which a compound is bound or released from soils is very complicated and can be affected by many variables, including the type of crop, temperature, delivery method, and harvesting practice. Another smaller source of uncertainty arises from the carbon content values applied to the unaccounted for portion of active ingredient. Carbon contents vary widely among pesticides, from 7 to 72 percent, and the remaining pesticides may have a chemical make-up that is very different from the 32 pesticides that have been examined.

### *TRI*

The major uncertainty in using the TRI data are the possibility of double counting of emissions that are already accounted for in the NMVOC data (see above) and in the storage and emission assumptions used. The approach for predicting environmental fate simplifies some complex processes, and the balance between storage and emissions is very sensitive to the assumptions on fate. Extrapolating from known to unknown characteristics also introduces uncertainty. The two extrapolations with the greatest uncertainty are: 1) that the release media and fate of the off-site releases were assumed to be the same as for on-site releases, and 2) that the carbon content of the least frequent 10 percent of TRI releases was assumed to be the same as for the chemicals comprising 90 percent of the releases. However, the contribution of these chemicals to the overall estimate is small. The off-site releases only

account for 3 percent of the total releases, by weight, and, by definition, the less frequent compounds only account for 10 percent of the total releases.

## Asphalt and Road Oil

Asphalt is one of the principal non-energy uses of fossil fuels. The term "asphalt" generally refers to a mixture of asphalt cement and a rock material aggregate, a volatile petroleum distillate, or water. For the purposes of this analysis, "asphalt" is used interchangeably with asphalt cement, a residue of crude oil. According to EIA (2000d), approximately 100 Tg $CO_2$ Eq. has been used in the production of asphalt cement annually. Though minor amounts of carbon are emitted during production, asphalt has an overall carbon storage factor of almost 100 percent.

Paving is the primary application of asphalt cement, comprising 86 percent of production. The three types of asphalt paving produced in the United States are hot mix asphalt (HMA), cut-backs, and emulsified asphalt. HMA, which makes up 90 percent of total asphalt paving (EPA 2000d), contains asphalt cement mixed with an aggregate of rock materials. Cut-back asphalt is composed of asphalt cement thinned with a volatile petroleum distillate (e.g., naphtha). Emulsified asphalt contains only asphalt cement and water. Roofing products are the other significant end use of asphalt cement, accounting for approximately 14 percent of U.S. production (Kelly 2000). No data were available on the fate of carbon in asphalt roofing; it was assumed that it has the same fate as carbon in asphalt paving applications.

### Methodology

A carbon storage factor was calculated for each type of asphalt paving. The fraction of carbon emitted by each asphalt type was multiplied by consumption data for asphalt paving (EPA 2000d, EIIP 1998) to come up with a weighted average carbon storage factor for asphalt as a whole.

The fraction of carbon emitted by HMA was determined by first calculating the organic emissions (volatile organic compounds [VOCs], carbon monoxide, polycyclic aromatic hydrocarbons [PAHs], hazardous air pollutants [HAPs], and phenol) from HMA paving, using emission factors reported in EPA (2000d) and total HMA production.[7] The next step was to estimate the carbon content of the organic emissions. This calculation was based on stoichiometry for carbon monoxide (CO) and phenol, and an assumption of 85 percent carbon content for PAHs and HAPs. The carbon content of asphalt paving is a function of the proportion of asphalt cement in asphalt paving and the proportion of carbon in asphalt cement. For the former factor, a 5 percent asphalt cement content was assumed based on personal communication with an expert from the National Asphalt Paving Association (Connolly 2000). For the latter factor, all paving types were characterized as having a mass fraction of 85 percent carbon in asphalt cement, based on the assumption that asphalt is primarily composed of saturated paraffinic hydrocarbons. By combining these estimates, the result is that over 99.99 percent of the carbon in asphalt cement was retained (i.e., stored), and less than 0.01 percent was emitted.

Cut-back asphalt is produced in three forms (i.e., rapid, medium and slow cure). All three forms emit carbon only from the volatile petroleum distillate used to thin the asphalt cement (EPA 1995). Because the petroleum distillates are not included in the EIA statistics for asphalt, the storage factor for cut-back is assumed to be 100 percent.

It was also assumed that there was no loss of carbon from emulsified asphalt (i.e., the storage factor is 100 percent) based on personal communication with an expert from Akzo Nobel Coatings, Inc. (James 2000).

### Data Sources

Data on asphalt and road oil consumption and carbon content factors were supplied by the EIA. Hot mix asphalt production and emissions factors were obtained from "Hot Mix Asphalt Plants Emissions Assessment Report" from the EPA publication *AP-42* (EPA 2000d). The asphalt cement content of HMA was provided by Una Connolly of National Asphalt Paving Association (Connolly 2000). The consumption data for cut-back and emulsified asphalts were taken from a Moulthrop, et al. study used as guidance for estimating air pollutant emissions

[7] The emission factors are expressed as a function of asphalt paving tonnage (i.e., including the rock aggregate as well as the asphalt cement).

from paving processes (EIIP 1998). "Asphalt Paving Operation" *AP-42* (EPA 1995) provided the emissions source information used in the calculation of the carbon storage factor for cut-back asphalt. The storage factor for emulsified asphalt was provided by Alan James of Akzo Nobel Coatings, Inc. (James 2000).

### Uncertainty

The principal source of uncertainty is that the available data are from short-term studies of emissions associated with the production and application of asphalt. As a practical matter, the cement in asphalt deteriorates over time, contributing to the need for periodic re-paving. Whether this deterioration is due to physical erosion of the cement and continued storage of carbon in a refractory form or physicochemical degradation and eventual release of $CO_2$ is uncertain. Long-term studies may reveal higher lifetime emissions rates associated with degradation.

Many of the values used in the analysis are also uncertain and are based on estimates and professional judgment. For example, the asphalt cement input for HMA was based on expert advice indicating that the range is variable—from about 3 to 5 percent—with actual content based on climate and geographical factors (Connolly 2000). Over this range, the effect on the calculated carbon storage factor is minimal (on the order of 0.1 percent). Similarly, changes in the assumed carbon content of asphalt cement would have only a minor effect.

The consumption figures for cut-back and emulsified asphalts are based on information reported for 1994. More recent trends indicate a decrease in cut-back use due to high VOC emission levels and a related increase in emulsified asphalt use as a substitute. However, because the carbon storage factor of each is 100 percent, use of more recent data would not affect the overall result.

## Lubricants

Lubricants are used in industrial and transportation applications. They can be subdivided into oils and greases, which differ in terms of physical characteristics (e.g., viscosity), commercial applications, and environmental fate. According to EIA (2000), the carbon content of U.S. production of lubricants in 1999 was approximately 28 Tg $CO_2$ Eq. Based on apportioning oils and greases to various environmental fates, and characterizing those fates as resulting in either long-term storage or emissions, the overall carbon storage factor was estimated to be 9 percent; thus, storage in 1999 was about 3 Tg $CO_2$ Eq.

### Methodology

For each lubricant category, a storage factor was derived by identifying disposal fates and applying assumptions as to the disposition of the carbon for each practice. An overall lubricant carbon storage factor was calculated by taking a production-weighted average of the oil and grease storage factors.

#### *Oils*

Regulation of used oil in the United States has changed dramatically over the past 15 years.[8] The effect of these regulations and policies has been to restrict land filling and dumping, and to encourage collection of used oil. Given the relatively inexpensive price of crude oil, the economics have not favored re-refining—instead, most of the used oil that has been collected has been combusted.

Table B-14 provides an estimated allocation of the fates of lubricant oils, along with an estimate of the proportion of carbon stored in each fate. The ultimate fate of the majority of oils (about 84 percent) is combustion, either during initial use or after collection as used oil. Combustion results in 99 percent oxidation to $CO_2$, with correspondingly little long-term storage of carbon in the form of ash. Dumping onto the ground or into storm sewers, primarily by "do-it-yourselfers" who change their own oil, is another fate that results in conversion to $CO_2$ given that the releases are generally small and most of the oil is biodegraded. In the landfill environment, which tends to be anaerobic, within municipal landfills, it is assumed that 90 percent of the oil persists in an undegraded form. Re-refining adds a recycling loop to the fate of oil; it was assumed that about 97 percent of the carbon in re-

[8] For example, the U.S. EPA "RCRA (Resource Conservation and Recovery Act) On-line" web site (http://www.epa.gov/rcraonline/) has over 50 entries on used oil regulation and policy for 1994 through 2000.

refined oil is ultimately oxidized. Because of the dominance of fates that result in eventual release as $CO_2$, only about 3 percent of the carbon in oil lubricants goes into long-term storage.

**Table B-14: Commercial and Environmental Fate of Oil Lubricants (Percent)**

| Fate of Oil | Portion of Total Oil | Carbon Stored |
|---|---|---|
| **Combusted During Use** | **20** | **1** |
| **Not Combusted During Use** | **80** | **-** |
| Combusted as Used Oil* | 64 | 1 |
| Dumped on the ground or in storm sewers | 6 | 0 |
| Landfilled | 2 | 90 |
| Re-refined into lube oil base stock and other products | 8 | 3 |
| **Weighted Average** | **-** | **2.9** |

* (e.g., in boilers or space heaters)
- Not applicable

### *Greases*

Table B-15 provides analogous estimates for lubricant greases. Unlike oils, grease is generally not combusted during use, and combustion for energy recovery and re-refining are thought to be negligible. Although little is known about the fate of waste grease, it was assumed that 90 percent of the non-combusted portion is landfilled, and the remainder is dumped onto the ground or storm sewers. Because much of the waste grease will be in containers that render it relatively inaccessible to biodegradation, it was assumed that 90 percent and 50 percent of the carbon in landfilled and dumped grease, respectively, would be stored. The overall storage factor is 82 percent for grease.

**Table B-15: Commercial and Environmental Fate of Grease Lubricants (Percent)**

| Fate of Grease | Total Grease | Carbon Stored |
|---|---|---|
| **Combusted During Use** | **5** | **1** |
| **Not Combusted During Use** | **95** | **-** |
| Landfilled | 85.5 | 90 |
| Dumped on the ground or in storm sewers | 9.5 | 50 |
| **Weighted Average** | **-** | **81.8** |

- Not applicable

Having derived separate storage factors for oil and grease, the last step was to estimate the weighted average for lubricants as a whole. No data were found apportioning the mass of lubricants into these two categories, but the U.S. Census Bureau does maintain records of the value of production of lubricating oils and lubricating greases. Assuming that the mass of lubricants can be allocated according to the proportion of value of production (92 percent oil, 8 percent grease), applying these weights to the storage factors for oils and greases (3 percent and 82 percent) yields an overall storage factor of 9 percent.

### Data Sources

The estimated volume of lubricants produced annually is based on statistics provided by EIA (2000), which conducts surveys of lubricating oil and grease consumption. Information on the value of lubricating oil and grease production was obtained from reports by the U.S. Census Bureau (1999).

The characterization of fate is based primarily on professional judgment of an EPA regulatory analyst with experience in used oil (Rinehart 2000). For the proportions combusted, one percent was assumed to remain un-oxidized in combustion processes (EIIP 1999); for other fates, estimates are based on professional judgment. The assumption that landfilled oil and grease results in 90 percent storage is based on analogy with the persistence of petroleum in native petroleum-bearing strata, which are both anaerobic. The assumption that oil dumped on the ground or in storm sewers is completely degraded is based on the observation that land farming—application to soil—is one of the most frequently used methods for degrading refinery wastes. The lower degradation rate for grease is based on the observation that greases contain longer chain paraffins, which are more persistent. Re-refined oil was assumed to have a storage factor equal to the weighted average for the other fates (i.e., after re-refining, the oil would have the same probability of combustion, landfilling, or dumping as virgin oil).

### Uncertainty

The principal sources of uncertainty for the disposition of lubricants are the estimates of the commercial use, post-use, and environmental fate of lubricants, which, as noted above, are largely based on assumptions and judgment. There is no comprehensive system to track used oil and greases, which makes it difficult to develop a verifiable estimate of the commercial fates of oil and grease. The environmental fate estimates for percent of carbon stored are less uncertain, but also introduce uncertainty in the estimate.

The assumption that the mass of oil and grease can be divided according to their value also introduces uncertainty. Given the large difference between the storage factors for oil and grease, changes in their share of total lubricant production has a large effect on the weighted storage factor.

# ANNEX C

## Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Ambient Air Pollutants from Stationary Combustion

### Estimates of $CH_4$ and $N_2O$ Emissions

Methane ($CH_4$) and nitrous oxide ($N_2O$) emissions from stationary combustion were estimated using IPCC emission factors and methods. Estimates were obtained by multiplying emission factors—by sector and fuel type—by fossil fuel and wood consumption data. This "top-down" methodology is characterized by two basic steps, described below. Data are presented in Table C-1 through Table C-5.

#### Step 1: Determine Energy Consumption by Sector and Fuel Type

Greenhouse gas emissions from stationary combustion activities were grouped into four sectors: industrial, commercial, residential, and electricity generation. For $CH_4$ and $N_2O$, estimates were based upon consumption of coal, gas, oil, and wood. Energy consumption data were obtained from EIA's *Annual Energy Review* (EIA 2001), and adjusted from higher to lower heating values by multiplying by 0.9 for natural gas and by 0.95 for coal and petroleum fuel. This is a simplified convention used by the International Energy Agency. Table C-1 provides annual energy consumption data for the years 1990 through 2000.

#### Step 2: Determine the Amount of $CH_4$ and $N_2O$ Emitted

Activity data for each sector and fuel type were then multiplied by emission factors to obtain emissions estimates. Emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Table C-2 provides emission factors used for each sector and fuel type.

### Estimates of $NO_x$, CO, and NMVOC Emissions

For ambient air pollutants, the major source categories included were those identified in EPA (2001): coal, fuel oil, natural gas, wood, other fuels (i.e., bagasse, liquefied petroleum gases, coke, coke oven gas, and others), and stationary internal combustion, which includes emissions from internal combustion engines not used in transportation. EPA (2001) periodically estimates emissions of $NO_x$, CO, and NMVOCs by sector and fuel type using a "bottom-up" estimating procedure. In other words, the emissions were calculated either for individual sources (e.g., industrial boilers) or for many sources combined, using basic activity data (e.g., fuel consumption or deliveries, etc.) as indicators of emissions. EPA (2001) projected emissions for years subsequent to their bottom-up estimates. The national activity data used to calculate the individual categories were obtained from various sources. Depending upon the category, these activity data may include fuel consumption or deliveries of fuel, tons of refuse burned, raw material processed, etc. Activity data were used in conjunction with emission factors that relate the quantity of emissions to the activity.

Table C-3 through Table C-5 present ambient air pollutant emission estimates for 1990 through 2000.

The basic calculation procedure for most source categories presented in EPA (2001) is represented by the following equation:

$$E_{p,s} = A_s \times EF_{p,s} \times (1 - C_{p,s}/100)$$

where,

E = emissions
p = pollutant
s = source category
A = activity level
EF = emission factor
C = percent control efficiency

The EPA currently derives the overall emission control efficiency of a category from a variety of sources, including published reports, the 1985 National Acid Precipitation and Assessment Program (NAPAP) emissions inventory, and other EPA databases. The U.S. approach for estimating emissions of $NO_x$, CO, and NMVOCs from stationary combustion as described above is similar to the methodology recommended by the IPCC (IPCC/UNEP/OECD/IEA 1997).

**Table C-1: Fuel Consumption by Stationary Combustion for Calculating $CH_4$ and $N_2O$ Emissions (TBtu)**

| Fuel/End-Use Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Coal** | **18,169** | **19,196** | **20,117** | **20,660** | **20,862** | **20,940** | **21,722** |
| Residential | 62 | 53 | 54 | 58 | 44 | 47 | 47 |
| Commercial | 93 | 80 | 82 | 87 | 66 | 70 | 70 |
| Industry | 1,478 | 1,427 | 1,370 | 1,381 | 1,317 | 1,271 | 1,119 |
| Electricity Generation | 16,536 | 17,635 | 18,610 | 19,135 | 19,434 | 19,553 | 20,487 |
| **Petroleum** | **11,655** | **11,277** | **11,941** | **12,186** | **12,199** | **12,376** | **12,067** |
| Residential | 1,266 | 1,361 | 1,457 | 1,432 | 1,324 | 1,456 | 1,492 |
| Commercial | 907 | 715 | 741 | 705 | 665 | 672 | 723 |
| Industry | 8,152 | 8,382 | 8,858 | 9,056 | 8,857 | 8,895 | 8,657 |
| Electricity Generation | 1,329 | 819 | 885 | 993 | 1,354 | 1,352 | 1,195 |
| **Natural Gas** | **18,230** | **21,087** | **21,475** | **21,522** | **20,871** | **21,146** | **22,233** |
| Residential | 4,519 | 4,984 | 5,390 | 5,125 | 4,669 | 4,858 | 5,081 |
| Commercial | 2,698 | 3,117 | 3,250 | 3,310 | 3,098 | 3,130 | 3,425 |
| Industry | 6,963 | 7,743 | 8,052 | 7,966 | 7,366 | 7,279 | 7,250 |
| Electricity Generation | 4,050 | 5,243 | 4,783 | 5,122 | 5,737 | 5,880 | 6,477 |
| **Wood** | **1,872** | **2,044** | **2,085** | **1,993** | **1,998** | **2,177** | **2,187** |
| Residential | 581 | 596 | 595 | 433 | 387 | 414 | 433 |
| Commercial | 37 | 45 | 49 | 47 | 47 | 51 | 52 |
| Industrial | 1,254 | 1,402 | 1,441 | 1,513 | 1,564 | 1,711 | 1,702 |
| Electricity Generation | NO | NO | NO | NO | NO | NO | NO |

Note: Totals may not sum due to independent rounding.
NO (Not occurring)

**Table C-2: $CH_4$ and $N_2O$ Emission Factors by Fuel Type and Sector (g/GJ)[1]**

| Fuel/End-Use Sector | $CH_4$ | $N_2O$ |
|---|---|---|
| **Coal** | | |
| Residential | 300 | 1.4 |
| Commercial | 10 | 1.4 |
| Industry | 10 | 1.4 |
| Electricity Generation | 1 | 1.4 |
| **Petroleum** | | |
| Residential | 10 | 0.6 |
| Commercial | 10 | 0.6 |
| Industry | 2 | 0.6 |
| Electricity Generation | 3 | 0.6 |
| **Natural Gas** | | |
| Residential | 5 | 0.1 |
| Commercial | 5 | 0.1 |
| Industry | 5 | 0.1 |
| Electricity Generation | 1 | 0.1 |
| **Wood** | | |
| Residential | 300 | 4.0 |
| Commercial | 300 | 4.0 |
| Industrial | 30 | 4.0 |
| Electricity Generation | 30 | 4.0 |

[1] GJ (Gigajoule) = $10^9$ joules. One joule = $9.486 \times 10^{-4}$ Btu

## Table C-3: $NO_x$ Emissions from Stationary Combustion (Gg)

| Sector/Fuel Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Electricity Generation** | **6,045** | **5,914** | **5,901** | **6,034** | **5,956** | **5,792** | **5,566** | **5,691** | **5,628** | **5,128** | **4,763** |
| Coal | 5,119 | 5,043 | 5,062 | 5,211 | 5,113 | 5,061 | 5,057 | 5,120 | 4,932 | 4,472 | 4,149 |
| Fuel Oil | 200 | 192 | 154 | 163 | 148 | 87 | 107 | 132 | 202 | 171 | 140 |
| Natural gas | 513 | 526 | 526 | 500 | 536 | 510 | 259 | 289 | 346 | 336 | 320 |
| Wood | NO | NO | NO | NO | NO | NO | NO | NO | NO | NO | NO |
| Internal Combustion | 213 | 152 | 159 | 160 | 159 | 134 | 143 | 150 | 149 | 151 | 154 |
| **Industrial** | **2,754** | **2,703** | **2,786** | **2,859** | **2,855** | **2,852** | **2,864** | **2,814** | **2,768** | **2,840** | **2,924** |
| Coal | 530 | 517 | 521 | 534 | 546 | 541 | 493 | 487 | 475 | 489 | 493 |
| Fuel Oil | 240 | 215 | 222 | 222 | 219 | 224 | 204 | 196 | 190 | 194 | 207 |
| Natural gas | 1,072 | 1,134 | 1,180 | 1,207 | 1,210 | 1,202 | 1,093 | 1,079 | 1,066 | 1,089 | 1,137 |
| Wood | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Other Fuels[a] | 119 | 117 | 115 | 113 | 113 | 111 | 109 | 104 | 104 | 107 | 112 |
| Internal Combustion | 792 | 720 | 748 | 783 | 767 | 774 | 965 | 948 | 933 | 961 | 976 |
| **Commercial** | **336** | **333** | **348** | **360** | **365** | **365** | **367** | **374** | **353** | **371** | **376** |
| Coal | 36 | 33 | 35 | 37 | 36 | 35 | 31 | 32 | 34 | 34 | 34 |
| Fuel Oil | 88 | 80 | 84 | 84 | 86 | 94 | 87 | 88 | 73 | 72 | 73 |
| Natural gas | 181 | 191 | 204 | 211 | 215 | 210 | 224 | 229 | 220 | 240 | 244 |
| Wood | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Other Fuels[a] | 31 | 29 | 25 | 28 | 28 | 27 | 24 | 25 | 26 | 25 | 26 |
| **Residential** | **749** | **829** | **879** | **827** | **817** | **813** | **726** | **699** | **651** | **683** | **677** |
| Coal[b] | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Fuel Oil[b] | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Natural Gas[b] | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Wood | 42 | 45 | 48 | 40 | 40 | 44 | 27 | 27 | 27 | 27 | 30 |
| Other Fuels[a] | 708 | 784 | 831 | 787 | 777 | 769 | 699 | 671 | 624 | 656 | 647 |
| **Total** | **9,884** | **9,779** | **9,914** | **10,080** | **9,993** | **9,822** | **9,522** | **9,577** | **9,400** | **9,022** | **8,740** |

IE (Included elsewhere)
NO (Not occurring)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2001).
[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2001).
Note: Totals may not sum due to independent rounding.

## Table C-4: CO Emissions from Stationary Combustion (Gg)

| Sector/Fuel Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Electricity Generation** | **329** | **317** | **318** | **329** | **335** | **338** | **363** | **376** | **379** | **367** | **380** |
| Coal | 213 | 212 | 214 | 224 | 224 | 227 | 228 | 233 | 220 | 208 | 212 |
| Fuel Oil | 18 | 17 | 14 | 15 | 13 | 9 | 11 | 13 | 17 | 17 | 16 |
| Natural gas | 46 | 46 | 47 | 45 | 48 | 49 | 72 | 76 | 88 | 87 | 95 |
| Wood | NO | NO | NO | NO | NO | NO | NO | NO | NO | NO | NO |
| Internal Combustion | 52 | 41 | 43 | 46 | 50 | 52 | 53 | 54 | 54 | 55 | 56 |
| **Industrial** | **798** | **835** | **867** | **946** | **944** | **958** | **1,080** | **1,055** | **1,044** | **1,067** | **1,108** |
| Coal | 95 | 92 | 92 | 92 | 91 | 88 | 100 | 99 | 96 | 99 | 100 |
| Fuel Oil | 67 | 54 | 58 | 60 | 60 | 64 | 49 | 47 | 46 | 47 | 50 |
| Natural gas | 205 | 257 | 272 | 292 | 306 | 313 | 308 | 308 | 305 | 308 | 327 |
| Wood | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Other Fuels[a] | 253 | 242 | 239 | 259 | 260 | 270 | 317 | 302 | 303 | 309 | 322 |
| Internal Combustion | 177 | 189 | 205 | 243 | 228 | 222 | 306 | 299 | 294 | 303 | 308 |
| **Commercial** | **205** | **196** | **204** | **207** | **212** | **211** | **130** | **133** | **130** | **135** | **137** |
| Coal | 13 | 13 | 13 | 14 | 13 | 14 | 13 | 13 | 14 | 14 | 14 |
| Fuel Oil | 16 | 16 | 16 | 16 | 16 | 17 | 17 | 18 | 15 | 15 | 15 |
| Natural gas | 40 | 40 | 46 | 48 | 49 | 49 | 58 | 59 | 57 | 62 | 63 |
| Wood | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Other Fuels[a] | 136 | 128 | 128 | 129 | 134 | 132 | 42 | 44 | 44 | 45 | 46 |
| **Residential** | **3,668** | **3,965** | **4,195** | **3,586** | **3,515** | **3,876** | **2,364** | **2,361** | **2,352** | **2,359** | **2,515** |
| Coal[b] | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Fuel Oil[b] | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Natural Gas[b] | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Wood | 3,430 | 3,711 | 3,930 | 3,337 | 3,272 | 3,628 | 2,133 | 2,133 | 2,133 | 2,133 | 2,292 |
| Other Fuels[a] | 238 | 255 | 265 | 249 | 243 | 248 | 231 | 229 | 220 | 226 | 223 |
| **Total** | **4,999** | **5,313** | **5,583** | **5,068** | **5,007** | **5,383** | **3,936** | **3,926** | **3,905** | **3,928** | **4,140** |

IE (Included elsewhere)
NO (Not occurring)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2001).
[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2001).
Note: Totals may not sum due to independent rounding.

## Table C-5: NMVOC Emissions from Stationary Combustion (Gg)

| Sector/Fuel Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Electricity Generation** | **43** | **40** | **40** | **41** | **41** | **40** | **44** | **47** | **50** | **50** | **51** |
| Coal | 25 | 25 | 25 | 26 | 26 | 26 | 25 | 26 | 26 | 26 | 27 |
| Fuel Oil | 5 | 5 | 4 | 4 | 4 | 2 | 3 | 4 | 5 | 5 | 4 |
| Natural gas | 2 | 2 | 2 | 2 | 2 | 2 | 7 | 7 | 9 | 9 | 10 |
| Wood | NO | NO | NO | NO | NO | NO | NO | NO | NO | NO | NO |
| Internal Combustion | 11 | 9 | 9 | 9 | 9 | 9 | 9 | 10 | 10 | 10 | 10 |
| **Industrial** | **165** | **177** | **169** | **169** | **178** | **187** | **162** | **160** | **159** | **162** | **169** |
| Coal | 7 | 5 | 7 | 5 | 7 | 5 | 6 | 6 | 6 | 6 | 6 |
| Fuel Oil | 11 | 10 | 11 | 11 | 11 | 11 | 8 | 7 | 7 | 7 | 8 |
| Natural gas | 52 | 54 | 47 | 46 | 57 | 66 | 54 | 54 | 54 | 54 | 57 |
| Wood | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Other Fuels[a] | 46 | 47 | 45 | 46 | 45 | 45 | 32 | 31 | 31 | 32 | 34 |
| Internal Combustion | 49 | 61 | 60 | 60 | 58 | 59 | 63 | 62 | 61 | 63 | 64 |
| **Commercial** | **18** | **18** | **20** | **22** | **21** | **21** | **24** | **24** | **24** | **26** | **26** |
| Coal | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Fuel Oil | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Natural gas | 7 | 8 | 9 | 10 | 10 | 10 | 13 | 13 | 12 | 14 | 14 |
| Wood | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Other Fuels[a] | 8 | 7 | 7 | 8 | 8 | 8 | 8 | 8 | 8 | 9 | 9 |
| **Residential** | **686** | **739** | **782** | **670** | **657** | **726** | **788** | **787** | **786** | **787** | **843** |
| Coal[b] | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Fuel Oil[b] | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Natural Gas[b] | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE | IE |
| Wood | 651 | 704 | 746 | 633 | 621 | 689 | 756 | 756 | 756 | 756 | 812 |
| Other Fuels[a] | 35 | 35 | 36 | 36 | 36 | 37 | 33 | 32 | 30 | 31 | 31 |
| **Total** | **912** | **975** | **1,011** | **901** | **898** | **973** | **1,020** | **1,019** | **1,018** | **1,025** | **1,089** |

IE (Included elsewhere)
NO (Not occurring)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2001).
[b] Coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2001).
Note: Totals may not sum due to independent rounding.

# ANNEX D

## Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Ambient Air Pollutants from Mobile Combustion

### Estimates of $CH_4$ and $N_2O$ Emissions

Greenhouse gas emissions from mobile combustion are reported by transport mode (e.g., road, rail, air, and water), vehicle type, and fuel type. The EPA does not systematically track emissions of $CH_4$ and $N_2O$ as is done in EPA (2001) for ambient air pollutants; therefore, estimates of these gases were developed using a methodology similar to that outlined in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Activity data were obtained from a number of U.S. government agency publications. Depending on the category, these basic activity data included such information as fuel consumption, fuel deliveries, and vehicle miles traveled (VMT).

#### *Highway Vehicles*

##### Step 1: Determine Vehicle Miles Traveled by Vehicle Type, Fuel Type, and Model Year

Vehicle miles traveled (VMT) by vehicle type were obtained from the Federal Highway Administration's (FHWA) *Highway Statistics* (FHWA 1996 through 2001). As these vehicle categories are not fuel-specific, VMT for each vehicle type was disaggregated by fuel type using fuel economy and consumption data, so that the appropriate emission factors could be applied. First, fuel economy and consumption data from FHWA's *Highway Statistics* were disaggregated by fuel type using a number of sources, including the Department of Energy's (DOE) *Transportation Energy Data Book* (DOE 1993 through 2001), FHWA's *Highway Statistics* (FHWA 1996 through 2001), EPA and DOE's *Fuel Economy 2001 Datafile* (EPA, DOE 2001), and the Vehicle Inventory and Use Survey (Census 1997). These data were used to distribute national VMT estimates across vehicle categories.[1]

National VMT data for gasoline and diesel highway vehicles are presented in Table D- 1 and Table D-2, respectively. Total VMT for each highway category (i.e., gasoline passenger cars, light-duty gasoline trucks, heavy-duty gasoline vehicles, diesel passenger cars, light-duty diesel trucks, heavy-duty diesel vehicles, and motorcycles) were distributed across 25 model years based on the VMT distribution by vehicle age shown in Table D-3. This distribution was derived by weighting the temporally fixed age distribution of the U.S. vehicle fleet according to vehicle registrations (Table D-3) by the average annual age-specific vehicle mileage accumulation of U.S. vehicles (Table D-4). Both were obtained from EPA's Mobile6 model (EPA 2000).

Activity data for gasoline passenger cars and light-duty trucks in California were developed separately due to the different emission control technologies deployed in that state relative to the rest of the country. Unlike the rest of the United States, beginning in model year 1994, a fraction of the computed California VMT for gasoline passenger cars and light-duty trucks was attributed to low emission vehicles (LEVs). LEVs have not yet been widely deployed in other states. The percent of national VMT represented by California for each year was obtained from the Federal Highway Administration (FHWA 1996 through 2001), and applied to national VMT estimates to estimate California VMT for gasoline passenger cars and light-duty trucks (presented in Table D- 1).

##### Step 2: Allocate VMT Data to Control Technology Type

VMT by vehicle type for each model year were distributed across various control technologies as shown in Table D-7 through Table D-11. Again, California gasoline-fueled passenger cars and light-duty trucks were treated separately due to that state's distinct vehicle emission standards—including the introduction of Low Emission Vehicles (LEVs) in 1994—compared with the rest of the United States. The categories "Tier 0" and "Tier 1" were

[1] This methodology is presented in more detail in ICF (2001).

substituted for the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the *Revised 1996 IPCC Guidelines*. Tier 0, Tier 1, and LEV are actually U.S. emission regulations, rather than control technologies; however, each does correspond to particular combinations of control technologies and engine design. Tier 1 and its predecessor Tier 0 both apply to vehicles equipped with three-way catalysts. The introduction of "early three-way catalysts," and "advance three-way catalysts" as described in the *Revised 1996 IPCC Guidelines*, roughly correspond to the introduction of Tier 0 and Tier 1 regulations (EPA 1998).

### Step 3: Determine the Amount of $CH_4$ and $N_2O$ Emitted by Vehicle, Fuel, and Control Technology Type

VMT for each highway category each year as described in Step 1 (see Table D-5) were first converted to vehicle kilometers traveled (VKT) so that IPCC emission factors could be applied. Emissions of $CH_4$ and $N_2O$ were then calculated by multiplying emission factors in IPCC/UNEP/OECD/IEA (1997) by the IPCC emission factors, which were derived from the EPA's MOBILE5a mobile source emissions model (EPA 1997). The MOBILE5a model uses information on ambient temperature, diurnal temperature range, altitude, vehicle speeds, national vehicle registration distributions, gasoline volatility, emission control technologies, fuel composition, and the presence or absence of vehicle inspection/maintenance programs in order to produce these factors.

Emissions of $N_2O$—in contrast to $CH_4$, CO, $NO_x$, and NMVOCs—have not been extensively studied and are currently not well characterized. The limited number of studies that have been performed on highway vehicle emissions of $N_2O$ have shown that emissions are generally greater from vehicles with catalytic converter systems than those without such controls, and greater from aged than from new catalysts. These systems control tailpipe emissions of $NO_x$ (i.e., NO and $NO_2$) by catalytically reducing $NO_x$ to $N_2$. Suboptimal catalyst performance, caused by as yet poorly understood factors, results in incomplete reduction and the conversion of some $NO_x$ to $N_2O$ rather than to $N_2$. Fortunately, newer vehicles with catalyst and engine designs meeting the more recent Tier 1 and LEV standards have shown reduced emission rates of both $NO_x$ and $N_2O$ compared with earlier catalyst designs.

In order to better characterize the process by which $N_2O$ is formed by catalytic controls and to develop a more accurate national emission estimate, the EPA's Office of Transportation and Air Quality—at its National Vehicle and Fuel Emissions Laboratory (NVFEL)—conducted a series of tests in order to measure emission rates of $N_2O$ from used Tier 1 and LEV gasoline-fueled passenger cars and light-duty trucks equipped with catalytic converters. These tests and a review of the literature were used to develop the emission factors for $N_2O$ (EPA 1998). The following references were used in developing the $N_2O$ emission factors for gasoline-fueled highway passenger cars presented in Table D-12:

- *LEVs*. Tests performed at NVFEL (EPA 1998)[2]
- *Tier 1*. Tests performed at NVFEL (EPA 1998)
- *Tier 0*. Smith and Carey (1982), Barton and Simpson (1994), and one car tested at NVFEL (EPA 1998)
- *Oxidation Catalyst*. Smith and Carey (1982), Urban and Garbe (1980)
- *Non-Catalyst*. Prigent and de Soete (1989), Dasch (1992), and Urban and Garbe (1979)

Nitrous oxide emission factors for other types of gasoline-fueled vehicles—light-duty trucks, heavy-duty vehicles, and motorcycles—were estimated by adjusting the factors for gasoline passenger cars, as described above, by their relative fuel economies. This adjustment was performed using miles per gallon data derived from (DOE 1993 through 2001), (FHWA 1996 through 2001), (EPA, DOE 2001), and (Census 1997) shown in Table D-13. Data from the literature and tests performed at NVFEL support the conclusion that light-duty trucks have higher emission rates than passenger cars. However, the use of fuel-consumption ratios to determine emission factors is considered a temporary measure only, to be replaced as soon as real data are available.

---

[2] LEVs are assumed to be operated using low-sulfur fuel (i.e., Indolene at 24 ppm sulfur). All other NVFEL tests were performed using a standard commercial fuel (CAAB at 285 ppm sulfur). Emission tests by NVFEL have consistently exhibited higher $N_2O$ emission rates from higher sulfur fuels on Tier 1 and LEV vehicles.

The resulting $N_2O$ emission factors employed for gasoline highway vehicles are lower than the U.S. default values presented in the *Revised 1996 IPCC Guidelines*, but are higher than the European default values, both of which were published before the more recent tests and literature review conducted by the NVFEL. The U.S. defaults in the *Guidelines* were based on three studies that tested a total of five cars using European rather than U.S. test procedures.

Nitrous oxide emission factors for diesel highway vehicles were taken from the European default values found in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Little data addressing $N_2O$ emissions from U.S. diesel-fueled vehicles exists, and in general, European countries have had more experience with diesel-fueled vehicles.

Compared to regulated tailpipe emissions, relatively little data are available to estimate emission factors for $N_2O$. Nitrous oxide is not a regulated ambient air pollutant, and measurements of it in automobile exhaust have not been routinely collected. Further testing is needed to reduce the uncertainty in nitrous oxide emission factors for all classes of vehicles, using realistic driving regimes, environmental conditions, and fuels.

#### *Non-Highway Vehicles*

Activity data for non-highway vehicles were based on annual fuel consumption statistics by transportation mode and fuel type. Consumption data for distillate and residual fuel oil by ships and boats (i.e., vessel bunkering), construction equipment, farm equipment, and locomotives were obtained from EIA (2000b). In the case of ships and boats, the EIA (2000b) vessel bunkering data were reduced by the amount of fuel used for international bunkers.[3] Data on the consumption of jet fuel in aircraft were obtained directly from DOT/BTS, as described under $CO_2$ from Fossil Fuel Combustion, and were reduced by the amount allocated to international bunker fuels. Data on aviation gasoline consumed in aircraft were taken from FAA (2000). Data on the consumption of motor gasoline by ships and boats, construction equipment, farm equipment, and locomotives data were drawn from FHWA (1996 through 2000). The activity data used for non-highway vehicles are included in Table D-6.

Emissions of $CH_4$ and $N_2O$ from non-highway vehicles were calculated by multiplying U.S. default emission factors in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) by activity data for each vehicle type (see Table D-13).

Table D-14 and Table D-15 provide complete emissions of $CH_4$ and $N_2O$ emissions, respectively, for 1990 through 2000.

### Estimates of $NO_x$, CO, and NMVOC Emissions

The emission estimates of $NO_x$, CO, and NMVOCs for mobile combustion were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900-2000* (EPA 2001). This EPA report provides emission estimates for these gases by sector and fuel type using a "top down" estimating procedure whereby emissions were calculated using basic activity data, such as amount of fuel delivered or miles traveled, as indicators of emissions.

Table D-16 through Table D-18 provide complete emissions estimates for 1990 through 2000.

[3] See International Bunker Fuels section of the Energy Chapter.

## Table D-1: Vehicle Miles Traveled for Gasoline Highway Vehicles ($10^9$ Miles)

| Year | Passenger Cars[a] | Light-Duty Trucks[a] | Heavy-Duty Vehicles | Motorcycles | Passenger Cars (CA)[b] | Light-Duty Trucks (CA)[b] |
|---|---|---|---|---|---|---|
| 1990 | 1,227.0 | 491.1 | 30.2 | 8.7 | 168.5 | 67.4 |
| 1991 | 1,186.3 | 556.7 | 32.1 | 8.8 | 159.9 | 75.0 |
| 1992 | 1,200.9 | 607.0 | 31.0 | 9.1 | 158.9 | 80.3 |
| 1993 | 1,205.1 | 640.6 | 30.3 | 9.3 | 158.2 | 84.1 |
| 1994 | 1,234.2 | 657.1 | 30.6 | 9.5 | 160.9 | 85.7 |
| 1995 | 1,264.3 | 679.9 | 30.5 | 9.8 | 162.8 | 87.5 |
| 1996 | 1,295.9 | 704.3 | 30.6 | 9.9 | 163.2 | 88.7 |
| 1997 | 1,325.5 | 733.7 | 30.6 | 10.1 | 166.3 | 92.1 |
| 1998 | 1,371.8 | 751.1 | 31.1 | 10.3 | 167.6 | 91.7 |
| 1999 | 1,385.4 | 776.9 | 31.2 | 10.6 | 173.9 | 97.5 |
| 2000 | 1,414.8 | 796.5 | 30.2 | 10.5 | 177.6 | 100.0 |

[a] Excludes California

[b] California VMT for passenger cars and light-duty trucks were disaggregated from national VMT using data from FHWA (1996 through 2001)

Source: Derived from FHWA (1996 through 2001).

## Table D-2: Vehicle Miles Traveled for Diesel Highway Vehicles ($10^9$ Miles)

| Year | Passenger Cars | Light-Duty Trucks | Heavy-Duty Vehicles |
|---|---|---|---|
| 1990 | 13.6 | 16.0 | 121.7 |
| 1991 | 12.4 | 17.6 | 123.2 |
| 1992 | 12.3 | 19.5 | 128.1 |
| 1993 | 12.1 | 21.1 | 135.8 |
| 1994 | 11.7 | 21.8 | 146.0 |
| 1995 | 11.2 | 22.6 | 154.0 |
| 1996 | 10.8 | 23.5 | 158.9 |
| 1997 | 10.7 | 25.0 | 167.7 |
| 1998 | 10.2 | 25.4 | 172.3 |
| 1999 | 9.9 | 26.6 | 179.1 |
| 2000 | 9.5 | 27.5 | 183.2 |

Source: Derived from FHWA (1996 through 2001).

## Table D-3: Age Distribution by Vehicle/Fuel Type for Highway Vehicles

| Vehicle Age | LDGV | LDGT | HDGV | LDDV | LDDT | HDDV | MC |
|---|---|---|---|---|---|---|---|
| 1 | 5.3% | 5.8% | 4.9% | 5.3% | 5.9% | 4.2% | 14.4% |
| 2 | 7.1% | 7.6% | 8.9% | 7.1% | 7.4% | 7.8% | 16.8% |
| 3 | 7.1% | 7.5% | 8.1% | 7.1% | 6.9% | 7.2% | 13.5% |
| 4 | 7.1% | 7.3% | 7.4% | 7.1% | 6.4% | 6.7% | 10.9% |
| 5 | 7.0% | 7.1% | 6.8% | 7.0% | 6.0% | 6.2% | 8.8% |
| 6 | 7.0% | 6.8% | 6.2% | 7.0% | 5.6% | 5.8% | 7.0% |
| 7 | 6.9% | 6.5% | 5.6% | 6.9% | 5.2% | 5.3% | 5.6% |
| 8 | 6.8% | 6.1% | 5.1% | 6.8% | 4.8% | 5.0% | 4.5% |
| 9 | 6.6% | 5.7% | 4.7% | 6.6% | 4.5% | 4.6% | 3.6% |
| 10 | 6.3% | 5.2% | 4.3% | 6.3% | 4.2% | 4.3% | 2.9% |
| 11 | 5.9% | 4.7% | 3.9% | 5.9% | 3.9% | 4.0% | 2.3% |
| 12 | 5.4% | 4.2% | 3.6% | 5.4% | 3.6% | 3.7% | 9.7% |
| 13 | 4.6% | 3.6% | 3.3% | 4.6% | 3.4% | 3.4% | 0.0% |
| 14 | 3.6% | 3.1% | 3.0% | 3.6% | 3.2% | 3.2% | 0.0% |
| 15 | 2.9% | 2.6% | 2.7% | 2.9% | 2.9% | 2.9% | 0.0% |
| 16 | 2.3% | 2.2% | 2.5% | 2.3% | 2.7% | 2.7% | 0.0% |
| 17 | 1.8% | 1.8% | 2.3% | 1.8% | 2.5% | 2.5% | 0.0% |
| 18 | 1.4% | 1.4% | 2.1% | 1.4% | 2.4% | 2.4% | 0.0% |
| 19 | 1.1% | 1.2% | 1.9% | 1.1% | 2.2% | 2.2% | 0.0% |
| 20 | 0.9% | 1.1% | 1.7% | 0.9% | 2.1% | 2.0% | 0.0% |
| 21 | 0.7% | 1.1% | 1.6% | 0.7% | 1.9% | 1.9% | 0.0% |
| 22 | 0.6% | 1.0% | 1.5% | 0.6% | 1.8% | 1.8% | 0.0% |
| 23 | 0.4% | 1.0% | 1.3% | 0.4% | 1.7% | 1.6% | 0.0% |
| 24 | 0.4% | 0.9% | 1.2% | 0.4% | 1.6% | 1.5% | 0.0% |
| 25 | 1.0% | 4.6% | 5.4% | 1.0% | 7.3% | 7.2% | 0.0% |
| **Total** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** |

LDGV (gasoline passenger cars, also referred to as light-duty gas vehicles)
LDGT (light-duty gas trucks)
HDGV (heavy-duty gas vehicles)
LDDV (diesel passenger cars, also referred to as light-duty diesel vehicles)
LDDT (light-duty diesel trucks)
HDDV (heavy-duty diesel vehicles)
MC (motorcycles)
Note: Based on vehicle registrations provided by EPA (2000).

**Table D-4: Annual Age-specific Vehicle Mileage Accumulation of U.S. Vehicles (Miles)**

| Vehicle Age | LDGV | LDGT | HDGV | LDDV | LDDT | HDDV | MC |
|---|---|---|---|---|---|---|---|
| 1 | 14,910 | 19,906 | 20,218 | 14,910 | 26,371 | 28,787 | 4,786 |
| 2 | 14,174 | 18,707 | 18,935 | 14,174 | 24,137 | 26,304 | 4,475 |
| 3 | 13,475 | 17,559 | 17,100 | 13,475 | 22,095 | 24,038 | 4,164 |
| 4 | 12,810 | 16,462 | 16,611 | 12,810 | 20,228 | 21,968 | 3,853 |
| 5 | 12,178 | 15,413 | 15,560 | 12,178 | 18,521 | 20,078 | 3,543 |
| 6 | 11,577 | 14,411 | 14,576 | 11,577 | 16,960 | 18,351 | 3,232 |
| 7 | 11,006 | 13,454 | 13,655 | 11,006 | 15,533 | 16,775 | 2,921 |
| 8 | 10,463 | 12,541 | 12,793 | 10,463 | 14,227 | 15,334 | 2,611 |
| 9 | 9,947 | 11,671 | 11,987 | 9,947 | 13,032 | 14,019 | 2,300 |
| 10 | 9,456 | 10,843 | 11,231 | 9,456 | 11,939 | 12,817 | 1,989 |
| 11 | 8,989 | 10,055 | 10,524 | 8,989 | 10,939 | 11,719 | 1,678 |
| 12 | 8,546 | 9,306 | 9,863 | 8,546 | 10,024 | 10,716 | 1,368 |
| 13 | 8,124 | 8,597 | 9,243 | 8,124 | 9,186 | 9,799 | 1,368 |
| 14 | 7,723 | 7,925 | 8,662 | 7,723 | 8,420 | 8,962 | 1,368 |
| 15 | 7,342 | 7,290 | 8,028 | 7,342 | 7,718 | 8,196 | 1,368 |
| 16 | 6,980 | 6,690 | 7,610 | 6,980 | 7,075 | 7,497 | 1,368 |
| 17 | 6,636 | 6,127 | 7,133 | 6,636 | 6,487 | 6,857 | 1,368 |
| 18 | 6,308 | 5,598 | 6,687 | 6,308 | 5,948 | 6,273 | 1,368 |
| 19 | 5,997 | 5,103 | 6,269 | 5,997 | 5,454 | 5,739 | 1,368 |
| 20 | 5,701 | 4,642 | 5,877 | 5,701 | 5,002 | 5,250 | 1,368 |
| 21 | 5,420 | 4,214 | 5,510 | 5,420 | 4,588 | 4,804 | 1,368 |
| 22 | 5,152 | 3,818 | 5,166 | 5,152 | 4,209 | 4,396 | 1,368 |
| 23 | 4,898 | 3,455 | 4,844 | 4,898 | 3,861 | 4,023 | 1,368 |
| 24 | 4,656 | 3,123 | 4,542 | 4,656 | 3,542 | 3,681 | 1,368 |
| 25 | 4,427 | 2,822 | 4,259 | 4,427 | 3,250 | 3,369 | 1,368 |

Source: EPA (2000).

**Table D-5: VMT Distribution by Vehicle Age and Vehicle/Fuel Type**

| Vehicle Age | LDGV | LDGT | HDGV | LDDV | LDDT | HDDV | MC |
|---|---|---|---|---|---|---|---|
| 1 | 7.51% | 9.41% | 7.89% | 7.51% | 11.50% | 8.27% | 19.39% |
| 2 | 9.52% | 11.56% | 13.48% | 9.52% | 13.07% | 14.00% | 21.15% |
| 3 | 9.05% | 10.62% | 11.11% | 9.05% | 11.15% | 11.86% | 15.82% |
| 4 | 8.59% | 9.70% | 9.85% | 8.59% | 9.51% | 10.05% | 11.82% |
| 5 | 8.14% | 8.80% | 8.43% | 8.14% | 8.11% | 8.52% | 8.77% |
| 6 | 7.68% | 7.92% | 7.21% | 7.68% | 6.92% | 7.22% | 6.37% |
| 7 | 7.22% | 7.04% | 6.16% | 7.22% | 5.90% | 6.13% | 4.60% |
| 8 | 6.72% | 6.19% | 5.27% | 6.72% | 5.04% | 5.20% | 3.31% |
| 9 | 6.20% | 5.36% | 4.51% | 6.20% | 4.30% | 4.41% | 2.33% |
| 10 | 5.64% | 4.57% | 3.86% | 5.64% | 3.67% | 3.74% | 1.62% |
| 11 | 5.03% | 3.82% | 3.31% | 5.03% | 3.13% | 3.18% | 1.09% |
| 12 | 4.38% | 3.14% | 2.83% | 4.38% | 2.67% | 2.70% | 3.73% |
| 13 | 3.54% | 2.52% | 2.42% | 3.54% | 2.28% | 2.29% | 0.00% |
| 14 | 2.67% | 1.99% | 2.07% | 2.67% | 1.95% | 1.94% | 0.00% |
| 15 | 2.01% | 1.54% | 1.76% | 2.01% | 1.66% | 1.65% | 0.00% |
| 16 | 1.52% | 1.16% | 1.52% | 1.52% | 1.42% | 1.40% | 0.00% |
| 17 | 1.14% | 0.87% | 1.30% | 1.14% | 1.21% | 1.19% | 0.00% |
| 18 | 0.86% | 0.64% | 1.12% | 0.86% | 1.04% | 1.01% | 0.00% |
| 19 | 0.65% | 0.50% | 0.96% | 0.65% | 0.89% | 0.86% | 0.00% |
| 20 | 0.49% | 0.43% | 0.82% | 0.49% | 0.76% | 0.73% | 0.00% |
| 21 | 0.37% | 0.37% | 0.70% | 0.37% | 0.65% | 0.62% | 0.00% |
| 22 | 0.28% | 0.32% | 0.60% | 0.28% | 0.55% | 0.53% | 0.00% |
| 23 | 0.21% | 0.27% | 0.52% | 0.21% | 0.47% | 0.45% | 0.00% |
| 24 | 0.16% | 0.23% | 0.44% | 0.16% | 0.40% | 0.38% | 0.00% |
| 25 | 0.43% | 1.04% | 1.85% | 0.43% | 1.75% | 1.65% | 0.00% |
| **Total** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** |

Note: Estimated by weighting data in Table D-3 by data in Table D-4.

## Table D-6: Fuel Consumption for Non-Highway Vehicles by Fuel Type (gallons)

| Vehicle Type/Year | Residual | Diesel | Jet Fuel | Gasoline[a] |
|---|---|---|---|---|
| **Aircraft** | | | | |
| 1990 | 0 | 0 | 18,280,476,364 | 374,216,115 |
| 1991 | 0 | 0 | 17,511,325,335 | 347,126,395 |
| 1992 | 0 | 0 | 17,281,746,858 | 341,582,453 |
| 1993 | 0 | 0 | 17,421,015,955 | 319,448,684 |
| 1994 | 0 | 0 | 18,270,975,739 | 317,306,704 |
| 1995 | 0 | 0 | 17,806,704,239 | 329,318,581 |
| 1996 | 0 | 0 | 18,746,820,369 | 310,796,773 |
| 1997 | 0 | 0 | 18,601,073,081 | 330,284,570 |
| 1998 | 0 | 0 | 19,057,517,441 | 295,344,794 |
| 1999 | 0 | 0 | 19,423,591,168 | 325,912,623 |
| 2000 | 0 | 0 | 20,474,811,494 | 301,892,666 |
| **Ships and Boats** | | | | |
| 1990 | 1,521,437,386 | 1,697,600,270 | 0 | 1,300,400,000 |
| 1991 | 1,486,167,178 | 1,693,361,391 | 0 | 1,709,700,000 |
| 1992 | 2,347,064,583 | 1,706,143,771 | 0 | 1,316,170,000 |
| 1993 | 2,758,924,466 | 1,546,310,902 | 0 | 873,687,000 |
| 1994 | 2,499,868,472 | 1,630,092,618 | 0 | 896,700,000 |
| 1995 | 2,994,692,916 | 1,518,608,116 | 0 | 1,060,394,000 |
| 1996 | 2,286,349,693 | 1,839,335,006 | 0 | 993,671,000 |
| 1997 | 1,011,486,526 | 1,801,798,270 | 0 | 987,193,000 |
| 1998 | 727,907,222 | 1,597,011,188 | 0 | 956,232,000 |
| 1999 | 2,388,334,968 | 1,855,327,478 | 0 | 956,232,001 |
| 2000 | 4,580,188,492 | 1,889,097,816 | 0 | 1,124,269,000 |
| **Construction Equip.** | | | | |
| 1990 | 0 | 1,581,500,000 | 0 | 318,200,000 |
| 1991 | 0 | 1,492,000,000 | 0 | 287,200,000 |
| 1992 | 0 | 1,514,205,000 | 0 | 272,900,000 |
| 1993 | 0 | 1,526,043,000 | 0 | 245,299,000 |
| 1994 | 0 | 1,531,300,000 | 0 | 272,852,000 |
| 1995 | 0 | 1,472,827,000 | 0 | 280,046,000 |
| 1996 | 0 | 1,645,647,000 | 0 | 283,911,000 |
| 1997 | 0 | 1,678,482,000 | 0 | 300,491,000 |
| 1998 | 0 | 1,749,317,000 | 0 | 234,705,000 |
| 1999 | 0 | 1,723,597,000 | 0 | 177,758,000 |
| 2000 | 0 | 1,899,837,000 | 0 | 191,516,000 |
| **Farm Equipment** | | | | |
| 1990 | 0 | 3,164,200,000 | 0 | 812,800,000 |
| 1991 | 0 | 3,144,200,000 | 0 | 776,200,000 |
| 1992 | 0 | 3,274,811,000 | 0 | 805,500,000 |
| 1993 | 0 | 3,077,122,000 | 0 | 845,320,000 |
| 1994 | 0 | 3,062,436,000 | 0 | 911,996,000 |
| 1995 | 0 | 3,093,224,000 | 0 | 926,732,000 |
| 1996 | 0 | 3,225,029,000 | 0 | 918,085,000 |
| 1997 | 0 | 3,206,359,000 | 0 | 984,450,000 |
| 1998 | 0 | 2,965,006,000 | 0 | 906,941,000 |
| 1999 | 0 | 2,805,157,000 | 0 | 702,700,000 |
| 2000 | 0 | 3,079,664,000 | 0 | 652,256,000 |
| **Locomotives** | | | | |
| 1990 | 25,422 | 3,210,111,000 | 0 | 0 |
| 1991 | 6,845 | 3,026,292,000 | 0 | 0 |
| 1992 | 8,343 | 3,217,231,000 | 0 | 0 |
| 1993 | 4,065 | 2,906,998,000 | 0 | 0 |
| 1994 | 5,956 | 3,063,441,000 | 0 | 0 |
| 1995 | 6,498 | 3,191,023,000 | 0 | 0 |
| 1996 | 9,309 | 3,266,861,000 | 0 | 0 |
| 1997 | 3,431 | 3,067,400,000 | 0 | 0 |
| 1998 | 2,587 | 2,833,276,000 | 0 | 0 |
| 1999 | 3,540 | 2,789,926,000 | 0 | 0 |

| | | | | |
|---|---|---|---|---|
| 2000 | 7,158 | 3,070,766,000 | 0 | 0 |
| Other[b] | | | | |
| 1990 | 0 | 926,800,000 | 0 | 1,205,400,000 |
| 1991 | 0 | 955,400,000 | 0 | 1,097,700,000 |
| 1992 | 0 | 773,437,000 | 0 | 1,219,300,000 |
| 1993 | 0 | 797,140,000 | 0 | 1,025,087,667 |
| 1994 | 0 | 905,842,000 | 0 | 1,039,309,667 |
| 1995 | 0 | 800,335,000 | 0 | 1,071,596,667 |
| 1996 | 0 | 741,326,000 | 0 | 1,081,639,667 |
| 1997 | 0 | 706,754,000 | 0 | 1,097,257,667 |
| 1998 | 0 | 682,865,000 | 0 | 1,139,228,667 |
| 1999 | 0 | 685,634,000 | 0 | 1,021,835,667 |
| 2000 | 0 | 610,078,000 | 0 | 1,040,137,667 |

- Not applicable
[a] For aircraft, this is aviation gasoline. For all other categories, this is motor gasoline.
[b] Other includes snowmobiles and industrial fuel consumption.

**Table D-7: Control Technology Assignments for Gasoline Passenger Cars (Percent of VMT)***

| Model Years | Non-catalyst | Oxidation | Tier 0 | Tier 1 |
|---|---|---|---|---|
| 1973-1974 | 100% | - | - | - |
| 1975 | 20% | 80% | - | - |
| 1976-1977 | 15% | 85% | - | - |
| 1978-1979 | 10% | 90% | - | - |
| 1980 | 5% | 88% | 7% | - |
| 1981 | - | 15% | 85% | - |
| 1982 | - | 14% | 86% | - |
| 1983 | - | 12% | 88% | - |
| 1984-1993 | - | - | 100% | - |
| 1994 | - | - | 60% | 40% |
| 1995 | - | - | 20% | 80% |
| 1996-2000 | - | - | - | 100% |

* Excluding California VMT
- Not applicable

**Table D-8: Control Technology Assignments for Gasoline Light-Duty Trucks (Percent of VMT)***

| Model Years | Non-catalyst | Oxidation | Tier 0 | Tier 1 |
|---|---|---|---|---|
| 1973-1974 | 100% | - | - | - |
| 1975 | 30% | 70% | - | - |
| 1976 | 20% | 80% | - | - |
| 1977-1978 | 25% | 75% | - | - |
| 1979-1980 | 20% | 80% | - | - |
| 1981 | - | 95% | 5% | - |
| 1982 | - | 90% | 10% | - |
| 1983 | - | 80% | 20% | - |
| 1984 | - | 70% | 30% | - |
| 1985 | - | 60% | 40% | - |
| 1986 | - | 50% | 50% | - |
| 1987-1993 | - | 5% | 95% | - |
| 1994 | - | - | 60% | 40% |
| 1995 | - | - | 20% | 80% |
| 1996-2000 | - | - | - | 100% |

* Excluding California VMT
- Not applicable.

## Table D-9: Control Technology Assignments for California Gasoline Passenger Cars and Light-Duty Trucks (Percent of VMT)

| Model Years | Non-catalyst | Oxidation | Tier 0 | Tier 1 | LEV |
|---|---|---|---|---|---|
| 1973-1974 | 100% | - | - | - | - |
| 1975-1979 | - | 100% | - | - | - |
| 1980-1981 | - | 15% | 85% | - | - |
| 1982 | - | 14% | 86% | - | - |
| 1983 | - | 12% | 88% | - | - |
| 1984-1991 | - | - | 100% | - | - |
| 1992 | - | - | 60% | 40% | - |
| 1993 | - | - | 20% | 80% | - |
| 1994 | - | - | - | 90% | 10% |
| 1995 | - | - | - | 85% | 15% |
| 1996-2000 | - | - | - | 80% | 20% |

* Excluding California VMT
- Not applicable

## Table D-10: Control Technology Assignments for Gasoline Heavy-Duty Vehicles (Percent of VMT)

| Model Years | Uncontrolled | Non-catalyst | Oxidation | Tier 0 |
|---|---|---|---|---|
| ≤1981 | 100% | - | - | - |
| 1982-1984 | 95% | - | 5% | - |
| 1985-1986 | - | 95% | 5% | - |
| 1987 | - | 70% | 15% | 15% |
| 1988-1989 | - | 60% | 25% | 15% |
| 1990-2000 | - | 45% | 30% | 25% |

* Excluding California VMT
- Not applicable

## Table D-11: Control Technology Assignments for Diesel Highway and Motorcycle VMT

| Vehicle Type/Control Technology | Model Years |
|---|---|
| **Diesel Passenger Cars and Light-Duty Trucks** | |
| Uncontrolled | 1966-1982 |
| Moderate control | 1983-1995 |
| Advanced control | 1996-2000 |
| **Heavy-Duty Diesel Vehicles** | |
| Uncontrolled | 1966-1972 |
| Moderate control | 1983-1995 |
| Advanced control | 1996-2000 |
| **Motorcycles** | |
| Uncontrolled | 1966-1995 |
| Non-catalyst controls | 1996-2000 |

**Table D-12: Emission Factors (g/km) for $CH_4$ and $N_2O$ and Fuel Economy (miles per gallon) for Highway Mobile Combustion**

| Vehicle Type/Control Technology | $N_2O$ | $CH_4$ | MPG |
|---|---|---|---|
| **Gasoline Passenger Cars** | | | **21.99** |
| Low Emission Vehicles[a] | 0.0176 | 0.025 | |
| Tier 1[b] | 0.0288 | 0.030 | |
| Tier 0[b] | 0.0507 | 0.040 | |
| Oxidation Catalyst | 0.0322 | 0.070 | |
| Non-Catalyst | 0.0103 | 0.120 | |
| Uncontrolled | 0.0103 | 0.135 | |
| **Gasoline Light-Duty Trucks** | | | **17.56** |
| Low Emission Vehicles[a] | 0.0220 | 0.030 | |
| Tier 1[b] | 0.0361 | 0.035 | |
| Tier 0[b] | 0.0635 | 0.070 | |
| Oxidation Catalyst | 0.0403 | 0.090 | |
| Non-Catalyst | 0.0129 | 0.140 | |
| Uncontrolled | 0.0129 | 0.135 | |
| **Gasoline Heavy-Duty Vehicles** | | | **7.60** |
| Tier 0[b] | 0.1085 | 0.075 | |
| Oxidation Catalyst[c] | 0.0689 | 0.090 | |
| Non-Catalyst Control | 0.0220 | 0.125 | |
| Uncontrolled | 0.0220 | 0.270 | |
| **Diesel Passenger Cars** | | | **19.38** |
| Advanced | 0.0100 | 0.01 | |
| Moderate | 0.0100 | 0.01 | |
| Uncontrolled | 0.0100 | 0.01 | |
| **Diesel Light Trucks** | | | **15.48** |
| Advanced | 0.0200 | 0.01 | |
| Moderate | 0.0200 | 0.01 | |
| Uncontrolled | 0.0200 | 0.01 | |
| **Diesel Heavy-Duty Vehicles** | | | **5.66** |
| Advanced | 0.0300 | 0.04 | |
| Moderate | 0.0300 | 0.05 | |
| Uncontrolled | 0.0300 | 0.06 | |
| **Motorcycles** | | | **50.00** |
| Non-Catalyst Control | 0.0044 | 0.13 | |
| Uncontrolled | 0.0044 | 0.26 | |

[a] Applied to California VMT only.
[b] The categories "Tier 0" and "Tier 1" were substituted for the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the Revised 1996 IPCC Guidelines.
[c] Methane emission factor assumed based on light-duty trucks oxidation catalyst value.

## Table D-13: Emission Factors for $CH_4$ and $N_2O$ Emissions from Non-Highway Mobile Combustion (g gas/kg fuel)

| Vehicle Type/Fuel Type | $N_2O$ | $CH_4$ |
|---|---|---|
| **Ships and Boats** | | |
| Residual | 0.08 | 0.23 |
| Distillate | 0.08 | 0.23 |
| Gasoline | 0.08 | 0.23 |
| **Locomotives** | | |
| Residual | 0.08 | 0.25 |
| Diesel | 0.08 | 0.25 |
| Coal | 0.08 | 0.25 |
| **Farm Equipment** | | |
| Gas/Tractor | 0.08 | 0.45 |
| Other Gas | 0.08 | 0.45 |
| Diesel/Tractor | 0.08 | 0.45 |
| Other Diesel | 0.08 | 0.45 |
| **Construction** | | |
| Gas Construction | 0.08 | 0.18 |
| Diesel Construction | 0.08 | 0.18 |
| **Other Non-Highway** | | |
| Gas Snowmobile | 0.08 | 0.18 |
| Gas Small Utility | 0.08 | 0.18 |
| Gas HD Utility | 0.08 | 0.18 |
| Diesel HD Utility | 0.08 | 0.18 |
| **Aircraft** | | |
| Jet Fuel | 0.1 | 0.087 |
| Aviation Gasoline | 0.04 | 2.64 |

## Table D-14: $CH_4$ Emissions from Mobile Combustion (Tg $CO_2$ Eq.)

| Fuel Type/Vehicle Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gasoline Highway** | **4.2** | **4.2** | **4.2** | **4.2** | **4.1** | **4.1** | **3.9** | **3.8** | **3.8** | **3.7** | **3.6** |
| Passenger Cars | 2.4 | 2.2 | 2.1 | 2.1 | 2.0 | 2.0 | 2.0 | 1.9 | 1.9 | 1.9 | 1.9 |
| Light-Duty Trucks | 1.6 | 1.7 | 1.8 | 1.9 | 1.9 | 1.8 | 1.7 | 1.7 | 1.6 | 1.6 | 1.5 |
| Heavy-Duty Vehicles | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Motorcycles | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Diesel Highway** | **0.2** | **0.2** | **0.2** | **0.2** | **0.3** | **0.3** | **0.3** | **0.3** | **0.3** | **0.3** | **0.3** |
| Passenger Cars | + | + | + | + | + | + | + | + | + | + | + |
| Light-Duty Trucks | + | + | + | + | + | + | + | + | + | + | + |
| Heavy-Duty Vehicles | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| **Non-Highway** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.5** |
| Ships and Boats | 0.1 | 0.1 | 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 |
| Farm Equipment | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Construction Equipment | + | + | + | + | + | + | + | + | + | + | + |
| Aircraft | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 0.2 | 0.2 |
| Other* | + | + | + | + | + | + | + | + | + | + | + |
| **Total** | **4.9** | **4.9** | **4.9** | **4.9** | **4.8** | **4.8** | **4.7** | **4.6** | **4.5** | **4.4** | **4.4** |

+ Does not exceed 0.05 Tg $CO_2$ Eq.

Note: Totals may not sum due to independent rounding.

* "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

## Table D-15: $N_2O$ Emissions from Mobile Combustion (Tg $CO_2$ Eq.)

| Fuel Type/Vehicle Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gasoline Highway** | **45.8** | **48.1** | **51.1** | **53.1** | **54.3** | **54.6** | **54.2** | **53.7** | **53.1** | **52.4** | **51.6** |
| Passenger Cars | 31.0 | 30.8 | 31.8 | 32.4 | 33.0 | 33.1 | 32.7 | 32.2 | 32.0 | 31.2 | 30.6 |
| Light-Duty Trucks | 14.2 | 16.7 | 18.6 | 20.1 | 20.6 | 20.8 | 20.7 | 20.7 | 20.3 | 20.4 | 20.1 |
| Heavy-Duty Vehicles | 0.5 | 0.6 | 0.6 | 0.6 | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 |
| Motorcycles | + | + | + | + | + | + | + | + | + | + | + |
| **Diesel Highway** | **2.1** | **2.1** | **2.2** | **2.3** | **2.5** | **2.6** | **2.7** | **2.8** | **2.9** | **3.0** | **3.1** |
| Passenger Cars | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | + | + |
| Light-Duty Trucks | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 |
| Heavy-Duty Vehicles | 1.8 | 1.8 | 1.9 | 2.0 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.7 |
| **Non-Highway** | **2.9** | **2.8** | **2.9** | **2.9** | **2.9** | **3.0** | **3.0** | **2.9** | **2.8** | **3.0** | **3.4** |
| Ships and Boats | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.4 | 0.3 | 0.3 | 0.4 | 0.6 |
| Locomotives | 0.3 | 0.2 | 0.3 | 0.2 | 0.2 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| Farm Equipment | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Construction Equipment | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.1 | 0.2 |
| Aircraft | 1.7 | 1.6 | 1.6 | 1.6 | 1.7 | 1.7 | 1.8 | 1.7 | 1.8 | 1.8 | 1.9 |
| Other* | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Total** | **50.7** | **53.0** | **56.2** | **58.3** | **59.8** | **60.1** | **59.8** | **59.4** | **58.8** | **58.4** | **58.0** |

+ Does not exceed 0.05 Tg $CO_2$ Eq.
Note: Totals may not sum due to independent rounding.
* "Other" includes snowmobiles, small gasoline powered utility equipment, heavy-duty gasoline powered utility equipment, and heavy-duty diesel powered utility equipment.

## Table D-16: $NO_x$ Emissions from Mobile Combustion, 1990-2000 (Gg)

| Fuel Type/Vehicle Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gasoline Highway** | **4,418** | **4,744** | **4,909** | **5,047** | **5,156** | **4,867** | **4,747** | **4,756** | **4,629** | **4,496** | **4,388** |
| Passenger Cars | 2,723 | 2,774 | 2,800 | 2,817 | 2,867 | 2,750 | 2,716 | 2,706 | 2,649 | 2,552 | 2,519 |
| Light-Duty Trucks | 1,408 | 1,669 | 1,818 | 1,933 | 1,959 | 1,807 | 1,550 | 1,580 | 1,545 | 1,520 | 1,459 |
| Heavy-Duty Vehicles | 277 | 291 | 281 | 286 | 318 | 300 | 470 | 458 | 424 | 413 | 398 |
| Motorcycles | 10 | 10 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 12 |
| **Diesel Highway** | **2,123** | **2,112** | **2,129** | **2,174** | **2,261** | **2,351** | **3,230** | **3,338** | **3,368** | **3,317** | **3,004** |
| Passenger Cars | 26 | 30 | 30 | 30 | 31 | 31 | 13 | 10 | 8 | 6 | 6 |
| Light-Duty Trucks | 57 | 10 | 10 | 11 | 11 | 11 | 7 | 6 | 5 | 5 | 4 |
| Heavy-Duty Vehicles | 2,040 | 2,072 | 2,089 | 2,133 | 2,219 | 2,308 | 3,210 | 3,322 | 3,355 | 3,306 | 2,994 |
| **Non-Highway** | **4,358** | **4,729** | **5,045** | **5,343** | **5,705** | **6,112** | **6,361** | **6,677** | **6,979** | **7,274** | **7,549** |
| Ships and Boats | 908 | 955 | 926 | 886 | 898 | 905 | 1,041 | 1,043 | 1,044 | 1,033 | 1,041 |
| Locomotives | 843 | 842 | 858 | 857 | 859 | 898 | 704 | 704 | 704 | 704 | 704 |
| Farm Equipment | 819 | 837 | 854 | 870 | 886 | 901 | 852 | 851 | 844 | 829 | 815 |
| Construction Equipment | 1,003 | 1,020 | 1,036 | 1,052 | 1,069 | 1,090 | 1,153 | 1,159 | 1,155 | 1,137 | 1,114 |
| Aircraft[a] | 143 | 141 | 142 | 142 | 146 | 150 | 73 | 73 | 73 | 73 | 76 |
| Other[b] | 642 | 934 | 1,230 | 1,536 | 1,848 | 2,168 | 2,537 | 2,846 | 3,159 | 3,498 | 3,799 |
| **Total** | **10,900** | **11,585** | **12,084** | **12,565** | **13,123** | **13,329** | **14,338** | **14,771** | **14,976** | **15,087** | **14,941** |

[a] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.
[b] "Other" includes gasoline powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel powered recreational, industrial, lawn and garden, light construction, airport service.
Note: Totals may not sum due to independent rounding.

### Table D-17: CO Emissions from Mobile Combustion, 1990-2000 (Gg)

| Fuel Type/Vehicle Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gasoline Highway** | **51,840** | **55,949** | **54,326** | **54,852** | **55,750** | **48,375** | **47,443** | **46,392** | **45,496** | **43,075** | **41,944** |
| Passenger Cars | 31,576 | 32,208 | 30,466 | 29,933 | 30,048 | 26,854 | 26,285 | 25,809 | 25,606 | 24,043 | 24,058 |
| Light-Duty Trucks | 15,530 | 18,709 | 19,538 | 20,679 | 20,515 | 17,630 | 15,307 | 15,376 | 15,375 | 14,998 | 14,367 |
| Heavy-Duty Vehicles | 4,562 | 4,871 | 4,160 | 4,067 | 5,011 | 3,722 | 5,679 | 5,034 | 4,338 | 3,868 | 3,338 |
| Motorcycles | 172 | 161 | 162 | 172 | 176 | 169 | 171 | 173 | 177 | 166 | 181 |
| **Diesel Highway** | **1,180** | **1,204** | **1,227** | **1,243** | **1,315** | **1,349** | **1,899** | **1,976** | **2,005** | **2,050** | **2,026** |
| Passenger Cars | 20 | 24 | 24 | 25 | 26 | 27 | 11 | 9 | 7 | 6 | 5 |
| Light-Duty Trucks | 42 | 8 | 8 | 9 | 9 | 9 | 6 | 5 | 5 | 4 | 4 |
| Heavy-Duty Vehicles | 1,119 | 1,172 | 1,195 | 1,209 | 1,280 | 1,313 | 1,882 | 1,961 | 1,993 | 2,040 | 2,017 |
| **Non-Highway** | **16,503** | **16,860** | **17,236** | **17,592** | **17,959** | **18,348** | **25,586** | **25,396** | **25,296** | **25,440** | **25,326** |
| Ships and Boats | 2,041 | 2,053 | 2,054 | 2,053 | 2,060 | 2,065 | 2,137 | 2,154 | 2,169 | 2,076 | 2,070 |
| Locomotives | 110 | 109 | 113 | 108 | 104 | 103 | 70 | 70 | 70 | 70 | 70 |
| Farm Equipment | 527 | 537 | 547 | 557 | 566 | 575 | 458 | 459 | 460 | 468 | 465 |
| Construction Equipment | 1,148 | 1,171 | 1,194 | 1,216 | 1,238 | 1,258 | 1,452 | 1,413 | 1,379 | 1,336 | 1,290 |
| Aircraft[a] | 820 | 806 | 818 | 821 | 830 | 855 | 327 | 327 | 327 | 327 | 331 |
| Other[b] | 11,857 | 12,184 | 12,511 | 12,837 | 13,162 | 13,492 | 21,141 | 20,974 | 20,892 | 21,163 | 21,100 |
| **Total** | **69,523** | **74,012** | **72,789** | **73,687** | **75,024** | **68,072** | **74,927** | **73,764** | **72,797** | **70,565** | **69,296** |

[a] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.
[b] "Other" includes gasoline powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel powered recreational, industrial, lawn and garden, light construction, airport service.
Note: Totals may not sum due to independent rounding.

### Table D-18: NMVOCs Emissions from Mobile Combustion, 1990-2000 (Gg)

| Fuel Type/Vehicle Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gasoline Highway** | **5,545** | **5,753** | **5,416** | **5,470** | **5,654** | **4,980** | **4,704** | **4,632** | **4,647** | **4,573** | **4,333** |
| Passenger Cars | 3,298 | 3,240 | 2,953 | 2,901 | 2,989 | 2,714 | 2,608 | 2,578 | 2,626 | 2,599 | 2,500 |
| Light-Duty Trucks | 1,829 | 2,103 | 2,129 | 2,241 | 2,257 | 1,937 | 1,621 | 1,623 | 1,622 | 1,596 | 1,501 |
| Heavy-Duty Vehicles | 368 | 378 | 304 | 296 | 375 | 295 | 442 | 398 | 363 | 340 | 293 |
| Motorcycles | 51 | 33 | 30 | 31 | 33 | 34 | 33 | 33 | 35 | 38 | 38 |
| **Diesel Highway** | **300** | **288** | **289** | **289** | **300** | **296** | **323** | **301** | **287** | **264** | **236** |
| Passenger Cars | 8 | 10 | 10 | 10 | 11 | 11 | 4 | 4 | 3 | 3 | 2 |
| Light-Duty Trucks | 21 | 4 | 4 | 5 | 5 | 5 | 3 | 3 | 2 | 2 | 2 |
| Heavy-Duty Vehicles | 270 | 275 | 274 | 274 | 284 | 280 | 316 | 295 | 282 | 259 | 232 |
| **Non-Highway** | **2,309** | **2,341** | **2,353** | **2,381** | **2,424** | **2,449** | **3,458** | **3,324** | **3,224** | **3,125** | **3,069** |
| Ships and Boats | 743 | 748 | 729 | 731 | 747 | 738 | 871 | 877 | 884 | 844 | 833 |
| Locomotives | 48 | 47 | 49 | 47 | 45 | 45 | 27 | 27 | 27 | 27 | 27 |
| Farm Equipment | 133 | 133 | 132 | 132 | 131 | 130 | 112 | 110 | 106 | 100 | 93 |
| Construction Equipment | 204 | 208 | 212 | 216 | 220 | 225 | 249 | 240 | 229 | 214 | 199 |
| Aircraft[a] | 163 | 161 | 162 | 160 | 159 | 161 | 29 | 29 | 29 | 29 | 26 |
| Other[b] | 1,018 | 1,045 | 1,068 | 1,095 | 1,122 | 1,150 | 2,169 | 2,041 | 1,950 | 1,911 | 1,891 |
| **Total** | **8,154** | **8,383** | **8,058** | **8,140** | **8,378** | **7,725** | **8,485** | **8,257** | **8,158** | **7,962** | **7,638** |

[a] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.
[b] "Other" includes gasoline powered recreational, industrial, lawn and garden, light commercial, logging, airport service, other equipment; and diesel powered recreational, industrial, lawn and garden, light construction, airport service.
Note: Totals may not sum due to independent rounding.

## Definitions of Emission Control Technologies and Standards

The $N_2O$ and $CH_4$ emission factors used depend on the level of control technology or the emission standard in place for each vehicle type. Table D-7 through Table D-11 show the years in which these technologies or standards were in place and the penetration level for each vehicle type, and these categories are defined below.

### Zero Emission Control

The category below is assigned to specific model years of gasoline or diesel vehicles for which no emissions control technologies had yet been employed.

#### *Uncontrolled*

Vehicles manufactured prior to the implementation of pollution control technologies are designated as uncontrolled. Gasoline light-duty cars and trucks (pre-1973), gasoline heavy-duty vehicles (pre-1984), diesel vehicles (pre-1983), and motorcycles (pre-1996) are assumed to not have significant control technologies in place.

### Gasoline Emission Controls

Below are the control technologies and emissions standards applicable to gasoline vehicles.

#### *Non-catalyst*

These emission controls were common in gasoline passenger cars and light-duty gasoline trucks during model years (1973-1974) but phased out thereafter, in heavy-duty gasoline vehicles beginning in the mid-1980s, and in motorcycles beginning in 1996. This technology reduces hydrocarbon (HC) and carbon monoxide (CO) emissions through adjustments to ignition timing and air-fuel ratio, air injection into the exhaust manifold, and exhaust gas recirculation (EGR) valves, which also helps meet vehicle $NO_x$ standards (EPA 1994b).

#### *Oxidation catalyst*

This control technology designation represents the introduction of the catalytic converter, and was the most common technology in gasoline passenger cars and light-duty gasoline trucks made from 1975 to 1980 (cars) and 1975 to 1985 (trucks). This technology was also used in some heavy-duty gasoline vehicles between 1982 and the present. The two-way catalytic converter oxidizes HC and CO, significantly reducing emissions over 80 percent beyond non-catalyst-system capacity (EPA 1993). One reason unleaded gasoline was introduced in 1975 was due to the fact that oxidation catalysts cannot function properly with leaded gasoline (EPA 1994a).

#### *Tier 0*

This emission standard from the Clean Air Act was met through the implementation of early "three-way" catalysts, therefore this technology was used in gasoline passenger cars and light-duty gasoline trucks sold beginning in the early 1980s, and remained common until 1994. This more sophisticated emission control system improves the efficiency of the catalyst by converting CO and HC to $CO_2$ and $H_2O$, reducing $NO_x$ to nitrogen and oxygen, and using an on-board computer and oxygen sensor (EPA 1994a). In addition, this type of catalyst includes a carburetor with electronic "trim" (IPCC 1996). New cars with three-way catalysts met the Clean Air Act's amended standards (enacted in 1977) of reducing HC to 0.41 g/mile by 1980, CO to 3.4 g/mile by 1981 and $NO_x$ to 1 g/mile by 1981.

#### *Tier 1*

This emission standard created through the 1990 amendments to the Clean Air Act called for a 40 percent reduction from the 1981 standard. This was met through the use of more advanced 3-way catalysts, and applied to light-duty gasoline vehicles beginning in 1994. This catalyst includes electronically controlled fuel injections and ignition timing, EGR, and air injection. The Tier 1 standards reduce $NO_x$ emissions to 0.6 g/mile for cars and 0.6 to 1.53 g/mile for trucks (EPA 1999).

#### *Low Emission Vehicles (LEV)*

This emission standard provides the highest mobile emission control in effect currently at the national level. Applied to light-duty gasoline passenger cars and trucks beginning in small numbers in the mid-1990's, LEV includes multi-port fuel injection with adaptive learning, an advanced computer diagnostics systems and heated catalysts with secondary air injection (IPCC 1997). Currently, only California is assumed to have a significant level of LEV vehicles. Ultra-low emission vehicles (ULEVs) and zero emission vehicles (ZEVs) are not incorporated into this analysis, as the number of these vehicles is not assumed to be significant.

### Diesel Emission Controls

Below are the two levels of emissions control for diesel vehicles.

#### *Moderate control*

Improved injection timing technology and combustion system design for light- and heavy-duty diesel vehicles (generally in place in model years 1983 to 1995) are considered moderate control technologies (IPCC 1997). These controls were implemented to meet emission standards for diesel trucks and buses adopted by the EPA in 1985 to be met in 1991 and 1994.

#### *Advanced control*

EGR and modern electronic control of the fuel injection system are designated as advanced control technologies. These technologies provide diesel vehicles with the current highest level of emission control, and were used in model years beginning in 1996.

## References


EPA (1993) *Automobiles and Carbon Monoxide.* Office of Mobile Sources, January, EPA 400-F-92-005. (Available on the internet at <http://www.epa.gov/otaq/03-co.htm>.)

EPA (1994a) *Automobile Emissions: An Overview.* Office of Mobile Sources, August, EPA 400-F-92-007. (Available on the internet at <http://www.epa.gov/otaq/05-autos.htm>.)

EPA (1994b) *Milestones in Auto Emissions Control.* Office of Mobile Sources, August, EPA 400-F-92-014. (Available on the internet at <http://www.epa.gov/otaq/12-miles.htm>.)

EPA (1998) *Emissions of Nitrous Oxide from Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-1996.* Office of Mobile Sources, Assessment and Modeling Division, August, EPA420-R-98-009. (Available on the internet at <http://www.epa.gov/oms/climate.htm>.)

EPA (1999) *Emission Facts: The History of Reducing Tailpipe Emissions.* Office of Mobile Sources, May, EPA 420-F-99-017. (Available on the internet at <http://www.epa.gov/oms/consumer/f99017.pdf>)

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

# ANNEX E

## Methodology for Estimating $CH_4$ Emissions from Coal Mining

The methodology for estimating methane emissions from coal mining consists of two distinct steps. The first step addresses emissions from underground mines. For these mines, emissions are estimated on a mine-by-mine basis and then are summed to determine total emissions. The second step of the analysis involves estimating methane emissions for surface mines and post-mining activities. In contrast to the methodology for underground mines, which uses mine-specific data, the surface mine and post-mining activities analysis consists of multiplying basin-specific coal production by basin-specific emission factors.

### Step 1: Estimate Methane Liberated and Methane Emitted from Underground Mines

Underground mines generate methane from ventilation systems and from degasification systems. Some mines recover and use methane generated from degasification systems, thereby reducing emissions to the atmosphere. Total methane emitted from underground mines equals the methane liberated from ventilation systems, plus the methane liberated from degasification systems, minus methane recovered and used.

#### *Step 1.1: Estimate Methane Liberated from Ventilation Systems*

All coal mines with detectable methane emissions[1] use ventilation systems to ensure that methane levels remain within safe concentrations. Many coal mines do not have detectable levels of methane, while others emit several million cubic feet per day (MMCFD) from their ventilation systems. On a quarterly basis, the U.S. Mine Safety and Health Administration (MSHA) measures methane emissions levels at underground mines. MSHA maintains a database of measurement data from all underground mines with detectable levels of methane in their ventilation air. Based on the four quarterly measurements, MSHA estimates average daily methane liberated at each of the underground mines with detectable emissions.

For the years 1990 through 1996 and 1998 through 2000, MSHA emissions data were obtained for a large but incomplete subset of all mines with detectable emissions. This subset includes mines emitting at least 0.1 MMCFD for some years and at least 0.5 MMCFD for other years, as shown in Table E-1. Well over 90 percent of all ventilation emissions were concentrated in these subsets. For 1997, the complete MSHA database for all 586 mines with detectable methane emissions was obtained. These mines were assumed to account for 100 percent of methane liberated from underground mines. Using the complete database from 1997, the proportion of total emissions accounted for by mines emitting less than 0.1 MMCFD or 0.5 MMCFD was estimated (see Table E-1). The proportion was then applied to the years 1990 through 2000 to account for the less than 10 percent of ventilation emissions coming from mines without MSHA data.

For 1990-1999, average daily methane emissions were multiplied by 365 to determine the annual emissions for each mine. For 2000, MSHA provided quarterly emissions. The average daily methane emissions were multiplied by the number of days corresponding to the number of quarters the mine vent was operating. For example, if the mine vent was operational in one out of the four quarters, the average daily methane emissions were multiplied by 92 days. Total ventilation emissions for a particular year were estimated by summing emissions from individual mines.

---

[1] MSHA records coal mine methane readings with concentrations of greater than 50 ppm (parts per million) methane. Readings below this threshold are considered non-detectable.

**Table E-1: Mine-Specific Data Used to Estimate Ventilation Emissions**

| Year | Individual Mine Data Used |
|---|---|
| 1990 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 1991 | 1990 Emissions Factors Used Instead of Mine-Specific Data |
| 1992 | 1990 Emissions Factors Used Instead of Mine-Specific Data |
| 1993 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 1994 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 1995 | All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total)* |
| 1996 | All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total)* |
| 1997 | All Mines with Detectable Emissions (Assumed to Account for 100% of Total) |
| 1998 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 1999 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 2000 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |

* Factor derived from a complete set of individual mine data collected for 1997.

### *Step 1.2: Esti mate Methane Liberated from Degasification Systems*

Coal mines use several different types of degasification systems to remove methane, including vertical wells and horizontal boreholes to recover methane prior to mining of the coal seam. Gob wells and cross-measure boreholes recover methane from the overburden (i.e., GOB area) after mining of the seam (primarily in longwall mines).

MSHA collects information about the presence and type of degasification systems in some mines, but does not collect quantitative data on the amount of methane liberated. Thus, the methodology estimated degasification emissions on a mine-by-mine basis based on other sources of available data. Many of the coal mines employing degasification systems have provided EPA with information regarding methane liberated from their degasification systems. For these mines, this reported information was used as the estimate. In other cases in which mines sell methane recovered from degasification systems to a pipeline, gas sales were used to estimate methane liberated from degasification systems (see Step 1.3). Finally, for those mines that do not sell methane to a pipeline and have not provided information to EPA, methane liberated from degasification systems was estimated based on the type of system employed. For example, for coal mines employing gob wells and horizontal boreholes, the methodology assumes that degasification emissions account for 40 percent of total methane liberated from the mine.

### *Step 1.3: Estimate Methane Recovered from Degasification Systems and Used (Emissions Avoided)*

In 2000, ten active coal mines had methane recovery and use projects and sold the recovered methane to a pipeline. One coal mine also used some recovered methane in a thermal dryer in addition to selling gas to a pipeline. In order to calculate emissions avoided from pipeline sales, information was needed regarding the amount of gas recovered and the number of years in advance of mining that wells were drilled. Several state agencies provided gas sales data, which were used to estimate emissions avoided for these projects. Additionally, coal mine operators provided information on gas sales and/or the number of years in advance of mining. Emissions avoided were attributed to the year in which the coal seam was mined. For example, if a coal mine recovered and sold methane using a vertical well drilled five years in advance of mining, the emissions avoided associated with those gas sales (cumulative production) were attributed to the well up to the time it was mined through (e.g., five years of gas production). Where individual well data is not available, estimated percentages of the operator's annual gas sales within the field around the coal mine are attributed to emissions avoidance. For some mines, individual well data were used to assign gas sales to the appropriate emissions avoided year. In most cases, coal mine operators provided this information, which was then used to estimate emissions avoided for a particular year. Additionally, several state agencies provided production data for individual wells.

### Step 2: Estimate Methane Emitted from Surface Mines and Post-Mining Activities

Mine-specific data were not available for estimating methane emissions from surface coal mines or for post-mining activities. For surface mines and post-mining activities, basin-specific coal production was multiplied by a basin-specific emission factor to determine methane emissions.

### *Step 2.1: Define the Geographic Resolution of the Analysis and Collect Coal Production Data*

The first step in estimating methane emissions from surface mining and post-mining activities was to define the geographic resolution of the analysis and to collect coal production data at that level of resolution. The analysis was conducted by coal basin as defined in Table E-2, which presents coal basin definitions by basin and by state.

The Energy Information Agency's (EIA) Coal Industry Annual reports state- and county-specific underground and surface coal production by year. To calculate production by basin, the state level data were grouped into coal basins using the basin definitions listed in Table E-2. For two states—West Virginia and Kentucky—county-level production data was used for the basin assignments because coal production occurred from geologically distinct coal basins within these states. Table E-3 presents the coal production data aggregated by basin.

### *Step 2.2: Estimate Emissions Factors for Each Emissions Type*

Emission factors for surface mined coal were developed from the *in situ* methane content of the surface coal in each basin. Based on an analysis presented in EPA (1993), surface mining emission factors were estimated to be from 1 to 3 times the average *in situ* methane content in the basin. For this analysis, the surface mining emission factor was determined to be twice the *in situ* methane content in the basin. Furthermore, the post-mining emission factors used were estimated to be 25 to 40 percent of the average *in situ* methane content in the basin. For this analysis, the post-mining emission factor was determined to be 32.5 percent of the *in situ* methane content in the basin. Table E-4 presents the average *in situ* content for each basin, along with the resulting emission factor estimates.

### *Step 2.3: Estimate Methane Emitted*

The total amount of methane emitted was calculated by multiplying the coal production in each basin by the appropriate emission factors.

Total annual methane emissions is equal to the sum of underground mine emissions plus surface mine emissions plus post-mining emissions. Table E-5 and Table E-6 present estimates of methane liberated, used, and emitted for 1990 through 2000. Table E-7 provides emissions by state.

**Table E-2: Coal Basin Definitions by Basin and by State**

| Basin | States |
|---|---|
| Northern Appalachian Basin | Maryland, Ohio, Pennsylvania, West Virginia North |
| Central Appalachian Basin | Kentucky East, Tennessee, Virginia, West Virginia South |
| Warrior Basin | Alabama, Mississippi |
| Illinois Basin | Illinois, Indiana, Kentucky West |
| South West and Rockies Basin | Arizona, California, Colorado, New Mexico, Utah |
| North Great Plains Basin | Montana, North Dakota, Wyoming |
| West Interior Basin | Arkansas, Iowa, Kansas, Louisiana, Missouri, Oklahoma, Texas |
| Northwest Basin | Alaska, Washington |

| State | Basin |
|---|---|
| Alabama | Warrior Basin |
| Alaska | Northwest Basin |
| Arizona | South West and Rockies Basin |
| Arkansas | West Interior Basin |
| California | South West and Rockies Basin |
| Colorado | South West and Rockies Basin |
| Illinois | Illinois Basin |
| Indiana | Illinois Basin |
| Iowa | West Interior Basin |
| Kansas | West Interior Basin |
| Kentucky East | Central Appalachian Basin |
| Kentucky West | Illinois Basin |
| Louisiana | West Interior Basin |
| Maryland | Northern Appalachian Basin |
| Mississippi | Warrior Basin |
| Missouri | West Interior Basin |
| Montana | North Great Plains Basin |
| New Mexico | South West and Rockies Basin |
| North Dakota | North Great Plains Basin |
| Ohio | Northern Appalachian Basin |
| Oklahoma | West Interior Basin |
| Pennsylvania. | Northern Appalachian Basin |
| Tennessee | Central Appalachian Basin |
| Texas | West Interior Basin |
| Utah | South West and Rockies Basin |
| Virginia | Central Appalachian Basin |
| Washington | Northwest Basin |
| West Virginia South | Central Appalachian Basin |
| West Virginia North | Northern Appalachian Basin |
| Wyoming | North Great Plains Basin |

## Table E-3: Annual Coal Production (Thousand Short Tons)

*Underground Coal Production*

| Basin | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N. Appalachia | 103,865 | 103,450 | 105,220 | 77,032 | 100,122 | 98,103 | 106,729 | 112,135 | 116,718 | 107,575 | 105,374 |
| Cent. Appalachia | 198,412 | 181,873 | 177,777 | 164,845 | 170,893 | 166,495 | 171,845 | 177,720 | 171,279 | 157,058 | 150,584 |
| Warrior | 17,531 | 17,062 | 15,944 | 15,557 | 14,471 | 17,605 | 18,217 | 18,505 | 17,316 | 14,799 | 15,895 |
| Illinois | 69,167 | 69,947 | 73,154 | 55,967 | 69,050 | 69,009 | 67,046 | 64,728 | 64,463 | 63,529 | 53,720 |
| S. West/Rockies | 32,754 | 31,568 | 31,670 | 35,409 | 41,681 | 42,994 | 43,088 | 44,503 | 45,983 | 46,957 | 45,742 |
| N. Great Plains | 1,722 | 2,418 | 2,511 | 2,146 | 2,738 | 2,018 | 2,788 | 2,854 | 1,723 | 1,673 | 1,210 |
| West Interior | 105 | 26 | 59 | 100 | 147 | 25 | 137 | 212 | 247 | 200 | 241 |
| Northwest | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | **423,556** | **406,344** | **406,335** | **351,056** | **399,102** | **396,249** | **409,850** | **420,657** | **417,729** | **391,791** | **372,766** |

*Surface Coal Production*

| Basin | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N. Appalachia | 60,761 | 51,124 | 50,512 | 48,641 | 44,960 | 39,372 | 39,788 | 40,179 | 41,043 | 33,928 | 34,908 |
| Cent. Appalachia | 94,343 | 91,785 | 95,163 | 94,433 | 106,129 | 106,250 | 108,869 | 113,275 | 108,345 | 107,507 | 110,479 |
| Warrior | 11,413 | 10,104 | 9,775 | 9,211 | 8,795 | 7,036 | 6,420 | 5,963 | 5,697 | 4,723 | 4,252 |
| Illinois | 72,000 | 63,483 | 58,814 | 50,535 | 51,868 | 40,376 | 44,754 | 46,862 | 47,715 | 40,474 | 33,631 |
| S. West/Rockies | 43,863 | 42,985 | 46,052 | 48,765 | 49,119 | 46,643 | 43,814 | 48,374 | 49,635 | 50,349 | 49,587 |
| N. Great Plains | 249,356 | 259,194 | 258,281 | 275,873 | 308,279 | 331,367 | 343,404 | 349,612 | 385,438 | 407,683 | 407,670 |
| West Interior | 64,310 | 61,889 | 63,562 | 60,574 | 58,791 | 59,116 | 60,912 | 59,061 | 57,951 | 58,309 | 54,170 |
| Northwest | 6,707 | 6,579 | 6,785 | 6,340 | 6,460 | 6,566 | 6,046 | 5,945 | 5,982 | 5,666 | 5,911 |
| **Total** | **602,753** | **587,143** | **588,944** | **594,372** | **634,401** | **636,726** | **654,007** | **669,271** | **699,608** | **708,639** | **700,608** |

*Total Coal Production*

| Basin | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N. Appalachia | 164,626 | 154,574 | 155,732 | 125,673 | 145,082 | 137,475 | 146,517 | 152,314 | 157,761 | 141,145 | 140,282 |
| Cent. Appalachia | 292,755 | 273,658 | 272,940 | 259,278 | 277,022 | 272,745 | 280,714 | 290,995 | 279,624 | 262,660 | 261,063 |
| Warrior | 28,944 | 27,166 | 25,719 | 24,768 | 23,266 | 24,641 | 24,637 | 24,468 | 23,013 | 19,499 | 20,147 |
| Illinois | 141,167 | 133,430 | 131,968 | 106,502 | 120,918 | 109,385 | 111,800 | 111,590 | 110,176 | 103,966 | 87,351 |
| S. West/Rockies | 76,617 | 74,553 | 77,722 | 84,174 | 90,800 | 89,637 | 86,902 | 92,877 | 95,618 | 96,207 | 95,239 |
| N. Great Plains | 251,078 | 261,612 | 260,792 | 278,019 | 311,017 | 333,385 | 346,192 | 352,466 | 387,161 | 406,324 | 408,880 |
| West Interior | 64,415 | 61,915 | 63,621 | 60,674 | 58,938 | 59,141 | 61,049 | 59,273 | 58,198 | 58,509 | 54,411 |
| Northwest | 6,707 | 6,579 | 6,785 | 6,340 | 6,460 | 6,566 | 6,046 | 5,945 | 5,982 | 5,665 | 5,911 |
| **Total** | **1,026,309** | **993,487** | **995,279** | **945,428** | **1,033,503** | **1,032,975** | **1,063,857** | **1,089,928** | **1,118,132** | **1,093,975** | **1,073,374** |

Source for 1990-99 data: EIA (1990-99), Coal Industry Annual. U.S.Department of Energy, Washington, DC, Table 3.
Source for 2000 data: EIA (2001) Personal Communication on August 29,2001, U.S. Department of Energy, Washington, DC.
Note: Totals may not sum due to independent rounding.

## Table E-4: Coal Surface and Post-Mining Methane Emission Factors ($ft^3$ per Short Ton)

| Basin | Surface Average *in situ* Content | Underground Average *In situ* Content | Surface Mine Factors | Post-Mining Surface Factors | Post Mining Underground |
|---|---|---|---|---|---|
| Northern Appalachia | 49.3 | 171.7 | 98.6 | 16.0 | 55.8 |
| Central Appalachia | 49.3 | 330.7 | 98.6 | 16.0 | 107.5 |
| Warrior | 49.3 | 318.0 | 98.6 | 16.0 | 103.4 |
| Illinois | 39.0 | 57.20 | 78.0 | 12.7 | 18.6 |
| S. West/Rockies | 15.3 | 225.8 | 30.6 | 5.0 | 73.4 |
| N. Great Plains | 3.2 | 41.67 | 6.4 | 1.0 | 13.5 |
| West Interior | 3.2 | 41.67 | 6.4 | 1.0 | 13.5 |
| Northwest | 3.2 | 41.67 | 6.4 | 1.0 | 13.5 |

Source: EPA (1993), Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to Congress, U.S. Environmental Protection Agency, Air and Radiation, April.

## Table E-5: Underground Coal Mining Methane Emissions (Billion Cubic Feet)

| Activity | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ventilation Output | 112 | NA | NA | 95 | 96 | 102 | 90 | 96 | 94 | 92 | 87 |
| Adjustment Factor for Mine Data* | 97.8% | NA | NA | 97.8% | 97.8% | 91.4% | 91.4% | 100% | 97.8% | 97.8% | 97.8% |
| Adjusted Ventilation Output | 114 | NA | NA | 97 | 98 | 111 | 99 | 96 | 96 | 94 | 89 |
| Degasification System Liberated | 54 | NA | NA | 45 | 46 | 46 | 50 | 42 | 49 | 41 | 45 |
| Total Underground Liberated | 167 | 164 | 162 | 142 | 144 | 157 | 149 | 138 | 146 | 135 | 134 |
| Recovered & Used | (14) | (15) | (17) | (23) | (27) | (30) | (36) | (28) | (35) | (32) | (36) |
| **Total** | **154** | **149** | **144** | **119** | **117** | **127** | **113** | **110** | **110** | **103** | **98** |

*Refer to Table E-1.
Note: Totals may not sum due to independent rounding.

## Table E-6: Total Coal Mining Methane Emissions (Billion Cubic Feet)

| Activity | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Underground Mining | 154 | 149 | 144 | 119 | 117 | 127 | 113 | 110 | 110 | 103 | 98 |
| Surface Mining | 25 | 23 | 23 | 23 | 24 | 22 | 23 | 24 | 23 | 22 | 22 |
| Post-Mining (Underground) | 33 | 31 | 30 | 27 | 30 | 30 | 31 | 32 | 31 | 29 | 28 |
| Post-Mining (Surface) | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| **Total** | **216** | **209** | **201** | **173** | **175** | **183** | **172** | **170** | **163** | **161** | **150** |

Note: Totals may not sum due to independent rounding.

## Table E-7: Total Coal Mining Methane Emissions by State (Million Cubic Feet)

| State | 1990 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|
| Alabama | 33,175 | 26,694 | 30,283 | 39,334 | 29,928 | 26,440 | 27,058 | 26,209 | 23,997 |
| Alaska | 13 | 12 | 12 | 13 | 11 | 11 | 10 | 12 | 12 |
| Arizona | 402 | 433 | 464 | 425 | 371 | 417 | 403 | 419 | 466 |
| Arkansas | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| California | 2 | - | - | - | - | - | 0 | 0 | 0 |
| Colorado | 10,117 | 7,038 | 9,029 | 8,541 | 5,795 | 9,057 | 9,057 | 9,296 | 10,677 |
| Illinois | 10,643 | 8,737 | 10,624 | 11,106 | 10,890 | 8,571 | 7,859 | 7,812 | 8,531 |
| Indiana | 3,149 | 2,623 | 2,791 | 2,106 | 2,480 | 3,088 | 3,239 | 2,980 | 2,492 |
| Iowa | 3 | 1 | 0 | - | - | - | 0 | 0 | 0 |
| Kansas | 5 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 1 |
| Kentucky | 21,229 | 19,823 | 21,037 | 19,103 | 18,292 | 20,089 | 19,240 | 18,255 | 16,910 |
| Louisiana | 24 | 23 | 26 | 28 | 24 | 26 | 24 | 22 | 27 |
| Maryland | 510 | 245 | 256 | 259 | 287 | 296 | 282 | 260 | 345 |
| Mississippi | - | - | - | - | - | - | 0 | 2 | 92 |
| Missouri | 20 | 5 | 6 | 4 | 5 | 3 | 3 | 3 | 3 |
| Montana | 280 | 267 | 310 | 294 | 283 | 305 | 319 | 306 | 285 |
| New Mexico | 905 | 1,186 | 1,223 | 980 | 856 | 961 | 1,026 | 1,042 | 972 |
| North Dakota | 217 | 238 | 240 | 224 | 222 | 220 | 223 | 232 | 233 |
| Ohio | 4,710 | 4,110 | 4,377 | 3,900 | 3,992 | 4,313 | 4,244 | 3,820 | 3,443 |
| Oklahoma | 13 | 14 | 52 | 14 | 14 | 132 | 137 | 209 | 208 |
| Pennsylvania | 22,573 | 26,437 | 24,026 | 27,086 | 26,567 | 30,339 | 29,853 | 24,088 | 25,352 |
| Tennessee | 800 | 350 | 338 | 366 | 418 | 390 | 309 | 349 | 306 |
| Texas | 415 | 406 | 389 | 392 | 410 | 397 | 391 | 395 | 361 |
| Utah | 4,562 | 4,512 | 3,696 | 3,541 | 4,061 | 4,807 | 5,060 | 4,851 | 4,045 |
| Virginia | 45,883 | 30,457 | 26,765 | 19,893 | 19,847 | 16,972 | 14,087 | 13,539 | 12,179 |
| Washington | 37 | 35 | 36 | 36 | 34 | 33 | 35 | 31 | 32 |
| West Virginia | 55,280 | 37,803 | 36,854 | 42,992 | 42,870 | 40,197 | 43,511 | 41,500 | 37,490 |
| Wyoming | 1,382 | 1,578 | 1,782 | 1,977 | 2,090 | 2,122 | 2,351 | 2,520 | 2,533 |
| **Total** | **216,350** | **173,029** | **174,622** | **182,616** | **169,750** | **169,190** | **168,725** | **158,153** | **151,397** |

+ Does not exceed 0.5 Million Cubic Feet
Note: The emission estimates provided above are inclusive of emissions from underground mines, surface mines and post-mining activities. The following states have neither underground nor surface mining and thus report no emissions as a result of coal mining: Connecticut, Delaware, Florida, Georgia, Hawaii, Idaho, Maine, Massachusetts, Michigan, Minnesota, Nebraska, Nevada, New Hampshire, New Jersey, New York, North Carolina, Oregon, Rhode Island, South Carolina, South Dakota, Vermont, and Wisconsin. Emission estimates are not given for 1991 and 1992 because underground mine data was not available for those years.

# ANNEX F

## Methodology for Estimating $CH_4$ Emissions from Natural Gas Systems

The following steps were used to estimate methane emissions from natural gas systems.

### Step 1: Calculate Emission Estimates for Base Year 1992 Using GRI/EPA Study

The first step in estimating methane emissions from natural gas systems was to develop a detailed base year estimate of emissions. The study by GRI/EPA (1996) divides the industry into four stages to construct a detailed emission inventory for the year 1992. These stages include: field production, processing, transmission and storage (i.e., both underground and liquefied gas storage), and distribution. This study produced emission factors and activity data for over 100 different emission sources within the natural gas system. Emissions for 1992 were estimated by multiplying activity levels by emission factors for each system component and then summing by stage. Since publication, the EPA has updated 1992 activity data for some of the components in the system. Table F-1 displays the 1992 GRI/EPA activity levels and emission factors for venting and flaring from the field production stage, and the current EPA activity levels and emission factors. These data are shown to illustrate the kind of data used to calculate emissions from all stages.

### Step 2: Collect Aggregate Statistics on Main Driver Variables

As detailed data on each of the over 100 sources were not available for the period 1990 through 1999, activity levels were estimated using aggregate statistics on key drivers, including: number of producing wells (IPAA 1990 through 2000, EIA 2000), number of gas plants (AGA 1990 through 1998; PennWell Corporation 1999, 2000, 2001), miles of transmission pipeline (OPS 1998, 1999, 2000, 2001), miles of distribution pipeline (OPS, 2001), miles of distribution services (OPS, 2001), and energy consumption (EIA 1998, 1999, 2000, 2001). Data on the distribution of gas mains and services by material type was not available for 1990 through 1992 from OPS. For those years, the distribution by type was back calculated from 1993 using compound growth rates determined for the years 1993 through 2000. Table F-2 provides the activity levels of some of the key drivers in the natural gas analysis.

### Step 3: Estimate Emission Factor Changes Over Time

For the period 1990 through 1995, the emission factors were held constant, based on 1992 values. However, the natural gas industry is experiencing ongoing broad based technology improvements, which are expected to continue. These improvements have increased operating efficiency, thus reducing methane emissions. An assumed improvement in technology and practices was estimated to reduce emission factors by 5 percent by the year 2020. This assumption, annualized, amounts to a 0.2 percent decline in the 1996 emission factor, a 0.4 percent decline in the 1997 emission factor, a 0.6 percent decline in the 1998 emission factor and a 0.8 percent decline in the 1999 emission factor, all relative to 1995 emission factors.

### Step 4: Estimate Emissions for Each Year and Stage

Emissions from each stage of the natural gas industry were estimated by multiplying the activity factors by the appropriate emission factors, summing all sources for each stage, and then subtracting the Natural Gas STAR emission reductions.[1] Methane reductions from the Natural Gas STAR program for the years 1994 through 2000 are presented in Table F- 3. Emission reductions by project are reported by industry partners using actual measurement data or equipment-specific emission factors. Before incorporating the reductions into the Inventory, quality assurance and quality control checks are undertaken to identify errors, inconsistencies, or irregular data. Total

[1] It is assumed that the 5 percent decline in the emissions factor from 1995 to 2020 does not reflect emission reductions attributed to Natural Gas STAR. The emission factor decline accounts for regular technology improvements only. This assumption is being investigated for future inventories.

emissions were estimated by adding the emission estimates from each stage. Table F-4 illustrates emission estimates for venting and flaring emissions from the field production stage using this methodology. Table F-5 presents total natural gas production and associated methane emissions.

## Table F-1: 1992 Data and Emissions (Mg) for Venting and Flaring from Natural Gas Field Production Stage

| Activity | *GRI/EPA Values* | | | *EPA Adjusted Values* | | |
|---|---|---|---|---|---|---|
| | Activity Data | Emission Factor | Emissions | Activity Data | Emission Factor | Emissions |
| Drilling and Well Completion | | | | | | |
| Completion Flaring | 844 compl/yr | 733 Scf/comp | 12 | 400 compl/yr | 733 scf/comp | 6 |
| Normal Operations | | | | | | |
| Pneumatic Device Vents | 249,111 controllers | 345 Scfd/device | 602,291 | 249,111 controllers | 345 scfd/device | 602,291 |
| Chemical Injection Pumps | 16,971 active pumps | 248 Scfd/pump | 29,501 | 16,971 active pumps | 248 scfd/pump | 29,502 |
| Kimray Pumps | 11,050,000 MMscf/yr | 368 Scf/MMscf | 78,024 | 7,380,194 MMscf/yr | 992 scf/MMscf | 140,566 |
| Dehydrator Vents | 12,400,000 MMscf/yr | 276 Scf/MMscf | 65,608 | 8,200,215 MMscf/yr | 276 scf/MMscf | 43,387 |
| Compressor Exhaust Vented Gas Engines | 27,460 MMHPhr | 0.24 Scf/HPhr | 126,536 | 27,460 MMHPhr | 0.24 scf/HPhr | 126,535 |
| Routine Maintenance | | | | | | |
| Well Workovers | | | | | | |
| Gas Wells | 9,392 w.o./yr | 2,454 scfy/w.o. | 443 | 9,392 w.o./yr | 2,454 scfy/w.o. | 443 |
| Well Clean Ups (LP Gas Wells) | 114,139 LP gas wells | 49,570 scfy/LP well | 108,631 | 114,139 LP gas wells | 49,570 scfy/LP well | 108,631 |
| Blowdowns | | | | | | |
| Vessel BD | 255,996 vessels | 78 scfy/vessel | 383 | 242,306 vessels | 78 scfy/vessel | 363 |
| Pipeline BD | 340,000 miles (gath) | 309 scfy/mile | 2,017 | 340,200 miles (gath) | 309 scfy/mile | 2,018 |
| Compressor BD | 17,112 compressors | 3,774 scfy/comp | 1,240 | 17,112 compressors | 3,774 scfy/comp | 1,240 |
| Compressor Starts | 17,112 compressors | 8,443 scfy/comp | 2,774 | 17,112 compressors | 8,443 scfy/comp | 2,774 |
| Upsets | | | | | | |
| Pressure Relief Valves | 529,440 PRV | 34.0 scfy/PRV | 346 | 529,440 PRV | 34.0 scfy/PRV | 346 |
| ESD | 1,115 platforms | 256,888 scfy/plat | 5,499 | 1,372 platforms | 256,888 scfy/plat | 6,767 |
| Mishaps | 340,000 miles | 669 scfy/mile | 4,367 | 340,200 miles | 669 scfy/mile | 4,370 |

## Table F-2: Activity Factors for Key Drivers

| Variable | Units | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|
| Transmission Pipelines Length | miles | 291,990 | 296,947 | 292,186 | 294,304 | 302,706 | 296,581 | 293,774 |
| Wells | | | | | | | | |
| GSAM Appalachia Wells* | # wells | 120,162 | 123,092 | 122,700 | 120,037 | 117,878 | 118,723 | 118,723 |
| GSAM N Central Associated Wells* | # wells | 3780 | 3641 | 3417 | 3409 | 3,361 | 3,361 | 3,361 |
| GSAM N Central Non-Associated Wells* | # wells | 3,105 | 6,323 | 7,073 | 6,701 | 8,664 | 8,548 | 8,548 |
| GSAM Rest of US Wells* | # wells | 145,100 | 164,750 | 173,928 | 173,550 | 190,387 | 180,178 | 180,178 |
| GSAM Rest of US Associated Wells* | # wells | 277,301 | 264,837 | 264,807 | 264,185 | 254,848 | 254,848 | 254,848 |
| Appalch. + N. Central Non-Assoc. + Rest of US | # wells | 268,367 | 294,165 | 303,701 | 300,288 | 316,929 | 307,449 | 307,449 |
| Platforms | | | | | | | | |
| Gulf of Mexico Off-shore Platforms | # platforms | 3,798 | 3,868 | 3,846 | 3,846 | 3,963 | 3,975 | 4019 |
| Rest of U.S. (offshore platforms) | # platforms | 24 | 23 | 24 | 23 | 23 | 23 | 23 |
| N. Central Non-Assoc. + Rest of US Wells | # platforms | 148,205 | 171,073 | 181,001 | 180,251 | 199,051 | 188,726 | 188,726 |
| Gas Plants | | | | | | | | |
| Number of Gas Plants | # gas plants | 761 | 675 | 623 | 615 | 558 | 581 | 585 |
| Distribution Services | | | | | | | | |
| Steel – Unprotected | # of services | 5,500,993 | 6,151,653 | 5,775,613 | 5,518,795 | 5,463,253 | 5,751,250 | 5,676,582 |
| Steel - Protected | # of services | 19,916,202 | 21,002,455 | 18,593,770 | 19,078,467 | 18,478,344 | 18,310,719 | 17,775,878 |
| Plastic | # of services | 16,269,414 | 26,044,545 | 26,187,536 | 27,800,401 | 28,629,388 | 28,796,952 | 31,644,014 |
| Copper | # of services | 1,379,237 | 1,445,380 | 1,519,625 | 1,498,050 | 1,464,019 | 1,458,518 | 1,434,091 |
| Total | # of services | 43,065,846 | 54,644,033 | 52,076,544 | 53,895,713 | 54,035,004 | 54,317,439 | 56,530,565 |
| Distribution Mains | | | | | | | | |
| Steel – Unprotected | miles | 91,267 | 94,058 | 88,412 | 85,166 | 86,639 | 84,534 | 82,817 |
| Steel – Protected | miles | 491,120 | 503,288 | 484,526 | 479,278 | 484,963 | 459,298 | 468,932 |
| Cast Iron | miles | 52,644 | 50,625 | 51,542 | 47,669 | 47,587 | 45,865 | 44,736 |
| Plastic | miles | 202,269 | 353,735 | 350,699 | 385,373 | 400,627 | 415,210 | 446,554 |
| Total | miles | 837,300 | 1,001,706 | 975,179 | 997,486 | 1,019,816 | 1,004,907 | 1,043,039 |

* GSAM (Gas Systems Analysis Model) is a natural gas supply, demand, and transportation model used by the Federal Energy Technology Center of the U.S. Department of Energy (GSAM 1997).

## Table F- 3. Methane reductions from the Natural Gas STAR program (Tg)

| Process | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Production | 0.10 | 0.12 | 0.19 | 0.25 | 0.29 | 0.38 | 0.48 |
| Processing | - | - | - | - | - | - | - |
| Transmission and Storage | 0.07 | 0.09 | 0.08 | 0.11 | 0.15 | 0.18 | 0.23 |
| Distribution | 0.02 | 0.02 | 0.01 | 0.03 | 0.02 | 0.02 | 0.02 |

## Table F-4: $CH_4$ Emission Estimates for Venting and Flaring from the Field Production Stage (Mg)

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Drilling and Well Completion | | | | | | | |
| Completion Flaring | 5.4 | 5.9 | 6.1 | 6.0 | 6.3 | 6.1 | 6.1 |
| Normal Operations | | | | | | | |
| Pneumatic Device Vents | 567,778 | 655,386 | 692,033 | 687,785 | 757,995 | 717,231 | 715,785 |
| Chemical Injection Pumps | 36,449 | 43,111 | 45,666 | 45,256 | 50,352 | 47,769 | 47,673 |
| Kimray Pumps | 134,247 | 147,191 | 151,572 | 149,492 | 157,342 | 152,492 | 152,184 |
| Dehydrator Vents | 41,436 | 45,432 | 46,784 | 46,142 | 48,565 | 47,068 | 46,973 |
| Compressor Exhaust Vented Gas Engines | 119,284 | 137,690 | 145,389 | 144,497 | 159,247 | 150,683 | 150,379 |
| Routine Maintenance | | | | | | | |
| Well Workovers Gas Wells | 531 | 582 | 600 | 591 | 622 | 603 | 602 |
| Well Clean Ups (LP Gas Wells) | 101,118 | 110,868 | 114,168 | 112,601 | 118,514 | 114,861 | 114,629 |
| Blowdowns | | | | | | | |
| Vessel BD | 256 | 292 | 306 | 303 | 329 | 314 | 314 |
| Pipeline BD | 1,710 | 1,852 | 1,908 | 1,894 | 1,997 | 1,932 | 1,928 |
| Compressor BD | 1,548 | 1,730 | 1,802 | 1,786 | 1,920 | 1,837 | 1,833 |
| Compressor Starts | 3,462 | 3,871 | 4,031 | 3,995 | 4,296 | 4,110 | 4,102 |
| Upsets | | | | | | | |
| Pressure Relief Valves | 326 | 376 | 397 | 395 | 435 | 412 | 411 |
| ESD | 6,764 | 6,882 | 6,834 | 6,816 | 7,006 | 7,013 | 7,075 |
| Mishaps | 925 | 1,003 | 1,033 | 1,025 | 1,081 | 1,045 | 1,043 |

## Table F-5: U.S. Total Natural Gas Production (Trillion $Ft^3$/yr) and Associated $CH_4$ Emissions (Gg)

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Production | 17.8 | 18.6 | 18.9 | 18.9 | 18.7 | 18.6 | 19.1 |
| $CH_4$ Emissions from Production | 1,404 | 1,470 | 1,466 | 1,397 | 1,496 | 1,329 | 1,226 |

# ANNEX G

## Methodology for Estimating $CH_4$ Emissions from Petroleum Systems

The methodology for estimating methane emissions from petroleum systems is based on the 1999 EPA draft report, *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999) and Radian's Study, *Methane Emissions from the U.S. Petroleum Industry* (Radian 1996). Seventy activities that emit methane from petroleum systems were examined for these reports. Most of the activities analyzed involve crude oil production field operations, which accounted for 97 percent of total oil industry emissions. Crude transportation and refining accounted for the remaining emissions at about one and two percent each, respectively.

The following steps were taken to estimate methane emissions from petroleum systems.

### Step 1: Determine Emission Factors for all activities

The emission factors for 1995 are taken from the 1999 EPA draft report, which contains the most recent and comprehensive determination of emission factors for the seventy methane emitting activities in the oil industry. The emission factors determined for 1995 are assumed to be representative of emissions from each source type over the period 1990 through 2000. Therefore, the same emission factors are used for each year throughout this period.

### Step 2: Determine Activity Levels for Each Year

Activity levels change from year to year. Some factors change in proportion to crude oil rates: production, transportation, or refinery runs. Some change in proportion to the number of facilities: oil wells or petroleum refineries. Some factors change proportional to both rate and number of facilities.

For fifty-seven of the seventy activities, activity levels for 1995 are taken from EPA. For the remaining thirteen activities, the activity level for 1993 is taken from Radian (1996). These thirteen activity levels were derived from field data collected in 1993, along with 1993 crude oil production and number of wells.

For both sets of data, a determination was made on a case-by-case basis, as to which measure of petroleum industry activity best reflects the change in annual activity relative to the base years (1993 and 1995). Publicly reported data from the Minerals Management Service (MMS), Energy Information Administration (EIA), American Petroleum Institute (API) and the Oil & Gas Journal (O&GJ) were used to extrapolate the activity levels from the base year to each year between 1990 to 2000. Data used include total domestic crude oil production, number of domestic crude oil wells, total imports and exports of crude oil, and total petroleum refinery crude runs. For a small number of sources, 2000 data were not yet available. In these cases, the 2000 activity factors were used. In the few cases where no data was located, activity data based on oil industry expert judgment were used.

### Step 3: Estimate Methane Emissions for Each Activity for Each Year

Annual emissions from each of the 70 petroleum system activities analyzed were estimated by multiplying the activity data for each year by the corresponding emission factor. These annual emissions for each activity are then summed to estimate the total annual methane emissions. Table G-1, Table G-2, and Table G-3 provide the 2000 activity factors, emission factors, and emission estimates.

Table G-4 provides a summary of emission estimates for the years 1990 through 2000.

## Table G-1: 2000 $CH_4$ Emissions from Petroleum Production Field Operations

| Activity/Equipment | Emission Factor | Units | Activity Factor | Units | Emissions (Bcf/yr) |
|---|---|---|---|---|---|
| **Vented Emissions** | | | | | **47.754** |
| Oil Tanks | 18 | scf of $CH_4$/bbl crude | 1,234 | MMbbl/yr (non stripper wells) | 22.086 |
| Pneumatic Devices, High Bleed | 345 | scfd $CH_4$/device | 142,840 | No. of high-bleed devices | 17.998 |
| Pneumatic Devices, Low Bleed | 35 | scfd $CH_4$/device | 265,275 | No. of low-bleed devices | 3.342 |
| Chemical Injection Pumps | 248 | scfd $CH_4$/pump | 28,595 | No. of pumps | 2.589 |
| Vessel Blowdowns | 78 | scfy $CH_4$/vessel | 186,502 | No. of vessels | 0.015 |
| Compressor Blowdowns | 3,775 | scf/yr of $CH_4$/compressor | 2,531 | No. of compressors | 0.010 |
| Compressor Starts | 8,443 | scf/yr. of $CH_4$/compressor | 2,531 | No. of compressors | 0.021 |
| Stripper wells | 2,345 | scf/yr of $CH_4$/stripper well | 348,867 | No. of stripper wells vented | 0.818 |
| Well Completion Venting | 733 | scf/completion | 4,731 | Oil well completions | 0.003 |
| Well Workovers | 96 | scf $CH_4$/workover | 40,050 | Oil well workovers | 0.004 |
| Pipeline Pigging | 2.40 | scfd of $CH_4$/pig station | 0 | No. of crude pig stations | 0.000 |
| Offshore Platforms, Gulf of Mexico | 1,283 | scfd $CH_4$/platform | 1,832 | No. of oil platforms | 0.858 |
| Offshore Platforms, Other U.S. Areas | 1,283 | scfd $CH_4$/platform | 23 | No. of oil platforms | 0.011 |
| **Fugitive Emissions** | | | | | **2.476** |
| Offshore Platforms, Gulf of Mexico | 56 | scfd $CH_4$/platform | 1,832 | No. of oil platforms | 0.037 |
| Offshore Platforms, Other U.S. Areas | 56 | scfd $CH_4$/platform | 23 | No. of oil platforms | 0.000 |
| Oil Wellheads (heavy crude) | 0.13 | scfd/well | 13,052 | No. of hvy. crude wells * | 0.001 |
| Oil Wellheads (light crude) | 16.6 | scfd/well | 172,081 | No. of lt. crude wells * | 1.045 |
| Separators (heavy crude) | 0.15 | scfd $CH_4$/separator | 10,970 | No. of hvy. crude seps. | 0.001 |
| Separators (light crude) | 14 | scfd $CH_4$/separator | 99,837 | No. of lt. crude seps. | 0.505 |
| Heater/Treaters (light crude) | 19 | scfd $CH_4$/heater | 75,695 | No. of heater treaters | 0.530 |
| Headers (heavy crude) | 0.08 | scfd $CH_4$/header | 13,929 | No. of hvy. crude hdrs. | 0.000 |
| Headers (light crude) | 11 | scfd $CH_4$/header | 43,183 | No. of lt. crude hdrs. | 0.171 |
| Floating Roof Tanks | 338,306 | scf $CH_4$/floating roof tank/yr. | 24 | No. of floating roof tanks | 0.008 |
| Compressors | 100 | scfd $CH_4$/compressor | 2,531 | No. of compressors | 0.092 |
| Large Compressors | 16,360 | scfd $CH_4$/compressor | 0 | No. of large comprs. | 0.000 |
| Sales Areas | 41 | scf $CH_4$/loading | 1,760,539 | Loadings/year | 0.071 |
| Pipelines | 0 | scfd of $CH_4$/mile of pipeline | 30,467 | Miles of gathering line | 0.000 |
| Well Drilling | 0 | scfd of $CH_4$/oil well drilled | 7,437 | No. of oil wells drilled | 0.000 |
| Battery Pumps | 0.24 | scfd of $CH_4$/pump | 160,200 | No. of battery pumps | 0.014 |

| | | | | |
|---|---|---|---|---|
| **Combustion Emissions** | | | | **1.630** |
| Gas Engines | 0.08 scf $CH_4$/HP-hr | 15,945 | MMHP-hr | 1.276 |
| Heaters | 0.52 scf $CH_4$/bbl | 2113.0 | MBbl/yr | 0.001 |
| Well Drilling | 2,453 scf $CH_4$/well drilled | 7,437 | Oil wells drilled, 1995 | 0.018 |
| Flares | 20 scf $CH_4$per Mcf flared | 485,883 | Mcf flared/yr | 0.010 |
| Offshore Platforms, Gulf of Mexico | 481 scfd $CH_4$/platform | 1,832 | No. of oil platforms | 0.321 |
| Offshore Platforms, Other U.S. Areas | 481 scfd $CH_4$/platform | 23 | No. of oil platforms | 0.004 |
| **Process Upset Emissions** | | | | **0.548** |
| Platform Emergency Shutdowns | 256,888 scfy/platform | 1,855 | No. of platforms | 0.477 |
| Pressure Relief Valves | 35 scf/yr/PR valve | 176,498 | No. of PR valves | 0.006 |
| Well Blowouts Offshore | 5.0 MMscf/blowout | 2.25 | No. of blowouts/yr | 0.011 |
| Well Blowouts Onshore | 2.5 MMscf/blowout | 24.8 | No. of blowouts/yr | 0.062 |
| **Total (excluding stripper wells)** | | | | **52.42** |

## Table G-2: 2000 $CH_4$ Emissions from Petroleum Transportation

| Activity/Equipment | Emission Factor | Units | Activity Factor | Units | Emissions (Bcf/yr) |
|---|---|---|---|---|---|
| **Vented Emissions** | | | | | **0.233** |
| Tanks | 0.021 | scf $CH_4$/yr/bbl of crude delivered to refineries | 5,514 | MMbbl crude feed/yr | 0.114 |
| Truck Loading | 0.520 | scf $CH_4$/yr/bbl of crude transported by truck | 50.6 | MMbbl crude feed/yr | 0.026 |
| Marine Loading | 2.544 | scf $CH_4$/1000 gal. crude marine loadings | 29,581,881 | 1,000 gal./yr loaded | 0.075 |
| Rail Loading | 0.520 | scf $CH_4$/yr/bbl of crude transported by rail | 7.3 | MMbbl. Crude by rail/yr | 0.004 |
| Pump Station Maintenance | 36.80 | scf $CH_4$/station/yr | 490 | No. of pump stations | 0.000 |
| Pipeline Pigging | 39 | scfd of $CH_4$/pig station | 980 | No. of pig stations | 0.014 |
| **Fugitive Emissions** | | | | | **0.050** |
| Pump Stations | 25 | scf$CH_4$/mile/yr. | 48,990 | No. of miles of crude p/l | 0.001 |
| Pipelines | 0 | scf $CH_4$/bbl crude transported by pipeline | 7,551 | MM bbl crude piped | 0.000 |
| Floating Roof Tanks | 58,965 | scf $CH_4$/floating roof tank/yr. | 824 | No. of floating roof tanks | 0.049 |
| **Combustion Emissions** | | | | | **0.000** |
| Pump Engine Drivers | 0.24 | scf $CH_4$/hp-hr | NA | No. of hp-hrs | NA |
| Heaters | 0.521 | scf $CH_4$/bbl.burned | NA | No. of bbl. Burned | NA |
| **Total** | | | | | **0.283** |

## Table G-3: 2000 $CH_4$ Emissions from Petroleum Refining

| Activity/Equipment | Emission Factor | Units | Activity Factor | Units | Emissions (Bcf/yr) |
|---|---|---|---|---|---|
| **Vented Emissions** | | | | | **1.260** |
| Tanks | 20.6 | $scfCH_4$/Mbbl | 1,938 | Mbbl/cd heavy crude feed | 0.015 |
| System Blowdowns | 137 | $scfCH_4$/Mbbl | 15,108 | Mbbl/cd refinery feed | 0.754 |
| Asphalt Blowing | 2,555 | $scfCH_4$/Mbbl | 527 | Mbbl/cd production | 0.491 |
| **Fugitive Emissions** | | | | | **0.093** |
| Fuel Gas System | 439 | $McfCH_4$/refinery/yr | 158 | Refineries | 0.069 |
| Floating Roof Tanks | 587 | scf $CH_4$/floating roof tank/yr. | 767 | No. of floating roof tanks | 0.000 |
| Wastewater Treating | 1.88 | $scfCH_4$/Mbbl | 15,108 | Mbbl/cd refinery feed | 0.010 |
| Cooling Towers | 2.36 | $scfCH_4$/Mbbl | 15,108 | Mbbl/cd refinery feed | 0.013 |
| **Combustion Emissions** | | | | | **0.092** |
| Atmospheric Distillation | 3.61 | $scfCH_4$/Mbbl | 15,108 | Mbbl/cd refinery feed | 0.020 |
| Vacuum Distillation | 3.61 | $scfCH_4$/Mbbl | 6,916 | Mbbl/cd feed | 0.009 |
| Thermal Operations | 6.02 | $scfCH_4$/Mbbl | 2,004 | Mbbl/cd feed | 0.004 |
| Catalytic Cracking | 5.17 | $scfCH_4$/Mbbl | 5,175 | Mbbl/cd feed | 0.010 |
| Catalytic Reforming | 7.22 | $scfCH_4$/Mbbl | 3,296 | Mbbl/cd feed | 0.009 |
| Catalytic Hydrocracking | 7.22 | $scfCH_4$/Mbbl | 1,334 | Mbbl/cd feed | 0.004 |
| Hydrorefining | 2.17 | $scfCH_4$/Mbbl | 1,591 | Mbbl/cd feed | 0.001 |
| Hydrotreating | 6.50 | $scfCH_4$/Mbbl | 8,462 | Mbbl/cd feed | 0.020 |
| Alkylation/Polymerization | 12.6 | $scfCH_4$/Mbbl | 1,147 | Mbbl/cd feed | 0.005 |
| Aromatics/Isomeration | 1.80 | $scfCH_4$/Mbbl | 929 | Mbbl/cd feed | 0.001 |
| Lube Oil Processing | 0.00 | $scfCH_4$/Mbbl | 163 | Mbbl/cd feed | 0.000 |
| Engines | 0.006 | $scfCH_4$/hp-hr | 1,467 | MMhp-hr/yr | 0.008 |
| Flares | 0.189 | $scfCH_4$/Mbbl | 15,108 | Mbbl/cd refinery feed | 0.001 |
| **Total** | | | | | **1.445** |

## Table G-4: Summary of $CH_4$ Emissions from Petroleum Systems (Gg)

| Activity | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Production Field Operations** | **1,227** | **1,245** | **1,201** | **1,159** | **1,139** | **1,122** | **1,114** | **1,112** | **1,081** | **1,028** | **1,008** |
| Tank venting | 564 | 570 | 548 | 519 | 502 | 493 | 485 | 484 | 466 | 433 | 425 |
| Pneumatic device venting | 525 | 535 | 517 | 507 | 504 | 497 | 496 | 495 | 485 | 470 | 460 |
| Wellhead fugitives | 25 | 26 | 25 | 24 | 25 | 25 | 25 | 24 | 23 | 21 | 20 |
| Combustion & process upsets | 47 | 48 | 46 | 45 | 45 | 44 | 45 | 45 | 44 | 42 | 42 |
| Misc. venting & fugitives | 66 | 66 | 65 | 64 | 64 | 63 | 63 | 63 | 63 | 62 | 61 |
| **Crude Oil Transportation** | **7** | **6** | **6** | **6** | **6** | **6** | **6** | **6** | **6** | **6** | **5** |
| **Refining** | **25** | **24** | **24** | **25** | **25** | **25** | **26** | **27** | **27** | **27** | **28** |
| **Total** | **1,258** | **1,276** | **1,231** | **1,190** | **1,170** | **1,154** | **1,145** | **1,144** | **1,114** | **1,061** | **1,041** |

Note: Totals may not sum due to independent rounding.

# ANNEX H

## Methodology for Estimating $CO_2$ Emissions from Municipal Solid Waste Combustion

Emissions of $CO_2$ from MSW combustion include $CO_2$ generated by the combustion of plastics, synthetic rubber and synthetic fibers in MSW, and combustion of synthetic rubber and carbon black in tires. Combustion of MSW also results in emissions of $N_2O$. The methodology for calculating emissions from each of these waste combustion sources is described in this Annex.

### $CO_2$ from Plastics Combustion

In the report, *Characterization of Municipal Solid Waste in the United States* (EPA 2000c), the flows of plastics in the U.S. waste stream are reported for seven resin categories. The 1998 quantity generated, recovered, and discarded for each resin is shown in Table H-1. The EPA report does not provide estimates for individual materials landfilled and combusted, although it does provide such an estimate for the waste stream as a whole. To estimate the quantity of plastics landfilled and combusted, total discards were apportioned based on the proportions of landfilling and combustion for the entire U.S. waste stream in 1998 (76 percent and 24 percent, respectively). Emissions for 1990 through 1997 were calculated using the same approach. Figures for 1999 and 2000 are calculated using 1998 resin ratios and forecasted from 1998 figures for generation and recovery using a 2.85 percent annual growth rate for plastics generation and a 5.4 percent growth rate for the plastics recovery rate, based on reported trends (EPA 2000c).

**Table H-1: 1998 Plastics in the Municipal Solid Waste Stream by Resin (Gg)**

| Waste Pathway | PET | HDPE | PVC | LDPE/ LLDPE | PP | PS | Other | Total |
|---|---|---|---|---|---|---|---|---|
| **Generation** | 2,023 | 4,500 | 1,243 | 4,844 | 2,576 | 1,969 | 3,139 | **20,294** |
| **Recovery** | 354 | 399 | 0 | 127 | 154 | 18 | 45 | **1,098** |
| **Discard** | 1,669 | 4,101 | 1,243 | 4,717 | 2,422 | 1,950 | 3,094 | **19,196** |
| Landfill | 1,269 | 3,116 | 945 | 3,585 | 1,841 | 1,482 | 2,351 | **14,589** |
| Combustion | 401 | 984 | 298 | 1,132 | 581 | 468 | 742 | **4,607** |
| **Recovery*** | 17% | 9% | 0% | 3% | 6% | 1% | 1% | **5%** |
| **Discard*** | 83% | 91% | 100% | 97% | 94% | 99% | 99% | **95%** |
| Landfill* | 63% | 69% | 76% | 74% | 71% | 75% | 75% | **72%** |
| Combustion* | 20% | 22% | 24% | 23% | 23% | 24% | 24% | **23%** |

*As a percent of waste generation.
Note: Totals may not sum due to independent rounding. Abbreviations: PET (polyethylene terephthalate), HDPE (high density polyethylene), PVC (polyvinyl chloride), LDPE/LLDPE (linear low density polyethylene), PP (polypropylene), PS (polystyrene).

Fossil fuel-based $CO_2$ emissions for 1998 were calculated as the product of plastic combusted, carbon content, and fraction oxidized (see Table H-2). The carbon content of each of the six types of plastics is listed, with the value for "other plastics" assumed equal to the weighted average of the six categories. The fraction oxidized was assumed to be 98 percent.

**Table H-2: 1998 Plastics Combusted (Gg), Carbon Content (%), and Carbon Combusted (Gg)**

| Factor | PET | HDPE | PVC | LDPE/ LLDPE | PP | PS | Other | Total |
|---|---|---|---|---|---|---|---|---|
| Quantity Combusted | 401 | 984 | 298 | 1,132 | 581 | 468 | 742 | **4,607** |
| Carbon Content of Resin | 63% | 86% | 38% | 86% | 86% | 92% | 66% [a] | - |
| Carbon in Resin Combusted | 250 | 844 | 115 | 970 | 498 | 432 | 489 | **3,598** |
| **Emissions (Tg $CO_2$ Eq.)[b]** | 0.9 | 3.0 | 0.4 | 3.5 | 1.8 | 1.6 | 1.8 | **12.9** |

[a] Weighted average of other plastics produced in 1998 production.
[b] Assumes a fraction oxidized of 98 percent.

## $CO_2$ from Combustion of Synthetic Rubber and Carbon Black in Tires

Emissions from tire combustion require two pieces of information: the amount of tires combusted and the carbon content of the tires. The *Scrap Tire Use/Disposal Study 1998/1999 Update* (STMC 1999) reports that 114 million of the 270 million scrap tires generated in 1998 (approximately 42 percent of generation) were used for fuel purposes. Using STMC estimates of average tire composition and weight, the weight of synthetic rubber and carbon black in scrap tires was determined. Synthetic rubber in tires was estimated to be 90 percent carbon by weight, based on the weighted average carbon contents of the major elastomers used in new tire consumption (see Table H-3).[1] Carbon black is 100 percent carbon. Multiplying the proportion of scrap tires combusted by the total carbon content of the synthetic rubber and carbon black portion of scrap tires yielded $CO_2$ emissions, as shown in Table H-4. Note that the disposal rate of rubber in tires (0.4 Tg/yr) is smaller than the consumption rate for tires based on summing the elastomers listed in Table H-3 (1.3 Tg/yr); this is due to the fact that much of the rubber is lost through tire wear during the product's lifetime and due to the lag time between consumption and disposal of tires. Tire production and fuel use for 1999 and 2000 were extrapolated from trend data for 1994 through 1998.

**Table H-3: Elastomers Consumed in 1998 (Gg)**

| Elastomer | Consumed | Carbon Content | Carbon Equivalent |
|---|---|---|---|
| **Styrene butadiene rubber solid** | **908** | **91%** | **828** |
| For Tires | 743 | 91% | 677 |
| For Other Products* | 165 | 91% | 151 |
| **Polybutadiene** | **561** | **89%** | **499** |
| For Tires | 404 | 89% | 359 |
| For Other Products | 157 | 89% | 140 |
| **Ethylene Propylene** | **320** | **86%** | **274** |
| For Tires | 10 | 86% | 8 |
| For Other Products | 310 | 86% | 266 |
| **Polychloroprene** | **69** | **59%** | **40** |
| For Tires | 0 | 59% | 0 |
| For Other Products | 69 | 59% | 40 |
| **Nitrile butadiene rubber solid** | **87** | **77%** | **67** |
| For Tires | 1 | 77% | 1 |
| For Other Products | 86 | 77% | 67 |
| **Polyisoprene** | **78** | **88%** | **69** |
| For Tires | 65 | 88% | 57 |
| For Other Products | 13 | 88% | 12 |
| **Others** | **369** | **88%** | **324** |
| For Tires | 63 | 88% | 56 |
| For Other Products | 306 | 88% | 268 |
| **Total** | **2,392** | - | **2,101** |

*Used to calculate carbon content of non-tire rubber products in municipal solid waste.
- Not applicable

**Table H-4: Scrap Tire Constituents and $CO_2$ Emissions from Scrap Tire Combustion in 1998**

| Material | Weight of Material (Tg) | Carbon Content | Percent Combusted | Emissions (Tg $CO_2$ Eq.)* |
|---|---|---|---|---|
| Synthetic Rubber | 0.4 | 90% | 42% | 1.1 |
| Carbon Black | 0.5 | 100% | 42% | 1.7 |
| **Total** | **0.8** | - | - | **2.9** |

* Assumes a fraction oxidized of 98 percent.
- Not applicable

[1] The carbon content of tires (1,158,000 Tg) divided by for the mass of tires (1,285,000 Tg) equals 90 percent.

## $CO_2$ from Combustion of Synthetic Rubber in Municipal Solid Waste

Similar to the methodology for scrap tires, $CO_2$ emissions from synthetic rubber in MSW were estimated by multiplying the amount of rubber combusted by an average rubber carbon content. The amount of rubber in the MSW stream was estimated from data provided in the *Characterization of Municipal Solid Waste in the United States* (EPA 2000c). The report divides rubber found in MSW into three product categories: other durables (not including tires), non-durables (which includes clothing and footwear and other non-durables), and containers and packaging. Since there was negligible recovery for these product types, all the waste generated can be considered discarded. Similar to the plastics method, discards were apportioned based on the proportions of landfilling and combustion for the entire U.S. waste stream (76 percent and 24 percent, respectively). The report aggregates rubber and leather in the MSW stream; an assumed synthetic rubber content was assigned to each product type, as shown in Table H-5.[2] A carbon content of 85 percent was assigned to synthetic rubber for all product types, according to the weighted average carbon content of rubber consumed for non-tire uses (see Table H-4). For 1999 and 2000, waste generation values were not available so an average annual rate of increase in generation of synthetic rubber in MSW of 1.85 percent (based on statistics in EPA 2000c) was used to project generation in these years.

**Table H-5: Rubber and Leather in Municipal Solid Waste in 1998**

| Product Type | Generation (Gg) | Synthetic Rubber (%) | Carbon Content (%) | Emissions (Tg $CO_2$ Eq.)* |
|---|---|---|---|---|
| **Durables (not Tires)** | **2,141** | **100%** | **85%** | **1.6** |
| **Non-Durables** | **744** | **100%** | **85%** | **0.2** |
| Clothing and Footwear | 526 | 25% | 85% | 0.1 |
| Other Non-Durables | 218 | 75% | 85% | 0.1 |
| **Containers and Packaging** | **18** | **100%** | **85%** | **+** |
| **Total** | **2,903** | **-** | **-** | **1.8** |

* Assumes a fraction oxidized of 98 percent.
+ Less than 0.05 Tg $CO_2$ Eq.
- Not applicable

## $CO_2$ from Combustion of Synthetic Fibers

Carbon dioxide emissions from synthetic fibers were estimated as the product of the amount of synthetic fiber discarded annually and the average carbon content of synthetic fiber. Fiber in the MSW stream was estimated from data provided in the *Characterization of Municipal Solid Waste in the United States* (EPA 2000c) for textiles. The amount of synthetic fiber in MSW was estimated by subtracting (a) the amount recovered from (b) the waste generated (see Table H-6). As with the other materials in the MSW stream, discards were apportioned based on the proportions of landfilling and combustion for the entire U.S. waste stream (76 percent and 24 percent, respectively). It was assumed that approximately 55 percent of the fiber was synthetic in origin, based on information received from the Fiber Economics Bureau (DeZan 2000). An average carbon content of 70 percent was assigned to synthetic fiber using the production-weighted average of the carbon contents of the four major fiber types (polyester, nylon, olefin, and acrylic) produced in 1998 (see Table H-7). The equation relating $CO_2$ emissions to the amount of textiles combusted is shown below. Since 1999 and 2000 values were not provided in the *Characterization* report, generation and recovery rates were forecast by applying their respective average annual growth rates for 1990 through 1998 to the 1998 values.

$CO_2$ Emissions from the Combustion of Synthetic Fibers = Annual Textile Combustion (Gg) ×

(Percent of Total Fiber that is Synthetic) × (Average Carbon Content of Synthetic Fiber) ×

(44g $CO_2$/12 g C)

[2] As a biogenic material, the combustion of leather is assumed to have no net carbon dioxide emissions.

**Table H-6: Textiles in MSW (Gg)**

| Year | Generation | Recovery | Discards | Combustion |
|---|---|---|---|---|
| 1990 | 2,884 | 328 | 2,557 | 614 |
| 1991 | 3,064 | 341 | 2,723 | 654 |
| 1992 | 3,225 | 354 | 2,901 | 696 |
| 1993 | 3,458 | 368 | 3,090 | 742 |
| 1994 | 3,674 | 382 | 3,291 | 790 |
| 1995 | 3,674 | 447 | 3,227 | 774 |
| 1996 | 3,832 | 472 | 3,361 | 807 |
| 1997 | 4,090 | 526 | 3,564 | 855 |
| 1998 | 4,269 | 551 | 3,781 | 892 |
| 1999* | 4,372 | 566 | 3,805 | 913 |
| 2000* | 4,490 | 584 | 3,906 | 937 |

*Projected using 1998 data and the 1997 to 2000 Average Annual Growth Rate for Generation (EPA 2000c).

**Table H-7: Synthetic Fiber Production in 1998**

| Fiber | Production (Tg) | Carbon Content | Carbon Equivalent (Tg $CO_2$ Eq.) |
|---|---|---|---|
| Polyester | 1.8 | 63% | 4.1 |
| Nylon | 1.3 | 64% | 3.0 |
| Olefin | 1.3 | 86% | 4.1 |
| Acrylic | 0.2 | 68% | 0.5 |
| **Total** | **4.6** | - | **11.7** |

- Not applicable

## $N_2O$ from Municipal Solid Waste Combustion

Estimates of $N_2O$ emissions from MSW combustion in the United States are based on the methodology outlined in the EPA's Compilation of Air Pollutant Emission Factors (EPA 1997). According to this methodology, emissions of $N_2O$ from MSW combustion are the product of the mass of MSW combusted, an emission factor of $N_2O$ emitted per unit mass of waste combusted, and an $N_2O$ emissions control removal efficiency. For MSW combustion in the United States, an emission factor of 30 g $N_2O$/metric ton MSW and an estimated emissions control removal efficiency of zero percent were used. No information was available on the mass of waste combusted in 2000. It was assumed for the purposes of this calculation that the mass of waste combusted in 2000 was the same as estimated for 1999.

# ANNEX I

## Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military

Bunker fuel emissions estimates for the Department of Defense (DoD) were developed using data primarily generated by the Defense Energy Support Center for aviation and naval fuels (DESC 2001). The Defense Energy Support Center (DESC) of the Defense Logistics Agency (DLA) prepared a special report based on data in the Defense Fuels Automated Management System (DFAMS). DFAMS contains data for 1995 through 2000, but the data set was not complete for years prior to 1995. Fuel quantities for 1990 to 1994 were estimated based on a back-calculation of the 1995 DFAMS values using DLA aviation and marine fuel procurement data. The back-calculation was refined last year to better account for the jet fuel conversion from JP4 to JP8 that occurred within the DoD between 1992 and 1995. Data for marine fuel consumption in 2000 were obtained from the Naval Operations Navy Strategic Mobility/Combat Logistics Division (N42 2001).

Gasoline and diesel fuel totals presented in Table I-1 were estimated using data provided by the military services. The 1991 through 1995 data points were interpolated from the inventory data. The 1997 through 1999 motor gasoline and diesel fuel data were extrapolated from the 1996 inventory data. Growth factors used for other diesel and gasoline were 5.2 percent and -21.1 percent, respectively. Data sets for other diesel and gasoline consumed by the military in 2000 were estimated based on Air Force ground fuels consumption trends. This method produced a result that was more consistent with expected consumption for 2000.

### Step 1: Omit Extra-Territorial Fuel Deliveries

Beginning with the complete DFAMS data set for each year, the first step in the development of DoD related emissions from international bunker fuels was to identify data that would be representative of international bunker fuel consumption as that term is defined by decisions of the UNFCCC (i.e., fuel sold to a vessel, aircraft, or installation within the United States or its territories and used in international maritime or aviation transport). Therefore, fuel data were categorized by the location of fuel delivery in order to identify and omit all extra-territorial fuel transactions/deliveries (i.e., sales abroad). Table I-1 displays the fuels that remain at the completion of Step 1, summarized by fuel type.

### Step 2: Omit Fuel Transactions Received by Military Services that are not Considered to be International Bunker Fuels

Next, fuel transaction/delivery records were sorted by Military Service. The following assumptions were made regarding bunker fuel use by Service, leaving only the Navy and Air Force as users of military international bunker fuels.

- Only fuel delivered to a ship, aircraft, or installation in the United States can be a potential international bunker fuel. Fuel consumed in international aviation or marine transport should be included in the bunker fuel estimate of the country where the ship or aircraft was fueled. Fuel consumed entirely within a country's borders is not bunker fuel.
- Based on discussions with the Army staff, only an extremely small percentage of Army aviation emissions, and none of its watercraft emissions, qualified as bunker fuel emissions. The magnitude of these emissions was judged to be insignificant when compared to Air Force and Navy emissions. Based on this, Army bunker fuel emissions are assumed to be zero.
- Marine Corps aircraft operating while embarked consume fuel reported as delivered to the Navy. Bunker fuel emissions from embarked Marine Corps aircraft are reported in the Navy bunker fuel estimates. Bunker fuel emissions from other Marine Corps operations and training are assumed to be zero.
- Bunker fuel emissions from other DoD and non-DoD activities (i.e., other federal agencies) that purchase fuel from DESC are assumed to be zero.

### Step 3: Omit Land-Based Fuels

Navy and Air Force land-based fuel consumption (i.e., fuel not used by ships or aircraft) were also omitted. The remaining fuels, listed below, were potential military international bunker fuels.

- Marine: naval distillate fuel (F76), marine gas oil (MGO), and intermediate fuel oil (IFO).
- Aviation: jet fuels (JP8, JP5, JP4, JAA, JA1, and JAB).

At the completion of step 3 of the 2000 estimate, it was apparent that the Navy maritime data provided by DESC were abnormal compared to those data for each year from 1995 to 1999. The Navy fuels and logistics office identified a separate data set that was used to compare the DESC 2000 data for Navy maritime fuel consumption. After comparing the 2000 data from DESC to that from the Navy, it was determined that the Navy data (N42 2001) should be used as the source of the 2000 maritime values. However, DoD will continue to investigate the 2000 maritime data from DESC, which Navy fuels experts consider an anomaly.

### Step 4: Determine Bunker Fuel Percentages

Next it was necessary to determine what percent of the marine and aviation fuels were used as international bunker fuels. Military aviation bunkers include international operations (i.e., sorties that originate in the United States and terminate in a foreign country), 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 (e.g., anti-submarine warfare flights). For the Air Force, a bunker fuel weighted average was calculated based on flying hours by major command. International flights were weighted by an adjustment factor to reflect the fact that they typically last longer than domestic flights. In addition, a fuel use correction factor was used to account for the fact that transport aircraft burn more fuel per hour of flight than most tactical aircraft. The Air Force bunker fuel percentage was determined to be 13.2 percent. This percentage was multiplied by total annual Air Force aviation fuel delivered for U.S. activities, producing an estimate for international bunker fuel consumed by the U.S. Air Force. The naval aviation bunker fuel percentage of total fuel was calculated using flying hour data from *Chief of Naval Operations Flying Hour Projection System Budget Analysis Report for FY 1998* (N45 1998), and estimates of bunker fuel percent of flights provided by the fleet. The naval aviation bunker fuel percentage, determined to be 40.4 percent, was multiplied by total annual Navy aviation fuel delivered for U.S. activities, yielding total Navy aviation bunker fuel consumed.

For marine bunkers, fuels consumed while ships were underway were assumed to be bunker fuels. For 2000, the Navy reported that 79 percent of vessel operations were underway, while the remaining 21 percent of operations occurred in port (i.e., pierside). Therefore, the Navy maritime bunker fuel percentage was determined to be 79 percent for 2000. The percentage of time underway may vary from year-to-year and the 2000 value represents a change from previous years, for which the bunker fuel percentage of 87 percent was applied. Table I-2 and Table I-3 display DoD bunker fuel totals for the Navy and Air Force.

### Step 5: Calculate Emissions from Military International Bunker Fuels

Bunker fuel totals were multiplied by appropriate emission factors to determine greenhouse gas emissions (see Table I-4 and Table I-5).

The rows labeled 'U.S. Military' and 'U.S. Military Naval Fuels' within Table 2-43 and Table 2-44 in the Energy Chapter were based on the international bunker fuel totals provided in Table I-2 and Table I-3, below. Total $CO_2$ emissions from military bunker fuels are presented in Table I-6. Carbon dioxide emissions from aviation bunkers and distillate marine bunkers presented in Table 2-42 are the total of military plus civil aviation and civil marine bunker fuels, respectively. The military component of each total is based on fuels tallied in Table I-2 and Table I-3.

## Table I-1: Transportation Fuels from Domestic Fuel Deliveries[a] (Million Gallons)

| Vehicle Type/Fuel | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Aviation** | **4,598.45** | **4,562.84** | **3,734.49** | **3,610.85** | **3,246.23** | **3,099.93** | **2,941.91** | **2,697.28** | **2,764.76** | **2,670.28** | **2,711.16** |
| JP8 | 285.75 | 283.54 | 234.46 | 989.38 | 1,598.07 | 2,182.80 | 2,253.15 | 2,083.64 | 2,145.89 | 2,101.52 | 2,169.42 |
| JP5 | 1,025.36 | 1,017.42 | 832.71 | 805.14 | 723.84 | 691.22 | 615.83 | 552.77 | 515.56 | 505.50 | 472.10 |
| Other Jet Fuels | 3,287.31 | 3,261.86 | 2,667.29 | 1,816.30 | 924.30 | 225.89 | 72.92 | 60.86 | 103.29 | 63.25 | 69.65 |
| Aviation Gasoline | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | + | 0.02 | 0.01 | 0.01 |
| **Marine** | **686.80** | **632.61** | **646.18** | **589.37** | **478.59** | **438.91** | **493.34** | **639.85** | **674.22** | **598.86** | **680.19** |
| Middle Distillate (MGO) | + | + | + | + | + | + | 38.52 | 47.48 | 51.14 | 49.22 | 97.61 |
| Naval Distillate (F76) | 686.80 | 632.61 | 646.18 | 589.37 | 478.59 | 438.91 | 448.96 | 583.41 | 608.39 | 542.94 | 549.57 |
| Intermediate Fuel Oil (IFO)[b] | + | + | + | + | + | + | 5.86 | 8.95 | 14.69 | 6.70 | 33.01 |
| **Other** | **717.11** | **590.41** | **491.68** | **415.10** | **356.06** | **310.95** | **276.90** | **251.66** | **233.47** | **220.92** | **201.45** |
| Diesel | 93.04 | 97.88 | 102.96 | 108.31 | 113.94 | 119.86 | 126.09 | 132.64 | 139.53 | 146.78 | 126.63 |
| Gasoline | 624.07 | 492.53 | 388.72 | 306.78 | 242.12 | 191.09 | 150.81 | 119.02 | 93.94 | 74.14 | 74.81 |
| **Total (Including Bunkers)** | **6,002.37** | **5,785.85** | **4,872.34** | **4,615.32** | **4,080.89** | **3,849.78** | **3,712.15** | **3,588.79** | **3,672.45** | **3,490.06** | **3,592.80** |

Note: Totals may not sum due to independent rounding.

[a] Includes fuel consumption in United States and U.S. Territories.

[b] Intermediate fuel oil (IFO 180 and IFO 380) is a blend of distillate and residual fuels. IFO is used by the Military Sealift Command.

+ Does not exceed 0.005 million gallons.

**Table I-2: Total U.S. Military Aviation Bunker Fuel (Million Gallons)**

| Fuel Type/Service | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **JP8** | **56.74** | **56.30** | **46.40** | **145.33** | **223.99** | **300.40** | **308.81** | **292.01** | **306.39** | **301.35** | **307.57** |
| Navy | 56.74 | 56.30 | 46.08 | 44.56 | 40.06 | 38.25 | 39.84 | 46.92 | 53.81 | 55.46 | 53.38 |
| Air Force | + | + | 0.32 | 100.77 | 183.93 | 262.15 | 268.97 | 245.09 | 252.59 | 245.89 | 254.19 |
| **JP5** | **370.53** | **367.66** | **300.92** | **290.95** | **261.57** | **249.78** | **219.40** | **194.16** | **184.38** | **175.37** | **160.35** |
| Navy | 365.29 | 362.46 | 296.66 | 286.83 | 257.87 | 246.25 | 216.09 | 191.15 | 181.36 | 170.59 | 155.60 |
| Air Force | 5.25 | 5.21 | 4.26 | 4.12 | 3.70 | 3.54 | 3.31 | 3.01 | 3.02 | 4.77 | 4.74 |
| **JP4** | **420.77** | **417.52** | **341.40** | **229.64** | **113.11** | **21.50** | **1.05** | **0.05** | **0.03** | **0.02** | **0.01** |
| Navy | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | + | + | + | + | + |
| Air Force | 420.75 | 417.50 | 341.39 | 229.62 | 113.10 | 21.49 | 1.05 | 0.05 | 0.03 | 0.02 | 0.01 |
| **JAA** | **13.70** | **13.60** | **11.13** | **10.76** | **9.67** | **9.24** | **10.27** | **9.42** | **10.84** | **10.78** | **12.46** |
| Navy | 8.45 | 8.39 | 6.86 | 6.64 | 5.97 | 5.70 | 6.58 | 5.88 | 6.63 | 6.32 | 7.95 |
| Air Force | 5.25 | 5.21 | 4.27 | 4.12 | 3.71 | 3.54 | 3.69 | 3.54 | 4.21 | 4.47 | 4.51 |
| **JA1** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **0.01** | **+** | **0.03** |
| Navy | + | + | + | + | + | + | + | + | + | + | 0.02 |
| Air Force | + | + | + | + | + | + | + | + | 0.01 | + | 0.01 |
| **JAB** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** |
| Navy | + | + | + | + | + | + | + | + | + | + | + |
| Air Force | + | + | + | + | + | + | + | + | + | + | + |
| **Navy Subtotal** | **430.50** | **427.17** | **349.62** | **338.04** | **303.91** | **290.21** | **262.51** | **243.95** | **241.80** | **232.37** | **216.90** |
| **Air Force Subtotal** | **431.25** | **427.91** | **350.23** | **338.63** | **304.44** | **290.72** | **277.02** | **251.70** | **259.86** | **255.14** | **263.50** |
| **Total** | **861.75** | **855.08** | **699.85** | **676.68** | **608.35** | **580.93** | **539.53** | **495.65** | **501.66** | **487.52** | **480.40** |

+ Does not exceed 0.005 million gallons.
Note: Totals may not sum due to independent rounding.

**Table I-3: Total U.S. DoD Maritime Bunker Fuel (Million Gallons)**

| Marine Distillates | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Navy - MGO | + | + | + | + | + | + | 30.34 | 35.57 | 31.88 | 39.74 | 77.11 |
| Navy - F76 | 522.37 | 481.15 | 491.47 | 448.27 | 364.01 | 333.82 | 331.88 | 441.65 | 474.23 | 465.97 | 434.16 |
| Navy - IFO | + | + | + | + | + | + | 4.63 | 7.07 | 11.61 | 5.29 | 26.08 |
| **Total** | **522.37** | **481.15** | **491.47** | **448.27** | **364.01** | **333.82** | **366.85** | **484.29** | **517.72** | **511.00** | **537.35** |

+ Does not exceed 0.005 million gallons.
Note: Totals may not sum due to independent rounding.

**Table I-4: Aviation and Marine Carbon Contents (Tg Carbon/QBtu) and Fraction Oxidized**

| Mode (Fuel) | Carbon Content Coefficient | Fraction Oxidized |
|---|---|---|
| Aviation (Jet Fuel) | variable | 0.99 |
| Marine (Distillate) | 19.95 | 0.99 |

**Table I-5: Annual Variable Carbon Content Coefficient for Jet Fuel (Tg Carbon/QBtu)**

| Fuel | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jet Fuel | 19.40 | 19.40 | 19.39 | 19.37 | 19.35 | 19.34 | 19.33 | 19.33 | 19.33 | 19.33 | 19.33 |

**Table I-6: Total U.S. DoD $CO_2$ Emissions from Bunker Fuels (Tg $CO_2$ Eq.)**

| Mode | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Aviation | 8.2 | 8.1 | 6.6 | 6.4 | 5.8 | 5.6 | 5.2 | 4.8 | 4.8 | 4.7 | 4.6 |
| Marine | 5.2 | 4.8 | 4.9 | 4.5 | 3.7 | 3.4 | 3.7 | 4.9 | 5.2 | 5.1 | 5.4 |
| **Total** | **13.4** | **12.9** | **11.6** | **10.9** | **9.5** | **8.9** | **8.9** | **9.6** | **10.0** | **9.8** | **10.0** |

Note: Totals may not sum due to independent rounding.

# ANNEX J

## Methodology for Estimating HFC, and PFC Emissions from Substitution of Ozone Depleting Substances

The Vintaging Model was developed as a tool for estimating the annual chemical emissions from industrial sectors that have historically used ozone depleting substances (ODSs) in their products. Under the terms of the Montreal Protocol and the Clean Air Act Amendments of 1990, the domestic production of ODSs, CFCs, halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs) – has been drastically reduced, forcing these industrial sectors to transition to more ozone friendly chemicals. As these industries have moved toward ODSs alternatives such as hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), the Vintaging Model has evolved into a tool for estimating the rise in consumption and emissions of these alternatives, and the decline of ODS consumption and emissions.

The Vintaging Model estimates emissions from six industrial sectors: refrigeration and air-conditioning, foams, aerosols, solvents, fire extinguishing, and sterilization. Within these sectors, there are over 40 independently modeled end-uses. The model requires information on the market growth for each of the end-uses, as well as a history of the market transition from ODSs to alternatives. As ODSs are phased out, a percentage of the market share originally filled by the ODSs is allocated to each of its substitutes.

The model, named for its method of tracking the emissions of annual "vintages" of new equipment that enter into service, is a "bottom-up" model. It models the consumption of chemicals based on estimates of the quantity of equipment or products sold, serviced, and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment. The Vintaging Model makes use of this market information to build an inventory of the in-use stocks of the equipment in each of the end-uses. Emissions are estimated by applying annual leak rates, service emission rates, and disposal emission rates to each population of equipment. By aggregating the emission and consumption output from the different end-uses, the model produces estimates of total annual use and emissions of each chemical.

The Vintaging Model synthesizes data from a variety of sources, including data from the ODS Tracking System maintained by the Global Programs Division and information from submissions to EPA under the Significant New Alternatives Policy (SNAP) program. Published sources include documents prepared by the United Nations Environment Programme (UNEP) Technical Options Committees, reports from the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), and proceedings from the international conferences on ozone protection technologies and Earth Technologies Forum. EPA also coordinates extensively with numerous trade associations and individual companies. For example, the Alliance for Responsible Atmospheric Policy, the Air-Conditioning and Refrigeration Institute, the Association of Home Appliance Manufacturers, the American Automobile Manufacturers Association, and many of their member companies, have provided valuable information over the years. In some instances the unpublished information that the EPA uses in the model is classified as Confidential Business Information (CBI). The annual emissions inventories of chemicals are aggregated in such a way that CBI cannot be inferred. Full public disclosure of the inputs to the Vintaging Model would jeopardize the security of the CBI that has been entrusted to the EPA.

The following sections discuss the forms of the emission estimating equations used in the Vintaging Model for each broad end-use category. These equations are applied separately for each chemical used within each of approximately 40 different end-uses. In the majority of these end-uses, more than one ODS substitute chemical is used.

In general, the modeled emissions are a function of the amount of chemical consumed in each end-use market. Estimates of the consumption of ODS alternatives can be inferred by extrapolating forward in time from the amount of regulated ODSs used in the early 1990s. Using data gleaned from a variety of sources, assessments are made regarding which alternatives will likely be used, and what fraction of the ODS market in each end-use will be captured by a given alternative. By combining this with estimates of the total end-use market growth, a consumption value can be estimated for each chemical used within each end-use.

Alternatively, "top-down" information on total U.S. consumption of a given chemical is sometimes available. This data can be used by estimating the fraction of this total that is consumed within each end-use. These allocation schemes are guided by EPA's synthesis of the data available through the aforementioned sources.

## Methodology

The methodology used by the vintaging model to calculate emissions varies by end-use sector. The methodologies and specific equations used by end-use sector are presented below.

### Refrigeration and Air-Conditioning

For refrigeration and air conditioning products, emission calculations are split into two categories: emissions during equipment lifetime, which arise from annual leakage and service losses, and disposal emissions, which occur at the time of discard. Two separate steps are required to calculate the lifetime emissions from leakage and service, and the emissions resulting from disposal of the equipment. These lifetime emissions and disposal emissions are summed to calculate the total emissions from refrigeration and air-conditioning. As new technologies replace older ones, it is generally assumed that there are improvements in their leak, service, and disposal emission rates.

#### Step 1: Calculate lifetime emissions

Lifetime emissions from any piece of equipment include both the amount of chemical leaked during equipment operation and during service recharges. Emissions from leakage and servicing can be expressed as follows:

$$Es_j = (l_a + l_s) \times \sum Qc_{j-i+1} \quad for\ i=1 \rightarrow k$$

Where,

$Es$ = Emissions from Equipment Serviced. Emissions in year $j$ from normal leakage and servicing (including recharging) of equipment.

$l_a$ = Annual Leak Rate. Average annual leak rate during normal equipment operation (expressed as a percentage of total chemical charge).

$l_s$ = Service Leak Rate. Average leakage during equipment servicing (expressed as a percentage of total chemical charge).

$Qc$ = Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in a given year, $j$, by weight.

$K$ = Lifetime. The average lifetime of the equipment.

#### Step 2: Calculate disposal emissions

The disposal emission equations assume that a certain percentage of the chemical charge will be emitted to the atmosphere when that vintage is discarded. Disposal emissions are thus a function of the quantity of chemical contained in the retiring equipment fleet and the proportion of chemical released at disposal:

$$Ed_j = Qc_{j-k+1} \times [1 - (rm \times rc)]$$

Where,

$Ed$ = Emissions from Equipment Disposed. Emissions in year $j$ from the disposal of equipment.

$Qc$ = Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in a given year, $j$, by weight.

$rm$ = Chemical Remaining. Amount of chemical remaining in equipment at the time of disposal (expressed as a percentage of total chemical charge)

$rc$ = Chemical Recovery Rate. Amount of chemical that is recovered just prior to disposal (expressed as a percentage of chemical remaining at disposal *(rm)*)

$k$ = Lifetime. The average lifetime of the equipment.

#### Step 3: Calculate total emissions

Finally, lifetime and disposal emissions are summed to provide an estimate of total emissions.

$$E_j = Es_j + Ed_j$$

Where,

$E$ = Total Emissions. Emissions from refrigeration and air conditioning equipment in year $j$.

$Es$ = Emissions from Equipment Serviced. Emissions in year $j$ from normal leakage and servicing (recharging) of equipment.

$Ed$ = Emissions from Equipment Disposed. Emissions in year $j$ from the disposal of equipment.

### Aerosols

All HFCs and PFCs used in aerosols are assumed to be emitted in the year of manufacture. Since there is currently no aerosol recycling, it is assumed that all of the annual production of aerosol propellants is released to the atmosphere. The following equation describes the emissions from the aerosols sector.

$$E_j = Qc_j$$

Where,

$E$ = Emissions. Total emissions of a specific chemical in year $j$ from use in aerosol products, by weight.

$Qc$ = Quantity of Chemical. Total quantity of a specific chemical contained in aerosol products sold in year $j$, by weight.

### Solvents

Generally, most solvents are assumed to remain in the liquid phase and are not emitted as gas. Thus, emissions are considered "incomplete," and are a fixed percentage of the amount of solvent consumed in a year. The remainder of the consumed solvent is assumed to be reused or disposed without being released to the atmosphere. The following equation calculates emissions from solvent applications.

$$E_j = l \times Qc_j$$

Where,

$E$ = Emissions. Total emissions of a specific chemical in year $j$ from use in solvent applications, by weight.

$L$ = Percent Leakage. The percentage of the total chemical that is leaked to the atmosphere.

$Qc$ = Quantity of Chemical. Total quantity of a specific chemical sold for use in solvent applications in the year j, by weight.

### Fire Extinguishing

Total emissions from fire extinguishing are assumed, in aggregate, to equal a percentage of the total quantity of chemical in operation at a given time. For modeling purposes, it is assumed that fire extinguishing equipment leaks at a constant rate for an average equipment lifetime. This percentage varies for streaming and flooding equipment.

**Step 1: Calculate emissions from streaming equipment**

$$E_j = l_{se} \times \sum Qc_{j-i+1} \quad for\ i=1 \rightarrow k$$

Where,

$E$ = Emissions. Total emissions of a specific chemical in year $j$ for streaming fire extinguishing equipment, by weight.

$l_{se}$ = Percent Leakage. The percentage of the total chemical in operation that is leaked to the atmosphere.

$Qc$ = Quantity of Chemical from streaming equipment. Total amount of a specific chemical used in new streaming fire extinguishing equipment in a given year, $j$, by weight.

$k$ = Lifetime. The average lifetime of the equipment.

**Step 2: Calculate emissions from flooding equipment**

$$E_j = l_{fe} \times \sum Qc_{j-i+1} \quad for\ i=1 \rightarrow k$$

Where,

$E$ = Emissions. Total emissions of a specific chemical in year $j$ for flooding fire extinguishing equipment, by weight.

$l_f$ = Percent Leakage. The percentage of the total chemical in operation that is leaked to the atmosphere.

$Qc$ = Quantity of Chemical from flooding equipment. Total amount of a specific chemical used in new flooding fire extinguishing equipment in a given year, $j$, by weight.

$k$ = Lifetime. The average lifetime of the equipment.

### Foam Blowing

Foams are given emission profiles depending on the foam type (open cell or closed cell). Open cell foams are assumed to be 100 percent emissive in the year of manufacture. Closed cell foams are assumed to emit a portion of their total HFC or PFC content upon manufacture, a portion at a constant rate over the lifetime of the foam, and a portion at disposal.

**Step 1: Calculate emissions from open-cell foam**

Emissions from open-cell foams are calculated using the following equation.

$$E_j = Qc_j$$

Where,

$E$ = Emissions. Total emissions of a specific chemical in year $j$ used for open-cell foam blowing, by weight.

$Qc$ = Quantity of Chemical. Total amount of a specific chemical used for open-cell foam blowing in year $j$, by weight.

**Step 2: Calculate emissions from closed-cell foam**

Emissions from closed-cell foams are calculated using the following equation.

$$E_j = \sum (ef_i \times Qc_{j-i+1}) \quad for\ i=1 \rightarrow k$$

Where,

$E$ = Emissions. Total emissions of a specific chemical in year $j$ for closed-cell foam blowing, by weight.

$ef$ = Emission Factor. Percent of foam's original charge emitted in each year ($1 \rightarrow k$). This emission factor is generally variable, including a rate for manufacturing emissions (occurs in the first year of foam life), annual emissions (every year throughout the foam lifetime), and disposal emissions (occurs during the final year of foam life).

$Qc$ = Quantity of Chemical. Total amount of a specific chemical used in closed-cell foams in year $j$.

$k$ = Lifetime. Average lifetime of foam product.

### Sterilization

For sterilization applications, all chemicals that are used in the equipment in any given year are assumed to be emitted in that year, as shown in the following equation.

$$E_j = Qc_j$$

Where,

$E$ = Emissions. Total emissions of a specific chemical in year $j$ from use in sterilization equipment, by weight.

$Qc$ = Quantity of Chemical. Total quantity of a specific chemical used in sterilization equipment in year $j$, by weight.

## Model Output

By repeating these calculations for each year, the Vintaging Model creates annual profiles of use and emissions for ODS and ODS substitutes. The results can be shown for each year in two ways: 1) on a chemical-by-chemical basis, summed across the end-uses, or 2) on an end-use basis. Values for use and emissions are calculated both in metric tons and in teragrams of carbon dioxide equivalents (Tg $CO_2$ Eq.). The conversion of metric tons of chemical to Tg $CO_2$ Eq. is accomplished through a linear scaling of tonnage by the global warming potential (GWP) of each chemical.

Throughout its development, the Vintaging Model has undergone annual modifications. As new or more accurate information becomes available, the model is adjusted in such a way that both past and future emission estimates are often altered.

# ANNEX K

## Methodology for Estimating $CH_4$ Emissions from Enteric Fermentation

Methane emissions from enteric fermentation were estimated for five livestock categories: cattle, horses, sheep, swine and goats. Emissions from cattle represent the majority of U.S. emissions, consequently, the more detailed IPCC Tier 2 methodology was used to estimate emissions from cattle and the IPCC Tier 1 methodology was use to estimate emissions from the other types of livestock.

### Estimate Methane Emissions from Cattle

This section describes the process used to estimate methane emissions from cattle enteric fermentation. A model based on recommendations provided in IPCC/UNEP/OECD/IEA (1997) and IPCC (2000) was developed that uses information on population, energy requirements, digestible energy, and methane conversion rates to estimate methane emissions. The emission methodology consists of the following three steps: (1) characterize the cattle population to account for animal population categories with different emissions profiles; (2) characterize cattle diets to generate information needed to estimate emissions factors; and (3) estimate emissions using these data and the IPCC Tier 2 equations.

#### Step 1: Characterize U.S. Cattle Population

Each stage in the cattle lifecycle was modeled to simulate the cattle population from birth to slaughter. This level of detail accounts for the variability in methane emissions associated with each life stage. Given that the time in which cattle can be in a stage can be less than one year (e.g., beef calves are weaned at 7 months), the stages are modeled on a per month basis. The type of cattle use also impacts methane emissions (e.g., beef versus dairy). Consequently, cattle life stages were modeled for several categories of dairy and beef cattle. These categories are listed in Table K-1.

**Table K-1: Cattle Population Categories Used for Estimating Methane Emissions**

| Dairy Cattle | Beef Cattle |
|---|---|
| Calves | Calves |
| Heifer Replacements | Heifer Replacements |
| Cows | Heifer and Steer Stockers |
| | Animals in Feedlots |
| | Cows |
| | Bulls |

The key variables tracked for each of these cattle population categories (except bulls[1]) are as follows:

- *Calving rates:* The number of animals born on a monthly basis was used to initiate monthly cohorts and to determine population age structure. The number of calves born each month was obtained by multiplying annual births by the percentage of births by month. Annual birth information was taken from USDA (2001a). Average percentage of births by month for beef from USDA (USDA/APHIS/VS 1998, 1994, 1993) were used for 1990 through 2000. For dairy animals, birth rates were assumed constant throughout the year. Whether calves were born to dairy or beef cows was estimated using the dairy cow calving rate and the total dairy cow population to determine the percent of births attributable to dairy cows, with the remainder assumed to be attributable to beef cows.
- *Average weights and weight gains:* Average weights were tracked for each monthly age group using starting weight and monthly weight gain estimates. Weight gain (i.e., pounds per month) was estimated based on weight gain needed to reach a set target weight, divided by the number of months remaining before target weight was achieved. Birth weight was assumed to be 88 pounds for both beef and dairy

[1] Only end-of-year census population statistics and a national emission factors are used to estimate methane emissions from the bull population.

animals. Weaning weights were estimated to range from 480 to 575 pounds. Other reported target weights were available for 12, 15, 24, and 36 month-old animals. Live slaughter weights were derived from dressed slaughter weight data (USDA 2001c, 2000c). Live slaughter weight was estimated as dressed weight divided by 0.63.

- *Feedlot placements:* Feedlot placement statistics were available that specify placement of animals from the stocker population into feedlots on a monthly basis by weight class. The model used these data to shift a sufficient number of animals from the stocker cohorts into the feedlot populations to match the reported data. After animals are placed in feedlots they progress through two steps. First, animals spend time on a step-up diet to become acclimated to the new feed type. Animals are then switched to a finishing diet for a period of time before they are slaughtered. The length of time an animal spends in a feedlot depends on the start weight (i.e., placement weight), the rate of weight gain during the start-up and finishing phase of diet, and the end weight (as determined by weights at slaughter). Weight gain during start-up diets is estimated to be 2.8 to 3 pounds per day. Weight gain during finishing diets is estimated to be 3 to 3.3 pounds per day (Johnson 1999). All animals are estimated to spend 25 days in the step-up diet phase (Johnson 1999). Length of time finishing can be calculated based on start weight, weight gain per day, and target slaughter weight.

- *Pregnancy and lactation:* Energy requirements and hence, composition of diets, level of intake, and emissions for particular animals, are greatly influenced by whether the animal is pregnant or lactating. Information is therefore needed on the percentage of all mature animals that are pregnant each month, as well as milk production, to estimate methane emissions. A weighted average percent of pregnant cows each month was estimated using information on births by month and average pregnancy term. For beef cattle, a weighted average total milk production per animal per month was estimated using information on typical lactation cycles and amounts (NRC 1999), and data on births by month. This results in a range of weighted monthly lactation estimates expressed as lbs/animal/month. The monthly estimates from January to December are 3.33, 5.06, 8.70, 12.01, 13.58, 13.32, 11.67, 9.34, 6.88, 4.45, 3.04, and 2.77. Monthly estimates for dairy cattle were taken from USDA monthly milk production statistics.

- *Death rates:* This factor is applied to all heifer and steer cohorts to account for death loss within the model on a monthly basis. The death rates are estimated by determining the death rate that results in model estimates of the end-of-year population for cows that match the published end-of-year population census statistics.

- *Number of animals per category each month:* The population of animals per category is calculated based on number of births (or graduates) into the monthly age group minus those animals that die or are slaughtered and those that graduate to next category (including feedlot placements). These monthly age groups are tracked in the enteric fermentation model to estimate emissions by animal type on a regional basis. Table K-2 provides the cattle population estimates as output from the enteric fermentation model from 1990 through 2000. This table includes the population categories used in the model to estimate total emissions, including tracking emissions that occur the following year for feedlot animals placed late in the year. Dairy lactation estimates for 1990 through 2000 are shown in Table K-3. Table K-4 provides the target weights used to track average weights of cattle by animal type. Table K-5 provides a summary of the reported feedlot placement statistics for 2000.

Cattle population data were taken from U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) reports. The USDA publishes monthly, annual, and multi-year livestock population and production estimates. Multi-year reports include revisions to earlier published data. Cattle and calf populations, feedlot placement statistics (e.g., number of animals placed in feedlots by weight class), slaughter numbers, and lactation data were obtained from the USDA (1990-2001). Beef calf birth percentages were obtained from the National Animal Health Monitoring System (NAHMS) (USDA/APHIS/VS 1998, 1994, 1993). Estimates of the number of animals in different population categories of the model differ from the reported national population statistics. This difference is due to model output indicating the average number of animals in that category for the year rather than the end of year population census.

### Step 2: Characterize U.S. Cattle Population Diets

To support development of digestible energy (DE, the percent of gross energy intake digestible to the animal) and methane conversion rate ($Y_m$, the fraction of gross energy converted to methane) values for each of the cattle population categories, data were collected on diets considered representative of different regions. For both grazing animals and animals being fed mixed rations, representative regional diets were estimated using information collected from state livestock specialists and from USDA (1996a). The data for each of the diets (e.g., proportions of different feed constituents, such as hay or grains) were used to determine chemical composition for use in estimating DE and $Y_m$ for each animal type. Additional detail on the regional diet characterization is provided in EPA (2000).

DE and $Y_m$ were used to estimate methane emissions from enteric fermentation and vary by diet and animal type. The IPCC recommends $Y_m$ values of 3.5 to 4.5 percent for feedlot cattle and 5.5 to 6.5 percent for all other cattle. 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[2] were developed. Table K-6 shows the regional DE, the $Y_m$, and percent of total U.S. cattle population in each region based on 2000 data.

DE and $Y_m$ values were estimated for each cattle population category based on physiological modeling and expert opinion. DE and $Y_m$ values for dairy cows and most grazing animals were estimated using a model (Donovan and Baldwin 1999) that represents physiological processes in the ruminant animals. The three major categories of input required by the model are animal description (e.g., cattle type, mature weight), animal performance (e.g., initial and final weight, age at start of period), and feed characteristics (e.g., chemical composition, habitat, grain or forage). Data used to simulate ruminant digestion is provided for a particular animal that is then used to represent a group of animals with similar characteristics. The model accounts for differing diets (i.e., grain-based, forage-based, range- based), so that $Y_m$ values for the variable feeding characteristics within the U.S. cattle population can be estimated.

For feedlot animals, DE and $Y_m$ values were taken from Johnson (1999). In response to peer reviewer comments (Johnson 2000), values for dairy replacement heifers are based on EPA (1993).

### Step 3: Estimate Methane Emissions from Cattle

Emissions were estimated in three steps: a) determine gross energy intake using the IPCC (2000) equations, b) determine an emissions factor using the GE values and other factors, and c) sum the daily emissions for each animal type. The necessary data values include:

- Body Weight (kg)
- Weight Gain (kg/day)
- Net Energy for Activity ($C_a$)[3]
- Standard Reference Weight[4] (Dairy = 1,324 kg; Beef = 1,195 kg)
- Milk Production (kg/day)
- Milk Fat (percent of fat in milk = 4)
- Pregnancy (percent of population that is pregnant)
- DE (percent of gross energy intake digestible)
- $Y_m$ (the fraction of gross energy converted to methane)

---

[2] In some cases, the $Y_m$ values used for this analysis extend beyond the range provided by the IPCC. However, EPA believes that these values are representative for the U.S. due to the research conducted to characterize the diets of U.S. cattle and to assess the $Y_m$ values associated with different animal performance and feed characteristics in the United States.

[3] Zero for feedlot conditions, 0.17 for grazing conditions, 0.37 for high quality grazing conditions. $C_a$ factor for dairy cows is weighted to account for the fraction of the population in the region that grazes during the year.

[4] Standard Reference Weight is used in the model to account for breed potential.

### *Step 3a: Gross Energy, GE*

As shown in the following equation, Gross Energy (GE) is derived based on the net energy estimates and the feed characteristics. Only variables relevant to each animal category are used (e.g., estimates for feedlot animals do not require the $NE_l$ factor). All net energy equations are provided in IPCC (2000).

$$GE = [((NE_m + NE_{mobilized} + NE_a + NE_l + NE_p) / \{NE_{ma}/DE\}) + (NE_g / \{NE_{ga}/DE\})] / (DE / 100)$$

Where,

GE = gross energy (MJ/day)

$NE_m$ = net energy required by the animal for maintenance (MJ/day)

$NE_{mobilized}$ = net energy due to weight loss (mobilized) (MJ/day)

$NE_a$ = net energy for animal activity (MJ/day)

$NE_l$ = net energy for lactation (MJ/day)

$NE_p$ = net energy required for pregnancy (MJ/day)

$\{NE_{ma}/DE\}$ = ratio of net energy available in a diet for maintenance to digestible energy consumed

$NE_g$ = net energy needed for growth (MJ/day)

$\{NE_{ga}/DE\}$ = ratio of net energy available for growth in a diet to digestible energy consumed

DE = digestible energy expressed as a percentage of gross energy (percent)

### *Step 3b: Emission Factor*

The emissions factor (DayEmit) was determined using the GE value and the methane conversion factor ($Y_m$) for each category. This is shown in the following equation:

$$DayEmit = [GE \times Y_m] / [55.65 \text{ MJ/kg } CH_4]$$

Where,

DayEmit = emission factor (kg $CH_4$/head/day)

GE = gross energy intake (MJ/head/day)

$Y_m$ = methane conversion rate which is the fraction of gross energy in feed converted to methane (percent)

The daily emission factors were estimated for each animal type, weight and region. The implied national annual average emission factors for each of the animal categories are shown in Table K-7. The implied factors are not used in the inventory, but are provided for comparative purposes only.

### *Step 3c: Estimate Total Emissions*

Emissions were summed for each month and for each population category using the daily emission factor for a representative animal and the number of animals in the category. The following equation was used:

$$Emissions = DayEmit \times Days/Month \times SubPop$$

Where,

DayEmit = the emission factor for the subcategory (kg $CH_4$/head/day)

Days/Month = the number of days in the month

SubPop = the number of animals in the subcategory during the month

This process was repeated for each month, and the totals for each subcategory were summed to achieve an emissions estimate for the entire year. The estimates for each of the 10 subcategories of cattle are listed in Table K-8. The emissions for each subcategory were then summed to estimate total emissions from beef cattle and dairy cattle for the entire year. The total emissions from 1990 through 2000 are shown in Table K-9.

## Emission Estimates from Other Livestock

All livestock population data, except for horses, were taken from U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) reports. For each animal category, the USDA publishes monthly, annual, and multi-year livestock population and production estimates. Multi-year reports include revisions to earlier published data. Recent reports were obtained from the USDA Economics and Statistics System, while historical data were downloaded from the USDA-NASS. The Food and Agriculture Organization (FAO) publishes horse population data. These data were accessed from the FAOSTAT database at http://apps.fao.org/. Methane emissions from sheep, goats, swine, and horses were estimated by multiplying published national population estimates by the national emission factor for each year. Table K-10 shows the populations used for these other livestock from 1990 to 2000 and Table K-11 shows the emission factors used for these other livestock.

A complete time series of enteric fermentation emissions from livestock is shown in Table K-12 (Tg $CO_2$ Eq.) and Table K-13 (Gg).

**Table K-2: Estimates of Average Annual Populations of U.S. Cattle (Thousand Head)[a]**

| Livestock Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Calves 0-6 months** | 22,561 | 22,531 | 22,707 | 23,004 | 23,346 | 23,468 | 23,255 | 22,810 | 22,674 | 22,655 | 22,564 |
| **Dairy** | | | | | | | | | | | |
| Cows | 10,015 | 9,965 | 9,728 | 9,658 | 9,528 | 9,487 | 9,416 | 9,309 | 9,191 | 9,133 | 9,190 |
| Replacements 7-11 months | 1,214 | 1,219 | 1,232 | 1,230 | 1,228 | 1,220 | 1,205 | 1,182 | 1,194 | 1,188 | 1,194 |
| Replacements 12-23 months | 2,915 | 2,874 | 2,901 | 2,926 | 2,907 | 2,905 | 2,877 | 2,838 | 2,797 | 2,846 | 2,811 |
| **Beef** | | | | | | | | | | | |
| Cows | 32,454 | 32,520 | 33,007 | 33,365 | 34,650 | 35,156 | 35,228 | 34,271 | 33,683 | 33,745 | 33,569 |
| Replacements 7-11 months | 1,269 | 1,315 | 1,402 | 1,465 | 1,529 | 1,492 | 1,462 | 1,378 | 1,321 | 1,303 | 1,313 |
| Replacements 12-23 months | 2,967 | 3,063 | 3,182 | 3,393 | 3,592 | 3,647 | 3,526 | 3,391 | 3,212 | 3,110 | 3,097 |
| Steer Stockers | 7,864 | 7,362 | 8,458 | 8,786 | 7,900 | 8,700 | 8,322 | 7,839 | 7,647 | 7,203 | 6,798 |
| Heifer Stockers | 4,806 | 4,572 | 4,809 | 4,944 | 4,715 | 5,083 | 4,933 | 4,987 | 4,838 | 4,671 | 4,407 |
| Total Adjusted Feedlot[b] | 10,574 | 10,461 | 10,409 | 9,901 | 10,775 | 11,344 | 11,353 | 11,528 | 11,517 | 12,858 | 12,774 |
| Bulls | 2,180 | 2,198 | 2,220 | 2,239 | 2,306 | 2,392 | 2,392 | 2,325 | 2,235 | 2,241 | 2,197 |
| Total Placements[c,d] | 25,587 | 25,396 | 25,348 | 25,586 | 26,615 | 27,623 | 27,580 | 28,518 | 27,111 | 29,424 | 27,921 |

Source: Enteric Fermentation Model.

[a] Populations represent the average of each population category throughout the year.

[b] Total Adjusted Feedlot = Average number in feedlots accounting for current year plus the population carried over from the previous year (e.g., the "next year" population numbers from this table are added into the following years "adjusted numbers").

[c] Placements represent a flow of animals from backgrounding situations to feedlots rather than an average annual population estimate.

[d] Reported placements from USDA are adjusted using a scaling factor based on the slaughter to placement ratio.

**Table K-3: Dairy Lactation by Region (lbs· year/cow)***

| Year | California | West | Northern Great Plains | Southcentral | Northeast | Midwest | Southeast |
|---|---|---|---|---|---|---|---|
| 1990 | 18,800 | 16,769 | 13,502 | 12,397 | 14,058 | 14,218 | 12,943 |
| 1991 | 18,771 | 16,631 | 13,316 | 12,389 | 14,560 | 14,555 | 12,850 |
| 1992 | 19,072 | 17,838 | 13,597 | 12,710 | 15,135 | 15,028 | 13,292 |
| 1993 | 18,852 | 17,347 | 14,109 | 13,034 | 14,937 | 15,203 | 13,873 |
| 1994 | 20,203 | 17,890 | 14,496 | 13,236 | 15,024 | 15,374 | 14,200 |
| 1995 | 19,573 | 17,724 | 14,650 | 13,228 | 15,398 | 15,728 | 14,384 |
| 1996 | 19,161 | 18,116 | 14,872 | 13,215 | 15,454 | 15,596 | 14,244 |
| 1997 | 19,829 | 18,248 | 15,013 | 13,212 | 15,928 | 16,027 | 14,548 |
| 1998 | 19,442 | 18,377 | 15,489 | 13,580 | 16,305 | 16,494 | 14,525 |
| 1999 | 20,788 | 19,330 | 15,910 | 13,476 | 16,571 | 16,655 | 14,930 |
| 2000 | 21,169 | 20,828 | 17,196 | 15,323 | 17,544 | 17,255 | 15,201 |

Source: USDA (2001d).

* Beef lactation data were developed using the methodology described in the text.

## Table K-4: Target Weights for Use in Estimating Average Weights and Weight Gains (lbs)

| Cattle Type | Typical Weights |
|---|---|
| **Beef Replacement Heifer Data** | |
| Replacement Weight at 15 months | 715 |
| Replacement Weight at 24 months | 1,078 |
| Mature Weight at 36 months | 1,172 |
| **Dairy Replacement Heifer Data** | |
| Replacement Weight at 15 months | 800 |
| Replacement Weight at 24 months | 1,225 |
| Mature Weight at 36 months | 1,350 |
| **Stockers Data – Grazing/Forage Based Only** | |
| Steer Weight Gain/Month to 12 months | 45 |
| Steer Weight Gain/Month to 24 months | 35 |
| Heifer Weight Gain/Month to 12 months | 35 |
| Heifer Weight Gain/Month to 24 months | 30 |

Source: Feedstuffs (1998), Western Dairyman (1998), Johnson (1999), NRC (1999).

## Table K-5: Feedlot Placements in the United States for 2000 (Number of animals placed in Thousand Head)

| Weight When Placed | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| < 600 lbs | 489 | 351 | 333 | 301 | 382 | 347 | 424 | 573 | 775 | 1066 | 757 | 504 | 6,302 |
| 600 - 700 lbs | 691 | 476 | 411 | 310 | 471 | 380 | 386 | 504 | 612 | 755 | 559 | 516 | 6,071 |
| 700 - 800 lbs | 654 | 596 | 717 | 577 | 794 | 498 | 592 | 691 | 681 | 531 | 405 | 406 | 7,142 |
| > 800 lbs | 382 | 457 | 570 | 519 | 658 | 439 | 505 | 672 | 618 | 477 | 293 | 273 | 5,863 |
| **Total** | **2,216** | **1,880** | **2,031** | **1,707** | **2,305** | **1,664** | **1,907** | **2,440** | **2,686** | **2,829** | **2,014** | **1,699** | **25,378** |

Source: USDA (2001g).
Note: Totals may not sum due to independent rounding.
* Data were available for 1996 through 2000. Data for 1990 to 1995 were based on the average of monthly placements from the 1996 to 1998 reported figures.

**Table K-6: Regional Digestible Energy (DE), Methane Conversion Rates ($Y_m$), and population percentages for Cattle in 2000**

| Animal Type | Data | California | West | Northern Great Plains | Southcentral | Northeast | Midwest | Southeast |
|---|---|---|---|---|---|---|---|---|
| Beef Repl. Heif.[a] | DE[b] | 67 | 66 | 68 | 66 | 64 | 68 | 68 |
| | Ym[c] | 8.0% | 7.4% | 8.0% | 8.3% | 8.4% | 8.0% | 7.8% |
| | Pop.[d] | 3% | 11% | 31% | 24% | 2% | 13% | 16% |
| Dairy Repl. Heif.[a] | DE | 66 | 66 | 66 | 64 | 68 | 66 | 66 |
| | Ym | 5.9% | 5.9% | 5.6% | 6.4% | 6.3% | 5.6% | 6.9% |
| | Pop. | 18% | 11% | 5% | 4% | 19% | 36% | 7% |
| Steer Stockers[a] | DE | 67 | 66 | 68 | 66 | 64 | 68 | 68 |
| | Ym | 8.0% | 7.4% | 8.0% | 8.3% | 8.4% | 8.0% | 7.8% |
| | Pop. | 4% | 8% | 41% | 23% | 2% | 18% | 4% |
| Heifer Stockers[a] | DE | 67 | 66 | 68 | 66 | 64 | 68 | 68 |
| | Ym | 8.0% | 7.4% | 8.0% | 8.3% | 8.4% | 8.0% | 7.8% |
| | Pop. | 2% | 7% | 50% | 22% | 1% | 15% | 4% |
| Steer Feedlot[e] | DE | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| | Ym | 3.0% | 3.0% | 3.0% | 3.0% | 3.0% | 3.0% | 3.0% |
| | Pop. | 3% | 7% | 47% | 24% | 1% | 17% | 1% |
| Heifer Feedlot[e] | DE | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| | Ym | 3.0% | 3.0% | 3.0% | 3.0% | 3.0% | 3.0% | 3.0% |
| | Pop. | 3% | 7% | 47% | 24% | 1% | 17% | 1% |
| Beef Cows[a] | DE | 67 | 66 | 68 | 66 | 64 | 68 | 68 |
| | Ym | 8.0% | 7.4% | 8.0% | 8.3% | 8.4% | 8.0% | 7.8% |
| | Pop. | 2% | 9% | 28% | 26% | 2% | 14% | 19% |
| Dairy Cows[e] | DE | 69 | 66 | 69 | 68 | 69 | 69 | 68 |
| | $Y_m$ | 4.8% | 5.8% | 5.8% | 5.7% | 5.8% | 5.8% | 5.6% |
| | Pop. | 16% | 13% | 5% | 6% | 19% | 34% | 8% |
| Steer Step-Up[e,f] | DE | 76 | 76 | 76 | 76 | 76 | 76 | 76 |
| | Ym | 5.5% | 5.5% | 5.5% | 5.5% | 5.5% | 5.5% | 5.5% |
| Heifer Step-Up[e] | DE | 76 | 76 | 76 | 76 | 76 | 76 | 76 |
| | Ym | 5.5% | 5.5% | 5.5% | 5.5% | 5.5% | 5.5% | 5.5% |

[a] Beef and Dairy grazing DE and $Y_m$ values were applied to all grazing beef animals. It was assumed that pasture quality remains relatively consistent at a regional scale.

[b] Digestible Energy in units of percent GE (MJ/Day).

[c] Methane Conversion Rate is the fraction of GE in feed converted to methane.

[d] Estimated percent of each subcategory population present in each region.

[e] DE and $Y_m$ values for 1990 through 1992 are values from the previous livestock characterization reported in the 1993 Report to Congress. Values for 1993 through 1995 are the mean of current values and the 1993 Report to Congress values. Values for 1996 through 2000 are values from the most recent livestock characterization.

[f] Characteristics of heifer and steer step-up diets (i.e., diets fed to animals entering feedlots) were assessed nationally to account for the difference between initial and finishing diets for feedlot animals.

## Table K-7: Implied Emission Factors for Cattle in the United States (kg $CH_4$/head/yr)

| Animal Category | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Calves 0-6 months | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Dairy | | | | | | | | | | | |
| Cows | 113 | 114 | 117 | 111 | 113 | 113 | 107 | 109 | 110 | 111 | 115 |
| Replacements 7-11 months | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| Replacements 12-23 months | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 | 63 |
| Beef | | | | | | | | | | | |
| Cows | 83 | 83 | 83 | 83 | 83 | 83 | 83 | 83 | 83 | 82 | 83 |
| Replacements 7-11 months | 47 | 47 | 47 | 47 | 47 | 47 | 47 | 47 | 48 | 47 | 47 |
| Replacements 12-23 months | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 74 | 74 | 73 |
| Steer Stockers | 63 | 63 | 64 | 64 | 63 | 64 | 64 | 63 | 63 | 63 | 63 |
| Heifer Stockers | 56 | 56 | 56 | 56 | 56 | 57 | 56 | 57 | 56 | 56 | 56 |
| Total Feedlot | 47 | 47 | 47 | 40 | 39 | 39 | 34 | 33 | 34 | 33 | 32 |
| Bulls | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

"0" = assumed to be zero.
Source: Enteric Fermentation Model.

## Table K-8: $CH_4$ Emissions from Cattle (Gg)

| Cattle Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dairy** | **1,369** | **1,370** | **1,368** | **1,307** | **1,307** | **1,308** | **1,241** | **1,240** | **1,234** | **1,246** | **1,283** |
| Cows | 1,136 | 1,140 | 1,135 | 1,073 | 1,074 | 1,076 | 1,010 | 1,013 | 1,010 | 1,018 | 1,058 |
| Replacements 7-11 months | 49 | 49 | 49 | 49 | 49 | 49 | 48 | 48 | 48 | 48 | 48 |
| Replacements 12-23 months | 184 | 181 | 183 | 185 | 184 | 184 | 182 | 179 | 177 | 180 | 177 |
| **Beef** | **4,444** | **4,408** | **4,550** | **4,536** | **4,615** | **4,768** | **4,673** | **4,541** | **4,453** | **4,429** | **4,365** |
| Cows | 2,682 | 2,687 | 2,728 | 2,758 | 2,865 | 2,907 | 2,912 | 2,832 | 2,784 | 2,777 | 2,774 |
| Replacements 7-11 months | 59 | 62 | 66 | 69 | 72 | 70 | 68 | 65 | 63 | 62 | 61 |
| Replacements 12-23 months | 217 | 224 | 233 | 248 | 263 | 267 | 258 | 248 | 238 | 230 | 226 |
| Steer Stockers | 499 | 467 | 539 | 561 | 502 | 556 | 529 | 497 | 484 | 453 | 428 |
| Heifer Stockers | 268 | 255 | 270 | 279 | 266 | 288 | 278 | 282 | 273 | 262 | 248 |
| Feedlot Cattle | 499 | 494 | 492 | 398 | 419 | 442 | 389 | 385 | 387 | 421 | 408 |
| Bulls | 218 | 220 | 222 | 224 | 231 | 239 | 239 | 233 | 223 | 224 | 220 |
| **Total** | **5,812** | **5,778** | **5,918** | **5,843** | **5,923** | **6,077** | **5,914** | **5,780** | **5,688** | **5,675** | **5,648** |

Note: Totals may not sum due to independent rounding.

## Table K-9: Cattle Emissions (Tg $CO_2$ Eq.)

| Cattle Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Dairy | 28.7 | 28.8 | 28.7 | 27.4 | 27.4 | 27.5 | 26.1 | 26.0 | 25.9 | 26.2 | 26.9 |
| Beef | 93.3 | 92.6 | 95.5 | 95.3 | 96.9 | 100.1 | 98.1 | 95.4 | 93.5 | 93.0 | 91.7 |
| **Total** | **122.1** | **121.3** | **124.3** | **122.7** | **124.4** | **127.6** | **124.2** | **121.4** | **119.4** | **119.2** | **118.6** |

Note: Totals may not sum due to independent rounding.

## Table K-10: Other Livestock Populations 1990-2000 (Thousand Head)

| Livestock Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sheep | 11,358 | 11,174 | 10,797 | 10,201 | 9,836 | 8,989 | 8,465 | 8,024 | 7,825 | 7,215 | 7,032 |
| Goats | 2,516 | 2,516 | 2,516 | 2,410 | 2,305 | 2,200 | 2,095 | 1,990 | 1,990 | 1,990 | 1,990 |
| Horses | 5,150 | 5,180 | 5,200 | 5,210 | 5,190 | 5,210 | 5,230 | 5,230 | 5,250 | 5,317 | 5,320 |
| Swine | 53,941 | 56,476 | 58,532 | 58,016 | 59,951 | 58,899 | 56,220 | 58,728 | 61,991 | 60,245 | 58,892 |

Source: USDA (2001b,e-f, 2000b,e 1999d-e,h, 1998, b-c, 1994a-b), FAO (2000,2001).

### Table K-11: Emission Factors for Other Livestock (kg $CH_4$/head/year)

| Livestock Type | Emission Factor |
|---|---|
| Sheep | 8 |
| Goats | 5 |
| Horses | 18 |
| Swine | 1.5 |

See Table K-7 for emission factors for cattle.
Source: IPCC (2000).

### Table K-12: $CH_4$ Emissions from Enteric Fermentation (Tg $CO_2$ Eq.)

| Livestock Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Beef Cattle | 93.3 | 92.6 | 95.5 | 95.3 | 96.9 | 100.1 | 98.1 | 95.4 | 93.5 | 93.0 | 91.7 |
| Dairy Cattle | 28.7 | 28.8 | 28.7 | 27.4 | 27.4 | 27.5 | 26.1 | 26.0 | 25.9 | 26.2 | 26.9 |
| Horses | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Sheep | 1.9 | 1.9 | 1.8 | 1.7 | 1.7 | 1.5 | 1.4 | 1.3 | 1.3 | 1.2 | 1.2 |
| Swine | 1.7 | 1.8 | 1.8 | 1.8 | 1.9 | 1.9 | 1.8 | 1.8 | 2.0 | 1.9 | 1.9 |
| Goats | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| **Total** | **127.9** | **127.2** | **130.9** | **128.5** | **130.1** | **133.2** | **129.6** | **126.8** | **124.9** | **124.5** | **123.9** |

### Table K-13: $CH_4$ Emissions from Enteric Fermentation (Gg)

| Livestock Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Beef Cattle | 4,444 | 4,408 | 4,550 | 4,536 | 4,615 | 4,768 | 4,673 | 4,541 | 4,453 | 4,429 | 4,365 |
| Dairy Cattle | 1,369 | 1,370 | 1,368 | 1,307 | 1,307 | 1,308 | 1,241 | 1,240 | 1,234 | 1,246 | 1,283 |
| Horses | 93 | 93 | 94 | 94 | 93 | 94 | 94 | 94 | 95 | 96 | 96 |
| Sheep | 91 | 89 | 86 | 82 | 79 | 72 | 68 | 64 | 63 | 58 | 56 |
| Swine | 81 | 85 | 88 | 87 | 90 | 88 | 84 | 88 | 93 | 90 | 88 |
| Goats | 13 | 13 | 13 | 12 | 12 | 11 | 10 | 10 | 10 | 10 | 10 |
| **Total** | **6,089** | **6,058** | **6,198** | **6,118** | **6,196** | **6,342** | **6,171** | **6,037** | **5,948** | **5,929** | **5,898** |

# ANNEX L

## Methodology for Estimating $CH_4$ and $N_2O$ Emissions from Manure Management

This annex presents a discussion of the methodology used to calculate methane and nitrous oxide emissions from manure management systems. More detailed discussions of selected topics may be found in supplemental memoranda in the supporting docket to this inventory.

The following steps were used to estimate methane and nitrous oxide emissions from the management of livestock manure. Nitrous oxide emissions associated with pasture, range, or paddock systems and daily spread systems are included in the emissions estimates for Agricultural Soil Management.

### Step 1: Livestock Population Characterization Data

Annual animal population data for 1990 through 2000 for all livestock types, except horses and goats, were obtained from the USDA National Agricultural Statistics Service (USDA, 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a-g, 2001a-f). The actual population data used in the emissions calculations for cattle and swine were downloaded from the USDA National Agricultural Statistics Service Population Estimates Data Base (<http://www.nass.usda.gov:81/ipedb/>). Horse population data were obtained from the FAOSTAT database (FAO 2001). Goat population data for 1992 and 1997 were obtained from the Census of Agriculture (USDA 1999d). Information regarding poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service personnel (Lange 2000).

A summary of the livestock population characterization data used to calculate methane and nitrous oxide emissions is presented in Table L-1.

*Dairy Cattle:* The total annual dairy cow and heifer state population data for 1990 through 2000 are provided in various USDA National Agricultural Statistics Service reports (USDA 1995a, 1999a, 2000a-b, 2001a-b). The actual total annual dairy cow and heifer state population data used in the emissions calculations were downloaded from the U.S. Department of Agriculture National Agricultural Statistics Service Published Estimates Database (<http://www.nass.usda.gov:81/ipedb/>) for Cattle and Calves. The specific data used to estimate dairy cattle populations are "Cows That Calved – Milk" and "Heifers 500+ Lbs – Milk Repl."

*Beef Cattle:* The total annual beef cattle population data for each state for 1990 through 2000 are provided in various USDA National Agricultural Statistics Service reports (USDA 1995a, 1999a, 2000a-b, 2001a-b). The actual data used in the emissions calculations were downloaded from the U.S. Department of Agriculture National Agricultural Statistics Service Published Estimates Database (<http://www.nass.usda.gov:81/ipedb/>), Cattle and Calves. The specific data used to estimate beef cattle populations are: "Cows That Calved—Beef," "Heifers 500+ Lbs—Beef Repl," "Heifers 500+ Lbs—Other," and "Steers 500+ Lbs." Additional information regarding the percent of beef steer and heifers on feedlots was obtained from contacts with the national USDA office (Milton 2000).

For all beef cattle groups (cows, heifers, steer, bulls, and calves), the USDA data provide cattle inventories from January and July of each year. Cattle inventory changes over the course of the year, sometimes significantly, as new calves are born and as fattened cattle are slaughtered; therefore, to develop the best estimate for the annual animal population, the average inventory of cattle by state was calculated. USDA provides January inventory data for each state; however, July inventory data is only presented as a total for the United States. In order to estimate average annual populations by state, a "scaling factor" was developed that adjusts the January state-level data to reflect July inventory changes. This factor equals the average of the US January and July data divided by the January data. The scaling factor is derived for each cattle group and is then applied to the January state-level data to arrive at the state-level annual population estimates.

*Swine:* The total annual swine population data for each state for 1990 through 2000 are provided in various USDA National Agricultural Statistics Service reports (USDA 1994a, 1998a, 2000c, 2001c). The USDA data provides quarterly data for each swine subcategory: breeding, market under 60 pounds (less than 27 kg), market 60 to 119 pounds (27 to 54 kg), market 120 to 179 pounds (54 to 81 kg), and market 180 pounds and over (greater than

82 kg). The average of the quarterly data was used in the emissions calculations. For states where only December inventory is reported, the December data were used directly. The actual data used in the emissions calculations were downloaded from the U.S. Department of Agriculture National Agricultural Statistics Service Published Estimates Database (<http://www.nass.usda.gov:81/ipedb/>), Hogs and Pigs.

*Sheep:* The total annual sheep population data for each state for 1990 through 2000 were obtained from USDA National Agricultural Statistics Service (USDA 1994b, 1999c, 2000f, 2001f). Population data for lamb and sheep on feed are not available after 1993. The number of lamb and sheep on feed for 1994 through 2000 were calculated using the average of the percent of lamb and sheep on feed from 1990 through 1993. In addition, all of the sheep and lamb "on feed" are not necessarily on "feedlots"; they may be on pasture/crop residue supplemented by feed. Data for those animals on feed that are on feedlots versus pasture/crop residue were provided only for lamb in 1993. To calculate the populations of sheep and lamb on feedlots for all years, it was assumed that the percentage of sheep and lamb on feed that are on feedlots versus pasture/crop residue is the same as that for lambs in 1993 (Anderson 2000).

*Goats:* Annual goat population data by state were available for only 1992 and 1997 (USDA 1999d). The data for 1992 were used for 1990 through 1992 and the data for 1997 were used for 1997 through 2000. Data for 1993 through 1996 were extrapolated using the 1992 and 1997 data.

*Poultry:* Annual poultry population data by state for the various animal categories (hens 1 year and older, pullets of laying age, pullets 3 months old and older not of laying age, pullets under 3 months of age, other chickens, broilers, and turkeys) were obtained from USDA National Agricultural Statistics Service (USDA 1995b, 1998b, 1999b, 2000d-e, 2000g, 2001d-e). The annual population data for boilers and turkeys were adjusted for turnover (i.e., slaughter) rate (Lange 2000).

*Horses:* The Food and Agriculture Organization (FAO) publishes annual horse population data, which were accessed from the FAOSTAT database at <http://apps.fao.org/> (FAO 2001).

### Step 2: Waste Characteristics Data

Methane and nitrous oxide emissions calculations are based on the following animal characteristics for each relevant livestock population:

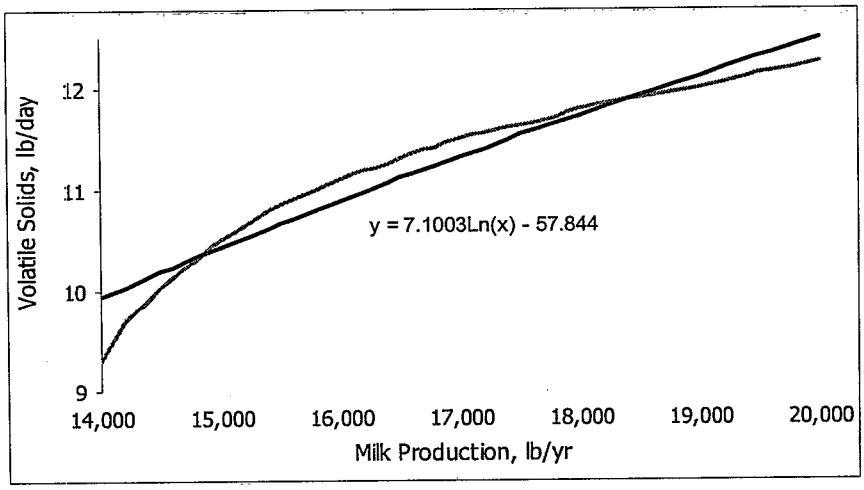
- Volatile solids excretion rate (VS)
- Maximum methane producing capacity ($B_o$) for U.S. animal waste
- Nitrogen excretion rate ($N_{ex}$)
- Typical animal mass (TAM)
- Annual state-specific milk production rate

Published sources were reviewed for U.S.-specific livestock waste characterization data that would be consistent with the animal population data discussed in Step 1. Data from the National Engineering Handbook, Agricultural Waste Management Field Handbook (USDA 1996a) were chosen as the primary source of waste characteristics. In some cases, data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1999) were used to supplement the USDA data. The volatile solids and nitrogen excretion data for breeding swine are a combination of the types of animals that make up this animal group, namely gestating and farrowing swine and boars. It is assumed that a group of breeding swine is typically broken out as 80 percent gestating sows, 15 percent farrowing swine, and 5 percent boars (Safley 2000).

Table L-2 presents a summary of the waste characteristics used in the emissions estimates.

The method for calculating volatile solids production from dairy cows is based on the relationship between milk production and volatile solids production. Cows that produce more milk per year also produce more volatile solids in their manure due to their increased feed. Figure 4-1 in the *Agricultural Waste Management Field Handbook* (USDA 1996a) was used to determine the mathematical relationship between volatile solids production and milk production for a 1,400-pound dairy cow. The resulting best fit equation is logarithmic, shown in Figure L-1.

**Figure L-1: Volatile Solids Production**




Annual milk production data, published by USDA's National Agricultural Statistics Service (USDA 2001g), was accessed for each state and for each year of the inventory. State-specific volatile solids production rates were then calculated for each year of the inventory and used instead of a single national volatile solids excretion rate constant. Table L-3 presents the volatile solids production rates used for 2000.

### Step 3: Waste Management System Usage Data

Estimates were made of the distribution of wastes by management system and animal type using the following sources of information:

- State contacts to estimate the breakout of dairy cows on pasture, range, or paddock, and the percent of wastes managed by daily spread systems (Deal 2000, Johnson 2000, Miller 2000, Stettler 2000, Sweeten 2000, Wright 2000)
- Data collected for EPA's Office of Water, including site visits, to medium and large beef feedlot, dairy, swine, and poultry operations (EPA 2001a)
- Contacts with the national USDA office to estimate the percent of beef steer and heifers on feedlots (Milton 2000)
- Survey data collected by USDA (USDA 1998d, 2000h) and re-aggregated by farm size and geographic location, used for small operations
- Survey data collected by the United Egg Producers (UEP 1999) and USDA (2000i) and previous EPA estimates (EPA 1992) of waste distribution for layers
- Survey data collected by Cornell University on dairy manure management operations in New York (Poe 1999)
- Previous EPA estimates of waste distribution for sheep, goat, and horse operations (EPA 1992)

*Beef Feedlots:* Based on EPA site visits and state contacts, beef feedlot manure is almost exclusively managed in drylots. Therefore, 100 percent of the manure excreted at beef feedlots is expected to be deposited in drylots and generate emissions. In addition, a portion of the manure that is deposited in the drylot will run off the drylot during rain events and be captured in a waste storage pond. An estimate of the runoff has been made by

EPA's Office of Water for various geographic regions of the United States. These runoff numbers were used to estimate emissions from runoff storage ponds located at beef feedlots (EPA 2001a).

*Dairy Cows:* Based on EPA site visits and state contacts, manure from dairy cows at medium (200 through 700 head) and large (greater than 700 head) operations are managed using either flush systems or scrape/slurry systems. In addition, they may have a solids separator in place prior to their storage component. Estimates of the percent of farms that use each type of system (by geographic region) were developed by EPA's Office of Water, and were used to estimate the percent of wastes managed in lagoons (flush systems), liquid/slurry systems (scrape systems), and solid storage (separated solids). (EPA 2001a). Manure management system data for small (fewer than 200 head) dairies were obtained from USDA (USDA 2000h). These operations are more likely to use liquid/slurry and solid storage management systems than anaerobic lagoon systems. The reported manure management systems were deep pit, liquid/slurry (also includes slurry tank, slurry earth-basin, and aerated lagoon), anaerobic lagoon, and solid storage (also includes manure pack, outside storage, and inside storage).

The percent of wastes by system was estimated using the USDA data broken out by geographic region and farm size. Farm-size distribution data reported in the 1992 and 1997 Census of Agriculture (USDA 1999e) were used to determine the percentage of all dairies using the various manure management systems. Due to lack of additional data for other years, it was assumed that the data provided for 1992 were the same as that for 1990 and 1991, and data provided for 1997 were the same as that for 1998, 1999, and 2000. Data for 1993 through 1996 were extrapolated using the 1992 and 1997 data.

Data regarding the use of daily spread and pasture, range, or paddock systems for dairy cattle were obtained from personal communications with personnel from several organizations. These organizations include state NRCS offices, state extension services, state universities, USDA National Agricultural Statistics Service (NASS), and other experts (Deal 2000, Johnson 2000, Miller 2000, Stettler 2000, Sweeten 2000, and Wright 2000). Contacts at Cornell University provided survey data on dairy manure management practices in New York (Poe 1999). Census of Agriculture population data for 1992 and 1997 (USDA 1999e) were used in conjunction with the state data obtained from personal communications to determine regional percentages of total dairy cattle and dairy wastes that are managed using these systems. These percentages were applied to the total annual dairy cow and heifer state population data for 1990 through 2000, which were obtained from the USDA National Agricultural Statistics Service (USDA 1995a, 1999a, 2000a-b, 2001a-b).

Of the dairies using systems other than daily spread and pasture, range, or paddock systems, some dairies reported using more than one type of manure management system. Therefore, the total percent of systems reported by USDA for a region and farm size is greater than 100 percent. Typically, this means that some of the manure at a dairy is handled in one system (e.g., a lagoon), and some of the manure is handled in another system (e.g., drylot). However, it is unlikely that the same manure is moved from one system to another. Therefore, to avoid double counting emissions, the reported percentages of systems in use were adjusted to equal a total of 100%, using the same distribution of systems. For example, if USDA reported that 65 percent of dairies use deep pits to manage manure and 55 percent of dairies use anaerobic lagoons to manage manure, it was assumed that 54 percent (i.e., 65 percent divided by 120 percent) of the manure is managed with deep pits and 46 percent (i.e., 55 percent divided by 120 percent) of the manure is managed with anaerobic lagoons (ERG 2000).

*Dairy Heifers:* The percent of dairy heifer operations that are pasture, range, or paddock or that operate as daily spread was estimated using the same approach as dairy cows. Similar to beef cattle, dairy heifers are housed on drylots when not pasture based. Based on data from EPA's Office of Water (EPA 2001a), it was assumed that 100% of the manure excreted by dairy heifers is deposited in drylots and generates emissions. Estimates of runoff have been made by EPA's Office of Water for various geographic regions of the US (EPA 2001a).

*Swine:* Based on data collected during site visits for EPA's Office of Water (ERG 2000), manure from swine at large (greater than 2000 head) and medium (200 through 2000 head) operations are primarily managed using deep pit systems, liquid/slurry systems, or anaerobic lagoons. Manure management system data were obtained from USDA (USDA 1998d). It was assumed those operations with less than 200 head use pasture, range, or paddock systems. The percent of waste by system was estimated using the USDA data broken out by geographic region and farm size. Farm-size distribution data reported in the 1992 and 1997 Census of Agriculture (USDA 1999e) were used to determine the percentage of all swine utilizing the various manure management systems. The reported manure management systems were deep pit, liquid/slurry (also includes above- and below-ground slurry), anaerobic lagoon, and solid storage (also includes solids separated from liquids).

Some swine operations reported using more than one management system; therefore, the total percent of systems reported by USDA for a region and farm size is greater than 100 percent. Typically, this means that some of the manure at a swine operation is handled in one system (e.g., liquid system), and some of the manure is handled in another system (e.g., dry system). However, it is unlikely that the same manure is moved from one system to another. Therefore, to avoid double counting emissions, the reported percentages of systems in use were adjusted to equal a total of 100 percent, using the same distribution of systems, as explained under "Dairy Cows".

*Sheep:* It was assumed that all sheep wastes not deposited on feedlots were deposited on pasture, range, or paddock lands (Anderson 2000).

*Goats/Horses:* Estimates of manure management distribution were obtained from EPA's previous estimates (EPA 1992).

*Poultry – Layers:* Waste management system data for layers for 1990 were obtained from Appendix H of *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). The percentage of layer operations using a shallow pit flush house with anaerobic lagoon or high-rise house without bedding was obtained for 1999 from United Egg Producers, voluntary survey, 1999 (UEP 1999). These data were augmented for key poultry states (AL, AR, CA, FL, GA, IA, IN, MN, MO, NC, NE, OH, PA, TX, and WA) with USDA data (USDA 2000i). It was assumed that the change in system usage between 1990 and 1999 is proportionally distributed among those years of the inventory. It was assumed that system usage in 2000 was equal to that estimated for 1999. It was also assumed that 1 percent of poultry wastes are deposited on pasture, range, or paddock lands (EPA 1992).

*Poultry - Broilers/Turkeys:* The percentage of turkeys and broilers on pasture or in high-rise houses without bedding was obtained from *Global Methane Emissions from Livestock and Poultry Manure* (EPA1992). It was assumed that 1 percent of poultry wastes are deposited in pastures, range, and paddocks (EPA 1992).

### Step 4: Emission Factor Calculations

Methane conversion factors (MCFs) and nitrous oxide emission factors (EFs) used in the emission calculations were determined using the methodologies shown below:

#### *Methane Conversion Factors (MCFs)*

*Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000) for anaerobic lagoon systems published default methane conversion factors of 0 to 100 percent, which reflects the wide range in performance that may be achieved with these systems. There exist relatively few data points on which to determine country-specific MCFs for these systems. Therefore, a climate-based approach was identified to estimate MCFs for anaerobic lagoon and other liquid storage systems.

The following approach was used to develop the MCFs for liquid systems, and is based on the van't Hoff-Arrhenius equation used to forecast performance of biological reactions. One practical way of estimating MCFs for liquid manure handling systems is based on the mean ambient temperature and the van't Hoff-Arrhenius equation with a base temperature of 30°C, as shown in the following equation (Safley and Westerman 1990):

$$f = \exp\left[\frac{E(T_2 - T_1)}{RT_1T_2}\right]$$

Where,

$T_1 = 303.16K$

$T_2$ = ambient temperature (K) for climate zone (in this case, a weighted value for each state)

E = activation energy constant (15,175 cal/mol)

R = ideal gas constant (1.987 cal/K mol)

The factor "f" represents the proportion of volatile solids that are biologically available for conversion to methane based on the temperature of the system. The temperature is assumed equal to the ambient temperature. For colder climates, a minimum temperature of 5°C was established for uncovered anaerobic lagoons and 7.5°C for other liquid manure handling systems. For those animal populations using liquid systems (i.e., dairy cow, dairy

heifer, layers, beef on feedlots, and swine) monthly average state temperatures were based on the counties where the specific animal population resides (i.e., the temperatures were weighted based on the percent of animals located in each county). The average county and state temperature data were obtained from the National Climate Data Center (NOAA 2001), and the county population data were based on 1992 and 1997 Census data (USDA 1999e). County population data for 1990 and 1991 were assumed to be the same as 1992; county population data for 1998 through 2000 were assumed to be the same as 1997; and county population data for 1993 through 1996 were extrapolated based on 1992 and 1997 data.

Annual MCFs for liquid systems are calculated as follows for each animal type, state, and year of the inventory:

1) Monthly temperatures are calculated by using county-level temperature and population data. The weighted-average temperature for a state is calculated using the population estimates and average monthly temperature in each county.

2) Monthly temperatures are used to calculate a monthly van't Hoff-Arrhenius "f" factor, using the equation presented above. A minimum temperature of 5°C is used for anaerobic lagoons and 7.5°C is used for liquid/slurry and deep pit systems.

3) Monthly production of volatile solids that are added to the system is estimated based on the number of animals present and, for lagoon systems, adjusted for a management and design practices factor. This factor accounts for other mechanisms by which volatile solids are removed from the management system prior to conversion to methane, such as solids being removed from the system for application to cropland. This factor, equal to 0.8, has been estimated using currently available methane measurement data from anaerobic lagoon systems in the United States (ERG 2001).

4) The amount of volatile solids available for conversion to methane is assumed to be equal to the amount of volatile solids produced during the month (from Step 3). For anaerobic lagoons, the amount of volatile solids available also includes volatile solids that may remain in the system from previous months.

5) The amount of volatile solids consumed during the month is equal to the amount available for conversion multiplied by the "f" factor.

6) For anaerobic lagoons, the amount of volatile solids carried over from one month to the next is equal to the amount available for conversion minus the amount consumed.

7) The estimated amount of methane generated during the month is equal to the monthly volatile solids consumed multiplied by the maximum methane potential of the waste ($B_o$).

8) The annual MCF is then calculated as:

$$MCF_{(annual)} = CH_4 \text{ generated}_{(annual)} / (VS \text{ generated}_{(annual)} \times B_o)$$

In order to account for the carry over of volatile solids from the year prior to the inventory year for which estimates are calculated, it is assumed in the MCF calculation for lagoons that a portion of the volatile solids from October, November, and December of the year prior to the inventory year are available in the lagoon system starting January of the inventory year.

Following this procedure, the resulting MCF accounts for temperature variation throughout the year, residual volatile solids in a system (carryover), and management and design practices that may reduce the volatile solids available for conversion to methane. The methane conversion factors presented in Table L-4 by state and waste management system represent the average MCF for 2000 by state for all animal groups located in that state. However, in the calculation of methane emissions, specific MCFs for each animal type in the state are used.

### *Nitrous Oxide Emission Factors*

Nitrous oxide emission factors for all manure management systems were set equal to the default IPCC factors (IPCC 2000).

### Step 5: Weighted Emission Factors

For beef cattle, dairy cattle, swine, and poultry, the emission factors for both methane and nitrous oxide were weighted to incorporate the distribution of wastes by management system for each state. The following equation was used to determine the weighted MCF for a particular animal type in a particular state:

$$MCF_{animal,\ state} = \sum_{system} (MCF_{system,\ state} \times \%Manure_{animal,\ system,\ state})$$

Where:

$MCF_{animal,\ state}$ = Weighted MCF for that animal group and state

$MCF_{system,\ state}$ = MCF for that system and state (see Step 4)

% $Manure_{animal,\ system,\ state}$ = Percent of manure managed in the system for that animal group in that state (expressed as a decimal)

The weighted nitrous oxide emission factor for a particular animal type in a particular state was determined as follows:

$$EF_{animal,\ state} = \sum_{system} (EF_{system} \times \% Manure_{animal,\ system,\ state})$$

Where,

$EF_{animal,\ state}$ = Weighted emission factor for that animal group and state

$EF_{system}$ = Emission factor for that system (see Step 4)

% $Manure_{animal,\ system,\ state}$ = Percent of manure managed in the system for that animal group in that state (expressed as a decimal)

Data for the calculated weighted factors for 1992 came from the 1992 Census of Agriculture, combined with assumptions on manure management system usage based on farm size, and were also used for 1990 and 1991. Data for the calculated weighted factors for 1997 came from the 1997 Census of Agriculture, combined with assumptions on manure management system usage based on farm size, and were also used for 1998, 1999, and 2000. Factors for 1993 through 1996 were calculated by interpolating between the two sets of factors. A summary of the weighted MCFs used to calculate beef feedlot, dairy cow and heifer, swine, and poultry emissions for 2000 are presented in Table L-5.

### Step 6: Methane and Nitrous Oxide Emission Calculations

For beef feedlot cattle, dairy cows, dairy heifers, swine, and poultry, methane emissions were calculated for each animal group as follows:

$$Methane_{\ animal\ group} = \sum_{state} (Population \times VS \times B_o \times MCF_{animal,\ state} \times 0.662)$$

Where:

$Methane_{animal\ group}$ = methane emissions for that animal group (kg $CH_4$/yr)

Population = annual average state animal population for that animal group (head)

VS = total volatile solids produced annually per animal (kg/yr/head)

$B_o$ = maximum methane producing capacity per kilogram of VS ($m^3$ $CH_4$/kg VS)

$MCF_{animal,\ state}$ = weighted MCF for the animal group and state (see Step 5)

0.662 = conversion factor of $m^3$ $CH_4$ to kilograms $CH_4$ (kg $CH_4$ /$m^3$ $CH_4$)

Methane emissions from other animals (i.e., sheep, goats, and horses) were based on the 1990 methane emissions estimated using the detailed method described in *Anthropogenic Methane Emissions in the United States:*

*Estimates for 1990, Report to Congress* (EPA 1993). This approach is based on animal-specific manure characteristics and management system data. This process was not repeated for subsequent years for these other animal types. Instead, national populations of each of the animal types were used to scale the 1990 emissions estimates to the period 1991 through 2000.

Nitrous oxide emissions were calculated for each animal group as follows:

$$\text{Nitrous Oxide}_{\text{animal group}} = \sum_{state} (Population \times N_{ex} \times EF_{animal,\,state} \times 44/28)$$

Where:

$\text{Nitrous Oxide}_{\text{animal group}}$ = nitrous oxide emissions for that animal group (kg/yr)

Population = annual average state animal population for that animal group (head)

$N_{ex}$ = total Kjeldahl nitrogen excreted annually per animal (kg/yr/head)

$EF_{animal,\,state}$ = weighted nitrous oxide emission factor for the animal group and state, kg $N_2O$-N/kg N excreted (see Step 5)

44/28 = conversion factor of $N_2O$-N to $N_2O$

Emission estimates are summarized in Table L-6 and Table L-7.

## Table L-1: Livestock Population (1,000 Head)

| Animal Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dairy Cattle** | **14,143** | **13,980** | **13,830** | **13,767** | **13,566** | **13,502** | **13,305** | **13,138** | **12,992** | **13,026** | **13,070** |
| Dairy Cows | 10,007 | 9,883 | 9,714 | 9,679 | 9,504 | 9,491 | 9,410 | 9,309 | 9,200 | 9,142 | 9,220 |
| Dairy Heifer | 4,135 | 4,097 | 4,116 | 4,088 | 4,062 | 4,011 | 3,895 | 3,829 | 3,793 | 3,884 | 3,850 |
| **Swine** | **53,941** | **56,476** | **58,530** | **58,016** | **59,951** | **58,899** | **56,220** | **58,728** | **61,991** | **60,245** | **58,892** |
| Market Swine | 47,043 | 49,246 | 51,274 | 50,859 | 52,669 | 51,973 | 49,581 | 51,888 | 55,150 | 53,871 | 52,658 |
| Market <60 lbs. | 18,359 | 19,212 | 19,851 | 19,434 | 20,157 | 19,656 | 18,851 | 19,886 | 20,691 | 19,928 | 19,582 |
| Market 60-119 lbs. | 11,734 | 12,374 | 12,839 | 12,656 | 13,017 | 12,836 | 12,157 | 12,754 | 13,552 | 13,256 | 12,933 |
| Market 120-179 lbs. | 9,440 | 9,840 | 10,253 | 10,334 | 10,671 | 10,545 | 10,110 | 10,480 | 11,235 | 11,043 | 10,753 |
| Market >180 lbs. | 7,510 | 7,821 | 8,331 | 8,435 | 8,824 | 8,937 | 8,463 | 8,768 | 9,672 | 9,645 | 9,390 |
| Breeding Swine | 6,899 | 7,231 | 7,255 | 7,157 | 7,282 | 6,926 | 6,639 | 6,840 | 6,841 | 6,374 | 6,233 |
| **Beef Cattle** | **86,087** | **87,267** | **88,548** | **90,321** | **92,571** | **94,391** | **94,269** | **92,290** | **90,730** | **90,032** | **89,403** |
| Feedlot Steers | 7,338 | 7,920 | 7,581 | 7,984 | 7,797 | 7,763 | 7,380 | 7,644 | 7,845 | 7,782 | 8,280 |
| Feedlot Heifers | 3,621 | 4,035 | 3,626 | 3,971 | 3,965 | 4,047 | 3,999 | 4,396 | 4,459 | 4,578 | 4,872 |
| NOF Bulls | 2,180 | 2,198 | 2,220 | 2,239 | 2,306 | 2,392 | 2,392 | 2,325 | 2,235 | 2,241 | 2,196 |
| NOF Calves | 23,909 | 23,854 | 24,118 | 24,209 | 24,586 | 25,170 | 25,042 | 24,363 | 24,001 | 23,895 | 23,508 |
| NOF Heifers | 8,872 | 8,938 | 9,520 | 9,850 | 10,469 | 10,680 | 10,869 | 10,481 | 9,998 | 9,725 | 9,352 |
| NOF Steers | 7,490 | 7,364 | 8,031 | 7,935 | 8,346 | 8,693 | 9,077 | 8,452 | 8,050 | 7,864 | 7,247 |
| NOF Cows | 32,677 | 32,960 | 33,453 | 34,132 | 35,101 | 35,645 | 35,509 | 34,629 | 34,143 | 33,948 | 33,948 |
| **Sheep** | **11,358** | **11,174** | **10,797** | **10,201** | **9,836** | **8,989** | **8,465** | **8,024** | **7,825** | **7,215** | **7,032** |
| Sheep not on Feed | 10,301 | 10,211 | 9,777 | 9,178 | 8,965 | 8,214 | 7,719 | 7,293 | 7,110 | 6,586 | 6,419 |
| Sheep on Feed | 1,058 | 963 | 1,020 | 1,023 | 871 | 775 | 745 | 731 | 715 | 629 | 613 |
| **Goats** | **2,516** | **2,516** | **2,516** | **2,410** | **2,305** | **2,200** | **2,095** | **1,990** | **1,990** | **1,990** | **1,990** |
| **Poultry** | **1,537,074** | **1,594,944** | **1,649,998** | **1,707,422** | **1,769,135** | **1,679,704** | **1,882,078** | **1,926,790** | **1,963,919** | **2,007,517** | **2,025,188** |
| Hens >1 yr. | 119,551 | 117,178 | 121,103 | 131,688 | 135,094 | 133,841 | 138,048 | 140,966 | 150,778 | 151,914 | 153,222 |
| Pullets laying | 153,916 | 162,943 | 163,397 | 158,938 | 163,433 | 165,230 | 165,874 | 171,171 | 169,916 | 177,391 | 178,983 |
| Pullets >3 mo | 34,222 | 34,272 | 34,710 | 33,833 | 33,159 | 34,004 | 33,518 | 35,578 | 39,664 | 38,587 | 38,325 |
| Pullets <3 mo | 38,945 | 42,344 | 45,160 | 47,941 | 46,694 | 47,365 | 48,054 | 54,766 | 56,054 | 58,775 | 56,083 |
| Chickens | 6,545 | 6,857 | 7,113 | 7,240 | 7,369 | 7,637 | 7,243 | 7,549 | 7,682 | 9,659 | 8,074 |
| Broilers | 1,066,209 | 1,115,845 | 1,164,089 | 1,217,147 | 1,275,916 | 1,184,667 | 1,381,229 | 1,411,673 | 1,442,596 | 1,481,093 | 1,502,296 |
| Turkeys | 117,685 | 115,504 | 114,426 | 110,635 | 107,469 | 106,960 | 108,112 | 105,088 | 97,229 | 90,098 | 88,205 |
| **Horses** | **5,150** | **5,180** | **5,200** | **5,210** | **5,190** | **5,210** | **5,230** | **5,230** | **5,250** | **5,317** | **5,320** |

Note: Totals may not sum due to independent rounding.

## Table L-2: Waste Characteristics Data

| Animal Group | Average TAM (kg) | Source | Total Kjeldahl Nitrogen, $N_{ex}$ (kg/day per 1,000 kg mass) | Source | Maximum Methane Generation Potential, $B_o$ ($m^3$ $CH_4$/kg VS added) | Source | Volatile Solids, VS (kg/day per 1,000 kg mass) | Source |
|---|---|---|---|---|---|---|---|---|
| Dairy Cow | 604 | Safley 2000 | 0.44 | USDA 1996a | 0.24 | Morris 1976 | Table L-3 | |
| Dairy Heifer | 476 | Safley 2000 | 0.31 | USDA 1996a | 0.17 | Bryant et. al. 1976 | 7.77 | USDA 1996a |
| Feedlot Steers | 420 | USDA 1996a | 0.30 | USDA 1996a | 0.33 | Hashimoto 1981 | 5.44 | USDA 1996a |
| Feedlot Heifers | 420 | USDA 1996a | 0.30 | USDA 1996a | 0.33 | Hashimoto 1981 | 5.44 | USDA 1996a |
| NOF Bulls | 750 | Safley 2000 | 0.31 | USDA 1996a | 0.17 | Hashimoto 1981 | 6.04 | USDA 1996a |
| NOF Calves | 159 | USDA 1998c | 0.30 | USDA 1996a | 0.17 | Hashimoto 1981 | 6.41 | USDA 1996a |
| NOF Heifers | 420 | USDA 1996a | 0.31 | USDA 1996a | 0.17 | Hashimoto 1981 | 6.04 | USDA 1996a |
| NOF Steers | 318 | Safley 2000 | 0.31 | USDA 1996a | 0.17 | Hashimoto 1981 | 6.04 | USDA 1996a |
| NOF Cows | 590 | Safley 2000 | 0.33 | USDA 1996a | 0.17 | Hashimoto 1981 | 6.20 | USDA 1996a |
| Market Swine <60 lbs. | 15.88 | Safley 2000 | 0.60 | USDA 1996a | 0.48 | Hashimoto 1984 | 8.80 | USDA 1996a |
| Market Swine 60-119 lbs. | 40.60 | Safley 2000 | 0.42 | USDA 1996a | 0.48 | Hashimoto 1984 | 5.40 | USDA 1996a |
| Market Swine 120-179 lbs. | 67.82 | Safley 2000 | 0.42 | USDA 1996a | 0.48 | Hashimoto 1984 | 5.40 | USDA 1996a |
| Market Swine >180 lbs. | 90.75 | Safley 2000 | 0.42 | USDA 1996a | 0.48 | Hashimoto 1984 | 5.40 | USDA 1996a |
| Breeding Swine | 198 | Safley 2000 | 0.24 | USDA 1996a | 0.48 | Hashimoto 1984 | 2.60 | USDA 1996a |
| Sheep | 27 | ASAE 1999 | 0.42 | ASAE 1999 | NA | NA | NA | NA |
| Goats | 64 | ASAE 1999 | 0.45 | ASAE 1999 | NA | NA | NA | NA |
| Horses | 450 | ASAE 1999 | 0.30 | ASAE 1999 | NA | NA | NA | NA |
| Hens >/= 1 yr | 1.8 | ASAE 1999 | 0.83 | USDA 1996a | 0.39 | Hill 1982 | 10.8 | USDA 1996a |
| Pullets - laying age | 1.8 | ASAE 1999 | 0.62 | USDA 1996a | 0.39 | Hill 1982 | 9.7 | USDA 1996a |
| Pullets - >/=3mo | 1.8 | ASAE 1999 | 0.62 | USDA 1996a | 0.39 | Hill 1982 | 9.7 | USDA 1996a |
| Pullets - </=3mo | 1.8 | ASAE 1999 | 0.62 | USDA 1996a | 0.39 | Hill 1982 | 9.7 | USDA 1996a |
| Other Chickens | 1.8 | ASAE 1999 | 0.83 | USDA 1996a | 0.39 | Hill 1982 | 10.8 | USDA 1996a |
| Broilers | 0.9 | ASAE 1999 | 1.10 | USDA 1996a | 0.36 | Hill 1984 | 15.0 | USDA 1996a |
| Turkeys | 6.8 | ASAE 1999 | 0.74 | USDA 1996a | 0.36 | Hill 1984 | 9.7 | USDA 1996a |

**Table L-3: Estimated Dairy Cow Volatile Solids Production Rate By State for 2000**

| State | Volatile Solids[1] (kg/day/1000 kg) |
|---|---|
| Alabama | 7.07 |
| Alaska | 7.28 |
| Arizona | 9.32 |
| Arkansas | 6.52 |
| California | 9.20 |
| Colorado | 9.30 |
| Connecticut | 8.48 |
| Delaware | 7.42 |
| Florida | 7.67 |
| Georgia | 7.93 |
| Hawaii | 7.23 |
| Idaho | 9.11 |
| Illinois | 8.22 |
| Indiana | 7.88 |
| Iowa | 8.46 |
| Kansas | 8.00 |
| Kentucky | 6.65 |
| Louisiana | 6.38 |
| Maine | 8.00 |
| Maryland | 7.80 |
| Massachusetts | 8.10 |
| Michigan | 8.65 |
| Minnesota | 8.31 |
| Mississippi | 7.49 |
| Missouri | 7.34 |
| Montana | 8.23 |
| Nebraska | 7.86 |
| Nevada | 8.66 |
| New Hampshire | 8.15 |
| New Jersey | 7.97 |
| New Mexico | 9.14 |
| New York | 8.20 |
| North Carolina | 8.01 |
| North Dakota | 7.21 |
| Ohio | 8.09 |
| Oklahoma | 7.18 |
| Oregon | 8.60 |
| Pennsylvania | 8.40 |
| Rhode Island | 7.67 |
| South Carolina | 7.79 |
| South Dakota | 7.78 |
| Tennessee | 7.38 |
| Texas | 7.93 |
| Utah | 8.25 |
| Vermont | 8.24 |
| Virginia | 7.73 |
| Washington | 9.54 |
| West Virginia | 7.65 |
| Wisconsin | 8.18 |
| Wyoming | 6.94 |

[1] Volatile solids production estimates based on state average annual milk production rates, combined with a mathematical relationship of volatile solids to milk production (USDA 1996a).

**Table L-4: Methane Conversion Factors By State for Liquid Systems[2] for 2000**

| State | Liquid/Slurry and Deep Pit | Anaerobic Lagoon |
|---|---|---|
| Alabama | 0.4122 | 0.7538 |
| Alaska | 0.1472 | 0.4677 |
| Arizona | 0.4919 | 0.7689 |
| Arkansas | 0.3823 | 0.7536 |
| California | 0.3440 | 0.7330 |
| Colorado | 0.2336 | 0.6705 |
| Connecticut | 0.2337 | 0.6642 |
| Delaware | 0.2927 | 0.7124 |
| Florida | 0.5193 | 0.7684 |
| Georgia | 0.3919 | 0.7411 |
| Hawaii | 0.5827 | 0.7869 |
| Idaho | 0.2247 | 0.6570 |
| Illinois | 0.2870 | 0.7128 |
| Indiana | 0.2714 | 0.6976 |
| Iowa | 0.2627 | 0.6981 |
| Kansas | 0.3439 | 0.7515 |
| Kentucky | 0.3151 | 0.7241 |
| Louisiana | 0.4790 | 0.7631 |
| Maine | 0.1917 | 0.6025 |
| Maryland | 0.2786 | 0.6999 |
| Massachusetts | 0.2243 | 0.6523 |
| Michigan | 0.2295 | 0.6576 |
| Minnesota | 0.2335 | 0.6675 |
| Mississippi | 0.4308 | 0.7584 |
| Missouri | 0.3245 | 0.7361 |
| Montana | 0.2073 | 0.6337 |
| Nebraska | 0.2856 | 0.7197 |
| Nevada | 0.2466 | 0.6787 |
| New Hampshire | 0.2007 | 0.6176 |
| New Jersey | 0.2605 | 0.6896 |
| New Mexico | 0.3272 | 0.7328 |
| New York | 0.2167 | 0.6402 |
| North Carolina | 0.3346 | 0.7255 |
| North Dakota | 0.2165 | 0.6482 |
| Ohio | 0.2573 | 0.6841 |
| Oklahoma | 0.3933 | 0.7602 |
| Oregon | 0.2112 | 0.6291 |
| Pennsylvania | 0.2485 | 0.6764 |
| Rhode Island | 0.2420 | 0.6765 |
| South Carolina | 0.3831 | 0.7401 |
| South Dakota | 0.2496 | 0.6911 |
| Tennessee | 0.3390 | 0.7367 |
| Texas | 0.4622 | 0.7613 |
| Utah | 0.2673 | 0.7029 |
| Vermont | 0.1965 | 0.6090 |
| Virginia | 0.2829 | 0.7009 |
| Washington | 0.2126 | 0.6329 |
| West Virginia | 0.2607 | 0.6850 |
| Wisconsin | 0.2278 | 0.6595 |
| Wyoming | 0.2184 | 0.6513 |

[2] As defined by IPCC (IPCC 2000).

## Table L-5: Weighted Methane Conversion Factors for 2000

| State | Beef Feedlot-Heifer | Beef Feedlot-Steer | Dairy Cow | Dairy Heifer | Swine - Market | Swine - Breeding | Layer | Broiler | Turkey |
|---|---|---|---|---|---|---|---|---|---|
| Alabama | 0.0204 | 0.0204 | 0.1029 | 0.0191 | 0.4962 | 0.4980 | 0.3239 | 0.0150 | 0.0150 |
| Alaska | 0.0169 | 0.0169 | 0.1601 | 0.0165 | 0.0150 | 0.0150 | 0.1282 | 0.0150 | 0.0150 |
| Arizona | 0.0169 | 0.0172 | 0.5989 | 0.0165 | 0.5225 | 0.5225 | 0.4695 | 0.0150 | 0.0150 |
| Arkansas | 0.0200 | 0.0199 | 0.0754 | 0.0188 | 0.5482 | 0.5515 | 0.0150 | 0.0150 | 0.0150 |
| California | 0.0192 | 0.0195 | 0.4993 | 0.0182 | 0.4862 | 0.4835 | 0.1034 | 0.0150 | 0.0150 |
| Colorado | 0.0159 | 0.0160 | 0.4395 | 0.0157 | 0.2874 | 0.2870 | 0.4055 | 0.0150 | 0.0150 |
| Connecticut | 0.0173 | 0.0173 | 0.1017 | 0.0169 | 0.1353 | 0.1340 | 0.0477 | 0.0150 | 0.0150 |
| Delaware | 0.0180 | 0.0180 | 0.0932 | 0.0174 | 0.3196 | 0.3196 | 0.0499 | 0.0150 | 0.0150 |
| Florida | 0.0219 | 0.0220 | 0.4154 | 0.0203 | 0.2146 | 0.2150 | 0.3299 | 0.0150 | 0.0150 |
| Georgia | 0.0201 | 0.0201 | 0.1435 | 0.0189 | 0.4897 | 0.4870 | 0.3168 | 0.0150 | 0.0150 |
| Hawaii | 0.0226 | 0.0226 | 0.5516 | 0.0208 | 0.3915 | 0.3915 | 0.2080 | 0.0150 | 0.0150 |
| Idaho | 0.0159 | 0.0159 | 0.4408 | 0.0157 | 0.2046 | 0.2038 | 0.3933 | 0.0150 | 0.0150 |
| Illinois | 0.0167 | 0.0167 | 0.1194 | 0.0164 | 0.3299 | 0.3300 | 0.0291 | 0.0150 | 0.0150 |
| Indiana | 0.0166 | 0.0166 | 0.0981 | 0.0164 | 0.3151 | 0.3154 | 0.0150 | 0.0150 | 0.0150 |
| Iowa | 0.0166 | 0.0166 | 0.1003 | 0.0163 | 0.4179 | 0.4188 | 0.0150 | 0.0150 | 0.0150 |
| Kansas | 0.0170 | 0.0171 | 0.1247 | 0.0167 | 0.3688 | 0.3680 | 0.0298 | 0.0150 | 0.0150 |
| Kentucky | 0.0181 | 0.0181 | 0.0416 | 0.0175 | 0.4471 | 0.4456 | 0.0504 | 0.0150 | 0.0150 |
| Louisiana | 0.0213 | 0.0213 | 0.1119 | 0.0198 | 0.2091 | 0.2089 | 0.4636 | 0.0150 | 0.0150 |
| Maine | 0.0169 | 0.0169 | 0.0596 | 0.0165 | 0.0150 | 0.0150 | 0.0446 | 0.0150 | 0.0150 |
| Maryland | 0.0177 | 0.0177 | 0.0890 | 0.0172 | 0.2891 | 0.2884 | 0.0499 | 0.0150 | 0.0150 |
| Massachusetts | 0.0172 | 0.0173 | 0.0725 | 0.0168 | 0.1840 | 0.1836 | 0.0468 | 0.0150 | 0.0150 |
| Michigan | 0.0164 | 0.0164 | 0.1537 | 0.0161 | 0.2834 | 0.2825 | 0.0281 | 0.0150 | 0.0150 |
| Minnesota | 0.0164 | 0.0164 | 0.0895 | 0.0162 | 0.2995 | 0.2992 | 0.0150 | 0.0150 | 0.0150 |
| Mississippi | 0.0206 | 0.0206 | 0.0946 | 0.0193 | 0.5673 | 0.5673 | 0.4607 | 0.0150 | 0.0150 |
| Missouri | 0.0169 | 0.0169 | 0.1103 | 0.0166 | 0.3538 | 0.3537 | 0.0150 | 0.0150 | 0.0150 |
| Montana | 0.0158 | 0.0158 | 0.2525 | 0.0156 | 0.2528 | 0.2529 | 0.3867 | 0.0150 | 0.0150 |
| Nebraska | 0.0167 | 0.0167 | 0.1075 | 0.0164 | 0.3320 | 0.3314 | 0.0292 | 0.0150 | 0.0150 |
| Nevada | 0.0159 | 0.0159 | 0.4958 | 0.0157 | 0.0150 | 0.0150 | 0.0150 | 0.0150 | 0.0150 |
| New Hampshire | 0.0170 | 0.0170 | 0.0687 | 0.0166 | 0.1150 | 0.1144 | 0.0453 | 0.0150 | 0.0150 |
| New Jersey | 0.0176 | 0.0176 | 0.0790 | 0.0171 | 0.1803 | 0.1828 | 0.0486 | 0.0150 | 0.0150 |
| New Mexico | 0.0163 | 0.0162 | 0.5236 | 0.0159 | 0.0150 | 0.0150 | 0.4539 | 0.0150 | 0.0150 |
| New York | 0.0172 | 0.0172 | 0.0875 | 0.0167 | 0.2010 | 0.2006 | 0.0463 | 0.0150 | 0.0150 |
| North Carolina | 0.0182 | 0.0182 | 0.0655 | 0.0176 | 0.5650 | 0.5638 | 0.3123 | 0.0150 | 0.0150 |
| North Dakota | 0.0163 | 0.0163 | 0.0655 | 0.0161 | 0.2527 | 0.2534 | 0.0274 | 0.0150 | 0.0150 |
| Ohio | 0.0165 | 0.0166 | 0.0994 | 0.0163 | 0.2952 | 0.2952 | 0.0150 | 0.0150 | 0.0150 |
| Oklahoma | 0.0166 | 0.0166 | 0.3562 | 0.0162 | 0.5717 | 0.5756 | 0.4610 | 0.0150 | 0.0150 |
| Oregon | 0.0178 | 0.0178 | 0.2594 | 0.0171 | 0.1092 | 0.1089 | 0.1652 | 0.0150 | 0.0150 |
| Pennsylvania | 0.0174 | 0.0175 | 0.0582 | 0.0169 | 0.3048 | 0.3036 | 0.0150 | 0.0150 | 0.0150 |
| Rhode Island | 0.0174 | 0.0174 | 0.0374 | 0.0169 | 0.1843 | 0.1843 | 0.0481 | 0.0150 | 0.0150 |
| South Carolina | 0.0199 | 0.0199 | 0.1031 | 0.0187 | 0.5018 | 0.5001 | 0.4514 | 0.0150 | 0.0150 |
| South Dakota | 0.0165 | 0.0165 | 0.0930 | 0.0162 | 0.3006 | 0.3010 | 0.0284 | 0.0150 | 0.0150 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Tennessee | 0.0183 | 0.0183 | 0.0559 | 0.0177 | 0.4274 | 0.4260 | 0.0511 | 0.0150 | 0.0150 |
| Texas | 0.0168 | 0.0167 | 0.5109 | 0.0163 | 0.5318 | 0.5315 | 0.1049 | 0.0150 | 0.0150 |
| Utah | 0.0160 | 0.0160 | 0.3772 | 0.0158 | 0.3282 | 0.3263 | 0.4317 | 0.0150 | 0.0150 |
| Vermont | 0.0170 | 0.0170 | 0.0785 | 0.0166 | 0.0150 | 0.0150 | 0.0443 | 0.0150 | 0.0150 |
| Virginia | 0.0178 | 0.0178 | 0.0523 | 0.0172 | 0.4817 | 0.4822 | 0.0490 | 0.0150 | 0.0150 |
| Washington | 0.0178 | 0.0179 | 0.3142 | 0.0171 | 0.2077 | 0.2052 | 0.0876 | 0.0150 | 0.0150 |
| West Virginia | 0.0176 | 0.0176 | 0.0684 | 0.0171 | 0.2048 | 0.2042 | 0.0486 | 0.0150 | 0.0150 |
| Wisconsin | 0.0163 | 0.0164 | 0.0976 | 0.0161 | 0.2693 | 0.2690 | 0.0279 | 0.0150 | 0.0150 |
| Wyoming | 0.0159 | 0.0159 | 0.2326 | 0.0157 | 0.2816 | 0.2792 | 0.3914 | 0.0150 | 0.0150 |

**Table L-6: $CH_4$ Emissions from Livestock Manure Management (Gg)**

| Animal Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dairy Cattle** | **457** | **491** | **483** | **505** | **545** | **571** | **577** | **604** | **624** | **634** | **653** |
| Dairy Cows | 447 | 480 | 472 | 495 | 535 | 561 | 567 | 594 | 614 | 624 | 643 |
| Dairy Heifer | 11 | 11 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| **Swine** | **621** | **675** | **667** | **680** | **741** | **763** | **729** | **782** | **864** | **839** | **814** |
| Market Swine | 482 | 524 | 522 | 534 | 584 | 608 | 582 | 626 | 706 | 683 | 665 |
| Market <60 lbs. | 101 | 110 | 108 | 109 | 119 | 121 | 116 | 125 | 138 | 131 | 128 |
| Market 60-119 lbs. | 101 | 111 | 109 | 110 | 119 | 124 | 117 | 127 | 141 | 136 | 132 |
| Market 120-179 lbs. | 136 | 147 | 146 | 151 | 164 | 170 | 164 | 175 | 197 | 191 | 185 |
| Market >180 lbs. | 144 | 156 | 159 | 165 | 182 | 193 | 185 | 198 | 230 | 225 | 220 |
| Breeding Swine | 139 | 152 | 146 | 146 | 156 | 155 | 148 | 156 | 158 | 156 | 149 |
| **Beef Cattle** | **151** | **155** | **155** | **159** | **163** | **166** | **165** | **163** | **161** | **160** | **161** |
| Feedlot Steers | 22 | 24 | 23 | 24 | 24 | 24 | 22 | 23 | 24 | 24 | 25 |
| Feedlot Heifers | 11 | 12 | 11 | 12 | 12 | 12 | 12 | 13 | 14 | 14 | 14 |
| NOF Bulls | 6 | 6 | 6 | 6 | 6 | 7 | 7 | 6 | 6 | 6 | 6 |
| NOF Calves | 15 | 15 | 15 | 15 | 15 | 16 | 16 | 15 | 15 | 15 | 15 |
| NOF Heifers | 14 | 14 | 15 | 15 | 16 | 17 | 17 | 16 | 16 | 15 | 15 |
| NOF Steers | 9 | 9 | 10 | 9 | 10 | 10 | 11 | 10 | 10 | 9 | 9 |
| NOF Cows | 74 | 74 | 75 | 77 | 79 | 80 | 80 | 78 | 77 | 77 | 77 |
| **Sheep** | **3** | **3** | **3** | **3** | **3** | **2** | **2** | **2** | **2** | **2** | **2** |
| **Goats** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** |
| **Poultry** | **128** | **129** | **125** | **129** | **129** | **124** | **125** | **127** | **130** | **124** | **124** |
| Hens >1 yr. | 33 | 31 | 33 | 34 | 34 | 33 | 32 | 31 | 33 | 30 | 30 |
| Total Pullets | 63 | 65 | 59 | 60 | 60 | 58 | 56 | 58 | 60 | 56 | 56 |
| Chickens | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 4 | 3 | 3 |
| Broilers | 19 | 20 | 21 | 21 | 22 | 21 | 24 | 25 | 25 | 26 | 26 |
| Turkeys | 10 | 10 | 10 | 10 | 9 | 9 | 9 | 9 | 8 | 8 | 8 |
| **Horses** | **29** | **29** | **29** | **29** | **29** | **29** | **29** | **29** | **29** | **30** | **30** |

## Table L-7: $N_2O$ Emissions from Livestock Manure Management (Gg)

| Animal Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dairy Cattle** | **13.6** | **13.3** | **13.2** | **13.1** | **12.9** | **12.9** | **12.6** | **12.4** | **12.3** | **12.3** | **12.3** |
| Dairy Cows | 9.2 | 9.0 | 8.7 | 8.6 | 8.4 | 8.3 | 8.2 | 8.0 | 7.8 | 7.7 | 7.7 |
| Dairy Heifer | 4.4 | 4.4 | 4.4 | 4.5 | 4.6 | 4.6 | 4.5 | 4.5 | 4.5 | 4.6 | 4.6 |
| **Swine** | **1.0** | **1.0** | **1.1** | **1.1** | **1.1** | **1.1** | **1.1** | **1.1** | **1.2** | **1.2** | **1.1** |
| Market Swine | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.9 | 0.9 | 0.9 |
| Market <60 lbs. | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Market 60-119 lbs. | + | + | + | + | + | + | + | + | + | + | + |
| Market 120-179 lbs. | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Market >180 lbs. | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 |
| Breeding Swine | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| **Beef Cattle** | **15.8** | **17.3** | **16.2** | **17.3** | **17.0** | **17.1** | **16.5** | **17.4** | **17.8** | **17.9** | **19.0** |
| Feedlot Steers | 10.6 | 11.5 | 11.0 | 11.5 | 11.3 | 11.2 | 10.7 | 11.1 | 11.3 | 11.3 | 12.0 |
| Feedlot Heifers | 5.2 | 5.8 | 5.2 | 5.7 | 5.7 | 5.9 | 5.8 | 6.4 | 6.4 | 6.6 | 7.0 |
| **Sheep** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** |
| **Goats** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** | **0.1** |
| **Poultry** | **20.5** | **20.9** | **21.3** | **21.6** | **22.1** | **20.9** | **23.2** | **23.3** | **23.2** | **23.2** | **23.3** |
| Hens >1 yr. | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| Pullets | 1.0 | 1.0 | 1.0 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| Chickens | + | + | + | + | + | + | + | + | + | + | + |
| Broilers | 12.0 | 12.5 | 13.1 | 13.7 | 14.3 | 13.3 | 15.5 | 15.9 | 16.2 | 16.7 | 16.9 |
| Turkeys | 6.7 | 6.6 | 6.5 | 6.3 | 6.1 | 6.1 | 6.2 | 6.0 | 5.6 | 5.1 | 5.0 |
| **Horses** | **0.6** | **0.6** | **0.6** | **0.6** | **0.6** | **0.6** | **0.6** | **0.6** | **0.7** | **0.7** | **0.7** |

+ Emission estimate is less than 0.1 Gg

# ANNEX M

## Methodology for Estimating $N_2O$ Emissions from Agricultural Soil Management

Nitrous oxide ($N_2O$) emissions from agricultural soil management covers activities that add nitrogen (N) to soils, and thereby enhance natural emissions of $N_2O$. The IPCC methodology (IPCC/UNEP/OECD/IEA 1997, IPCC 2000), which is used here, divides this source category into three components: (1) direct $N_2O$ emissions from managed soils; (2) direct $N_2O$ emissions from pasture, range, and paddock livestock manure; and (3) indirect $N_2O$ emissions from soils induced by applications of nitrogen.

There are five steps in estimating $N_2O$ emissions from agricultural soil management. First, the activity data are derived for each of the three components. Note that some of the data used in the first component are also used in the third component. In the second, third, and fourth steps, $N_2O$ emissions from each of the three components are estimated. In the fifth step, emissions from the three components are summed to estimate total emissions. The remainder of this annex describes these steps, and data used in these steps, in detail.

### Step 1: Derive Activity Data

The activity data for this source category are annual amounts of nitrogen added to soils for each relevant activity, except for histosol cultivation, for which the activity data are annual histosol areas cultivated.[1] The activity data are derived from statistics, such as fertilizer consumption data or livestock population data, and various factors used to convert these statistics to annual amounts of nitrogen, such as fertilizer nitrogen contents or livestock excretion rates. Activity data were derived for each of the three components, as described below.

#### *Step 1a: Direct $N_2O$ Emissions from Managed Soils.*

The activity data for this component include: a) the amount of nitrogen in synthetic and organic commercial fertilizers that are applied annually, b) the amount of nitrogen in livestock manure that is applied annually through both daily spread operations and the eventual application of manure that had been stored in manure management systems, c) the amount of nitrogen in sewage sludge that is applied annually, d) the amount of nitrogen in the aboveground biomass of nitrogen-fixing crops that are produced annually, e) the amount of nitrogen in crop residues that are retained on soils annually, and f) the area of histosols cultivated annually.

*Application of synthetic and organic commercial fertilizer:* Annual commercial fertilizer consumption data for the United States were taken from annual publications of synthetic and organic fertilizer statistics (TVA 1991, 1992a, 1993, 1994; AAPFCO 1995, 1996, 1997, 1998, 1999, 2000b) and a recent AAPFCO database (AAPFCO 2000a). These data were manipulated in several ways to derive the activity data needed for the inventory. First, the manure and sewage sludge portions of the organic fertilizers were subtracted from the total organic fertilizer consumption data because these nitrogen additions are accounted for under "manure application" and "sewage sludge application."[2] Second, the organic fertilizer data, which are recorded in mass units of fertilizer, had to be converted to mass units of nitrogen by multiplying by the average organic fertilizer nitrogen contents provided in the annual fertilizer publications. These nitrogen contents are weighted average values, so they vary from year-to-year (ranging from 2.3 percent to 3.9 percent over the period 1990 through 2000). The synthetic fertilizer data are recorded in units of nitrogen, so these data did not need to be converted. Lastly, both the synthetic and organic fertilizer consumption data are recorded in "fertilizer year" totals (i.e., July to June); therefore, the data were converted to calendar year totals. This was done by assuming that approximately 35 percent of fertilizer usage occurred from July to December, and 65 percent from January to June (TVA 1992b). July to December values were

[1] Histosols are soils with a high organic carbon content. All soils with more than 20 to 30 percent organic matter by weight (depending on the clay content) are classified as histosols (Brady and Weil 1999).

[2] Organic fertilizers included in these publications are manure, compost, dried blood, sewage sludge, tankage, and "other." (Tankage is dried animal residue, usually freed from fat and gelatin). The manure and sewage sludge used as commercial fertilizer are accounted for elsewhere, so these were subtracted from the organic fertilizer statistics to avoid double counting.

not available for calendar year 2000, so a "least squares line" statistical extrapolation using the previous ten years of data was used to arrive at an approximate value. Annual consumption of commercial fertilizers—synthetic and non-manure/non-sewage organic—in units of nitrogen and on a calendar year basis are presented in Table M-1.

*Application of livestock manure:* To estimate the amount of livestock manure nitrogen applied to soils, it was assumed that all of the manure produced by livestock would be applied to soils with two exceptions. These exceptions were: (1) the portion of poultry manure that is used as a feed supplement for ruminants, and (2) the manure that is deposited on soils by livestock on pasture, range, and paddock. In other words, all of the manure that is managed, except the portion of poultry manure that is used as a feed supplement, is assumed to be applied to soils. The amount of managed manure for each livestock type was calculated by determining the population of animals that were on feedlots or otherwise housed in order to collect and manage the manure. In some instances, the number of animals in managed systems was determined by subtracting the number of animals in pasture, range, and paddock from the total animal population for a particular animal type.

Annual animal population data for all livestock types, except horses and goats, were obtained from the USDA National Agricultural Statistics Service (USDA 1994b,c; 1995a,b; 1998a; 1998c; 1999a-c; 2000a-g; 2001b-g). Horse population data were obtained from the FAOSTAT database (FAO 2001). Goat population data were obtained from the Census of Agriculture (USDA 1999d). 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 Census of Agriculture (USDA 1999e).

Information regarding the percentage of manure handled using various manure management systems for dairy cattle, beef cattle, and sheep was obtained from communications with personnel from state Natural Resource Conservation Service offices, state universities, National Agricultural Statistics Service, and other experts (Poe et al. 1999, Anderson 2000, Deal 2000, Johnson 2000, Miller 2000, Milton 2000, Stettler 2000, Sweeten 2000, Wright 2000). Information regarding the percentage of manure handled using various manure management systems for swine, poultry, goats, and horses was obtained from Safley et al. (1992). A more detailed discussion of manure management system usage is provided in Annex L.

Once the animal populations for each livestock type and management system were estimated, these populations were then multiplied by an average animal mass constant (USDA 1996, USDA 1998d, ASAE 1999, Safley 2000) to derive total animal mass for each animal type in each management system. Total Kjeldahl nitrogen[3] excreted per year for each livestock type and management system was then calculated using daily rates of nitrogen excretion per unit of animal mass (USDA 1996, ASAE 1999). The total poultry manure nitrogen in managed systems was reduced by the amount assumed to be used as a feed supplement (i.e., 4.2 percent of the managed poultry manure; Carpenter 1992). The annual amounts of Kjeldahl nitrogen were then summed over all livestock types and management systems to derive estimates of the annual manure nitrogen applied to soils (Table M-2).

*Application of sewage sludge:* Estimates of annual nitrogen additions from land application of sewage sludge were derived from periodic estimates of sludge generation and disposal rates that were developed by EPA. Sewage sludge is generated from the treatment of raw sewage in public or private wastewater treatment works. Based on a 1988 questionnaire returned from 600 publicly owned treatment works (POTWs), the EPA estimated that 5.4 million metric tons of dry sewage sludge were generated by POTWs in the United States in that year (EPA 1993). Of this total, 43.7 percent was applied to land, including agricultural applications, compost manufacture, forest land application, the reclamation of mining areas, and other forms of surface disposal. A subsequent EPA report (EPA, 1999) compiled data from several national studies and surveys, and estimated that approximately 6.7 and 6.9 million metric tons of dry sewage sludge were generated in 1996 and 1998, respectively, and projected that approximately 7.1 million metric tons would be generated in 2000. The same study concluded that 60 percent of the sewage sludge generated in 1998 was applied to land (based on the results of a 1995 survey), and projected that 63 percent would be land applied in 2000. These EPA estimates of sludge generation and percent land applied were linearly interpolated to derive estimates for each year in the 1990 to 2000 period. To estimate annual amounts of nitrogen applied, the annual amounts of dry sewage sludge applied were multiplied by an average nitrogen content of 3.3 percent (Metcalf and Eddy, Inc. 1991). Final estimates of annual amounts of sewage sludge nitrogen applied to land are presented in Table M-1.

---

[3] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen in both the solid and liquid wastes.

*Production of nitrogen-fixing crops:* Annual production statistics for beans, pulses, and alfalfa were taken from U.S. Department of Agriculture crop production reports (USDA 1994a, 1998b, 2000i, 2001a). Annual production statistics for the remaining nitrogen-fixing crops (i.e., the major non-alfalfa forage crops, specifically red clover, white clover, birdsfoot trefoil, arrowleaf clover, and crimson clover) were derived from information in a book on forage crops (Taylor and Smith 1995, Pederson 1995, Beuselinck and Grant 1995, Hoveland and Evers 1995), and personal communications with forage experts (Cropper 2000, Evers 2000, Gerrish 2000, Hoveland 2000, and Pederson 2000).

The production statistics for beans, pulses, and alfalfa were in tons of product, which needed to be converted to tons of aboveground biomass nitrogen. This was done by multiplying the production statistics by one plus the aboveground residue to crop product mass ratios, dry matter fractions, and nitrogen contents. The residue to crop product mass ratios for soybeans and peanuts, and the dry matter content for soybeans, were obtained from Strehler and Stützle (1987). The dry matter content for peanuts was obtained through personal communications with Ketzis (1999). The residue to crop product ratios and dry matter contents for the other beans and pulses were estimated by taking averages of the values for soybeans and peanuts. The dry matter content for alfalfa was obtained through personal communications with Karkosh (2000). The IPCC default nitrogen content of 3 percent (IPCC/UNEP/OECD/IEA 1997) was used for all beans, pulses, and alfalfa.[4]

The production statistics for the non-alfalfa forage crops were derived by multiplying estimates of areas planted by estimates of annual yields, in dry matter mass units. These derived production statistics were then converted to units of nitrogen by applying the IPCC default nitrogen content of 3 percent (IPCC/UNEP/OECD/IEA 1997).

The final estimates of annual aboveground biomass production, in units of nitrogen, are presented in Table M-3. The residue to crop product mass ratios and dry matter fractions used in these calculations are presented in Table M-6.

*Retention of crop residue:* It was assumed that 90 percent of residues from corn, wheat, barley, sorghum, oats, rye, millet, soybeans, peanuts, and other beans and pulses are left on the field after harvest (e.g., rolled into the soil, chopped and disked into the soil, or otherwise left behind) (Karkosh 2000).[5] It was also assumed that 100 percent of unburned rice residue is left on the field.[6]

The derivation of residue nitrogen activity data was very similar to the derivation of nitrogen-fixing crop activity data. Crop production statistics were multiplied by aboveground residue to crop product mass ratios, residue dry matter fractions, residue nitrogen contents, and the fraction of residues left on soils. Annual production statistics for all crops except rice in Florida were taken from U.S. Department of Agriculture reports (USDA 1994a, 1998b, 2000i, 2001a). Production statistics for rice in Florida, which are not recorded by USDA, were estimated by applying an average rice crop yield for Florida (Smith 2001) to annual Florida rice acreages (Schueneman 1999, 2001). Residue to crop product ratios for all crops were obtained from, or derived from, Strehler and Stützle (1987). Dry matter contents for wheat, rice, corn, and barley residue were obtained from Turn et al. (1997). Soybean and millet residue dry matter contents were obtained from Strehler and Stützle (1987). Peanut, sorghum, oat, and rye residue dry matter contents were obtained through personal communications with Ketzis (1999). Dry matter contents for all other beans and pulses were estimated by averaging the values for soybeans and peanuts. The residue nitrogen contents for wheat, rice, corn, and barley are from Turn et al. (1997). The nitrogen content of soybean residue is from Barnard and Kristoferson (1985), the nitrogen contents of peanut, sorghum, oat, and rye residue are from Ketzis (1999), and the nitrogen content of millet residue is from Strehler and Stützle (1987). Nitrogen contents of all other beans and pulses were estimated by averaging the values for soybeans and peanuts. Estimates of the amounts of rice residue burned annually were derived using information obtained from agricultural

---

[4] This nitrogen content may be an overestimate for the residue portion of the aboveground biomass of the beans and pulses. Also, the dry matter fractions used for beans and pulses were taken from literature on crop residues, and so may be underestimates for the product portion of the aboveground biomass.

[5] Although the mode of residue application would likely affect the magnitude of $N_2O$ emissions, an emission estimation methodology that accounts for this has not been developed.

[6] Some of the rice residue may be used for other purposes, such as for biofuel or livestock bedding material. Research to obtain more detailed information regarding final disposition of rice residue, as well as the residue of other crops, will be undertaken for future inventories.

extension agents in each of the rice-growing states (see Agricultural Residue Burning section of Agriculture Chapter for more detail).

The final estimates of residue retained on soil, in units of nitrogen (N), are presented in Table M-4. The residue to crop product mass ratios, residue dry matter fractions, and residue nitrogen contents used in these calculations are presented in Table M-6.

*Cultivation of histosols:* Estimates of the areas of histosols cultivated in 1982, 1992, and 1997 were obtained from the USDA's *1997 National Resources Inventory* (USDA 2000h, as extracted by Eve 2001, and revised by Ogle 2002).[7] These areas were grouped by broad climatic region[8] using temperature and precipitation estimates from Daly et al. (1994, 1998), and then further aggregated to derive a temperate total and a sub-tropical total. These final areas were then linearly interpolated to obtain estimates for 1990 through 1996, and linearly extrapolated to obtain area estimates for 1998 through 2000 (Table M-5).

### *Step 1b: Direct $N_2O$ Emissions from Pasture, Range, and Paddock Livestock Manure.*

Estimates of $N_2O$ emissions from this component were based on livestock manure that is not managed in manure management systems, but instead is deposited directly on soils by animals in pasture, range, and paddock. The livestock included in this component were: dairy cattle, beef cattle, swine, sheep, goats, poultry, and horses.

*Dairy Cattle:* Information regarding dairy farm grazing was obtained from communications with personnel from state Natural Resource Conservation Service offices, state universities, and other experts (Poe et al. 1999, Deal 2000, Johnson 2000, Miller 2000, Stettler 2000, Sweeten 2000, Wright 2000). Because grazing operations are typically related to the number of animals on a farm, farm-size distribution data reported in the *1992 and 1997 Census of Agriculture* (USDA 1999e) were used in conjunction with the state data obtained from personal communications to determine the percentage of total dairy cattle that graze. An overall percent of dairy waste that is deposited in pasture, range, and paddock was developed for each region of the United States. This percentage was applied to the total annual dairy cow and heifer state population data for 1990 through 2000, which were obtained from the USDA National Agricultural Statistics Service (USDA 1995a; 1999a; 2000a,b; 2001b,c).

*Beef Cattle:* To determine the population of beef cattle that are on pasture, range, and paddock, the following assumptions were made: 1) beef cows, bulls, and calves were not housed on feedlots; 2) a portion of heifers and steers were on feedlots; and 3) all beef cattle that were not housed on feedlots were located on pasture, range, and paddock (i.e., total population minus population on feedlots equals population of pasture, range, and paddock) (Milton 2000). Information regarding the percentage of heifers and steers on feedlots was obtained from USDA personnel (Milton 2000) and used in conjunction with USDA National Agricultural Statistics Service population data (USDA 1995a; 1999a; 2000a,b; 2001b,c) to determine the population of steers and heifers on pasture, range, and paddock.

*Swine:* Based on the assumption that smaller facilities are less likely to utilize manure management systems, farm-size distribution data reported in the *1992 and 1997 Census of Agriculture* (USDA 1999e) were used to determine the percentage of all swine whose manure is not managed (i.e., the percentage on pasture, range, and paddock). These percentages were applied to the average of the quarterly USDA National Agricultural Statistics Service population data for swine (USDA 1994b, 1998a, 2000e, 2001d) to determine the population of swine on pasture, range, and paddock.

*Sheep:* It was assumed that all sheep and lamb manure not deposited on feedlots was deposited on pasture, range, and paddock (Anderson 2000). Sheep population data were obtained from the USDA National Agricultural Statistics Service (USDA 1994c, 1999c, 2000g, 2001f). However, population data for lamb and sheep on feed were not available after 1993. The number of lamb and sheep on feed for 1994 through 2000 were calculated using the average of the percent of lamb and sheep on feed from 1990 through 1993. In addition, all of the sheep and lamb "on feed" were not necessarily on "feedlots"; they may have been on pasture/crop residue supplemented by feed. Data for those feedlot animals versus pasture/crop residue were provided only for lamb in 1993. To calculate the

---

[7] These areas do not include Alaska, but Alaska's cropland area accounts for less than 0.1 percent of total U.S. cropland area, so this omission is not significant.

[8] These climatic regions were: 1) cold temperate, dry, 2) cold temperate, moist, 3) sub-tropical, dry, 4) sub-tropical, moist, 5) warm temperate, dry, and 6) warm temperate, moist.

populations of sheep and lamb on feedlots for all years, it was assumed that the percentage of sheep and lamb on feedlots versus pasture/crop residue is the same as that for lambs in 1993 (Anderson 2000).

*Goats:* It was assumed that 92 percent of goat manure was deposited on pasture, range, and paddock (Safley et al. 1992). Annual goat population data by state were available for only 1992 and 1997 (USDA 1999d). The data for 1992 were used for 1990 through 1992 and the data for 1997 were used for 1997 through 2000. Data for 1993 through 1996 were extrapolated using the 1992 and 1997 data.

*Poultry:* It was assumed that one percent of poultry manure was deposited on pasture, range, and paddock (Safley et al. 1992). Poultry population data were obtained from USDA National Agricultural Statistics Service (USDA 1995b, 1998a, 1999b, 2000c, 2000d, 2000f, 2001f). The annual population data for boilers and turkeys were adjusted for turnover (i.e., slaughter) rate (Lange 2000).

*Horses:* It was assumed that 92 percent of horse manure was deposited on pasture, range, and paddock (Safley et al. 1992). Horse population data were obtained from the FAOSTAT database (FAO 2001).

For each animal type, the population of animals within pasture, range, and paddock systems was multiplied by an average animal mass constant (USDA 1996, ASAE 1999, USDA 1998d, Safley 2000) to derive total animal mass for each animal type. Total Kjeldahl nitrogen excreted per year was then calculated for each animal type using daily rates of nitrogen excretion per unit of animal mass (USDA 1996, ASAE 1999). Annual nitrogen excretion was then summed over all animal types to yield total nitrogen in pasture, range, and paddock manure (Table M-2).

### *Step 1c: Indirect $N_2O$ Emissions from Soils Induced by Applications of Nitrogen.*

This component accounts for $N_2O$ that is emitted indirectly from nitrogen applied as commercial fertilizer, sewage sludge, and livestock manure. Through volatilization, some of this nitrogen enters the atmosphere as $NH_3$ and $NO_x$, and subsequently returns to soils through atmospheric deposition, thereby enhancing $N_2O$ production. Additional nitrogen is lost from soils through leaching and runoff, and enters groundwater and surface water systems, from which a portion is emitted as $N_2O$. These two indirect emission pathways are treated separately, although the activity data used, except for livestock manure, are identical. The activity data for commercial fertilizer and sewage sludge are the same as those used in the calculation of direct emissions from managed soils (Table M-1). The activity data for livestock manure are different from those used in other calculations. Here, total livestock manure (i.e., the sum of applied manure, manure in pasture, range, and paddock, and manure used as a livestock feed supplement) is used in the volatilization and deposition calculation; and livestock manure applied or deposited on soils (i.e., the sum of applied manure and manure in pasture, range, and paddock) in the leaching and runoff calculation. These data are presented in Table M-2.

**Table M-1: Commercial Fertilizer Consumption & Land Application of Sewage Sludge (Gg N)**

| Fertilizer Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Synthetic | 10,104 | 10,275 | 10,352 | 10,719 | 11,160 | 10,798 | 11,156 | 11,172 | 11,193 | 11,229 | 11,241 |
| Other Organics* | 5 | 9 | 6 | 5 | 8 | 11 | 13 | 15 | 13 | 11 | 12 |
| Sewage Sludge | 91 | 98 | 106 | 113 | 121 | 129 | 133 | 135 | 137 | 142 | 148 |

* Excludes manure and sewage sludge used as commercial fertilizer.

**Table M-2: Livestock Manure Nitrogen (Gg)**

| Activity | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Applied to Soils | 2,608 | 2,678 | 2,685 | 2,720 | 2,737 | 2,708 | 2,743 | 2,799 | 2,829 | 2,828 | 2,869 |
| Pasture, Range, & Paddock | 4,152 | 4,171 | 4,266 | 4,308 | 4,416 | 4,478 | 4,470 | 4,334 | 4,245 | 4,206 | 4,152 |
| Total Manure | 6,792 | 6,881 | 6,984 | 7,062 | 7,188 | 7,219 | 7,249 | 7,170 | 7,111 | 7,072 | 7,059 |

## Table M-3: Aboveground Biomass Nitrogen in Nitrogen-Fixing Crops (Gg)

| Crop Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Soybeans | 4,241 | 4,374 | 4,823 | 4,117 | 5,538 | 4,788 | 5,241 | 5,921 | 6,036 | 5,844 | 6,099 |
| Peanuts | 84 | 115 | 100 | 79 | 99 | 81 | 86 | 83 | 93 | 90 | 77 |
| Dry Edible Beans | 98 | 102 | 68 | 66 | 87 | 93 | 84 | 89 | 92 | 100 | 80 |
| Dry Edible Peas | 7 | 11 | 8 | 10 | 7 | 14 | 8 | 17 | 18 | 14 | 11 |
| Austrian Winter Peas | + | + | + | + | + | + | + | + | + | + | + |
| Lentils | 3 | 5 | 5 | 6 | 6 | 7 | 4 | 7 | 6 | 7 | 9 |
| Wrinkled Seed Peas | 3 | 3 | 2 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 2 |
| Alfalfa | 1,730 | 1,729 | 1,642 | 1,662 | 1,683 | 1,746 | 1,642 | 1,655 | 1,708 | 1,740 | 1,642 |
| Red Clover | 513 | 513 | 513 | 513 | 513 | 513 | 513 | 513 | 513 | 513 | 513 |
| White Clover | 2,735 | 2,735 | 2,735 | 2,735 | 2,735 | 2,735 | 2,735 | 2,735 | 2,735 | 2,735 | 2,735 |
| Birdsfoot Trefoil | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 |
| Arrowleaf Clover | 67 | 67 | 67 | 65 | 63 | 61 | 58 | 56 | 54 | 52 | 50 |
| Crimson Clover | 21 | 21 | 21 | 19 | 18 | 17 | 16 | 14 | 13 | 12 | 11 |
| **Total** | **9,600** | **9,774** | **10,082** | **9,375** | **10,850** | **10,156** | **10,488** | **11,192** | **11,368** | **11,207** | **11,327** |

+ Less than 0.5 Gg N.
Note: Totals may not sum due to independent rounding.

## Table M-4: Nitrogen in Crop Residues Retained on Soils (Gg)

| Product Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Corn | 957 | 902 | 1,143 | 765 | 1,213 | 893 | 1,114 | 1,111 | 1,177 | 1,138 | 1,203 |
| Wheat | 501 | 364 | 453 | 440 | 426 | 401 | 418 | 456 | 468 | 422 | 408 |
| Barley | 71 | 78 | 77 | 67 | 63 | 61 | 66 | 61 | 59 | 47 | 54 |
| Sorghum | 180 | 184 | 275 | 168 | 203 | 144 | 250 | 199 | 164 | 187 | 148 |
| Oats | 39 | 27 | 32 | 23 | 25 | 18 | 17 | 18 | 18 | 16 | 16 |
| Rye | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 1 |
| Millet | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 1 |
| Rice | 51 | 53 | 61 | 52 | 65 | 60 | 57 | 66 | 69 | 75 | 69 |
| Soybeans | 1,982 | 2,045 | 2,254 | 1,924 | 2,588 | 2,238 | 2,450 | 2,767 | 2,821 | 2,731 | 2,851 |
| Peanuts | 13 | 18 | 16 | 13 | 16 | 13 | 14 | 13 | 15 | 14 | 12 |
| Dry Edible Beans | 11 | 12 | 8 | 7 | 10 | 10 | 10 | 10 | 10 | 11 | 9 |
| Dry Edible Peas | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | 1 |
| Austrian Winter Peas | + | + | + | + | + | + | + | + | + | + | + |
| Lentils | + | 1 | 1 | 1 | 1 | 1 | + | 1 | 1 | 1 | 1 |
| Wrinkled Seed Peas | + | + | + | + | + | + | + | + | + | + | + |
| **Total** | **3,814** | **3,689** | **4,326** | **3,466** | **4,616** | **3,845** | **4,402** | **4,709** | **4,810** | **4,650** | **4,775** |

+ Less than 0.5 Gg N.
Note: Totals may not sum due to independent rounding.

## Table M-5: Cultivated Histosol Area (Thousand Hectares)

| Year | Temperate Area | Sub-Tropical Area |
|---|---|---|
| 1990 | 432 | 192 |
| 1991 | 431 | 193 |
| 1992 | 429 | 194 |
| 1993 | 431 | 194 |
| 1994 | 433 | 195 |
| 1995 | 435 | 195 |
| 1996 | 437 | 196 |
| 1997 | 439 | 196 |
| 1998 | 441 | 197 |
| 1999 | 443 | 197 |
| 2000 | 445 | 197 |

**Table M-6: Key Assumptions for Nitrogen-Fixing Crop Production and Crop Residue**

| Crop | Residue/Crop Ratio | Residue Dry Matter Fraction | Residue Nitrogen Fraction |
|---|---|---|---|
| Soybeans | 2.1 | 0.87 | 0.023 |
| Peanuts | 1.0 | 0.86 | 0.0106 |
| Dry Edible Beans | 1.55 | 0.87 | 0.0062 |
| Dry Edible Peas | 1.55 | 0.87 | 0.0062 |
| Austrian Winter Peas | 1.55 | 0.87 | 0.0062 |
| Lentils | 1.55 | 0.87 | 0.0062 |
| Wrinkled Seed Peas | 1.55 | 0.87 | 0.0062 |
| Alfalfa | 0 | 0.85 | NA |
| Corn | 1.0 | 0.91 | 0.0058 |
| Wheat | 1.3 | 0.93 | 0.0062 |
| Barley | 1.2 | 0.93 | 0.0077 |
| Sorghum | 1.4 | 0.91 | 0.0108 |
| Oats | 1.3 | 0.92 | 0.007 |
| Rye | 1.6 | 0.90 | 0.0048 |
| Millet | 1.4 | 0.89 | 0.007 |
| Rice | 1.4 | 0.91 | 0.0072 |

Note: For the derivation of activity data for nitrogen-fixing crop production, the IPCC default nitrogen content of aboveground biomass (3 percent) was used.

### Step 2: Estimate Direct $N_2O$ Emissions from Managed Soils Due to Nitrogen Additions and Cultivation of Histosols

In this step, $N_2O$ emissions were calculated for each of two parts (direct $N_2O$ emissions due to nitrogen additions and direct $N_2O$ emissions due to histosol cultivation), which were then summed to yield total direct $N_2O$ emissions from managed soils (Table M-7).

#### *Step 2a: Direct $N_2O$ Emissions Due to Nitrogen Additions.*

To estimate these emissions, the amounts of nitrogen applied were each reduced by the IPCC default fraction of nitrogen that is assumed to volatilize, the unvolatilized amounts were then summed, and the total unvolatilized nitrogen was multiplied by the IPCC default emission factor of 0.0125 kg $N_2O$-N/kg Nitrogen (IPCC/UNEP/OECD/IEA 1997). The volatilization assumptions are described below.

- *Application of synthetic and organic commercial fertilizer:* The total amounts of nitrogen applied in the form of synthetic commercial fertilizers and non-manure/non-sewage organic commercial fertilizers were reduced by 10 percent and 20 percent, respectively, to account for the portion that volatilizes to $NH_3$ and $NO_x$ (IPCC/UNEP/OECD/IEA 1997).
- *Application of livestock manure:* The total amount of livestock manure nitrogen applied to soils was reduced by 20 percent to account for the portion that volatilizes to $NH_3$ and $NO_x$ (IPCC/UNEP/OECD/IEA 1997).
- *Application of sewage sludge:* The total amount of sewage sludge nitrogen applied to soils was reduced by 20 percent to account for the portion that volatilizes to $NH_3$ and $NO_x$ (IPCC/UNEP/OECD/IEA 1997, IPCC 2000).
- *Production of nitrogen-fixing crops:* None of the nitrogen in the aboveground biomass of nitrogen-fixing crops was assumed to volatilize.
- *Retention of crop residue:* None of the nitrogen in retained crop residue was assumed to volatilize.

#### *Step 2b: Direct $N_2O$ Emissions Due to Cultivation of Histosols.*

To estimate annual $N_2O$ emissions from histosol cultivation, the temperate histosol area was multiplied by the IPCC default emission factor for temperate soils (8 kg $N_2O$-N/ha cultivated; IPCC 2000), and the sub-tropical

histosol area was multiplied by the average of the temperate and tropical IPCC default emission factors (12 kg $N_2O$-N/ha cultivated; IPCC 2000).

### Step 3: Estimate Direct $N_2O$ Emissions from Pasture, Range, and Paddock Livestock Manure

To estimate direct $N_2O$ emissions from soils due to the deposition of pasture, range, and paddock manure, the total nitrogen excreted by these animals was multiplied by the IPCC default emission factor (0.02 kg $N_2O$-N/kg N excreted) (see Table M-8).

### Step 4: Estimate Indirect $N_2O$ Emissions Induced by Applications of Nitrogen

In this step, $N_2O$ emissions were calculated for each of two parts (indirect $N_2O$ emissions due to volatilization of applied nitrogen and indirect $N_2O$ emissions due to leaching and runoff of applied nitrogen), which were then summed to yield total direct $N_2O$ emissions from managed soils.

#### *Step 4a: Indirect Emissions Due to Volatilization.*

To estimate these emissions, first the amounts of commercial fertilizer nitrogen and sewage sludge nitrogen applied, and the total amount of manure nitrogen produced, were each multiplied by the IPCC default fraction of nitrogen that is assumed to volatilize to $NH_3$ and $NO_x$ (10 percent for synthetic fertilizer nitrogen; and 20 percent for nitrogen in organic fertilizer, sewage sludge, and livestock manure). Next, the volatilized amounts of nitrogen were summed, and then the total volatilized nitrogen was multiplied by the IPCC default emission factor of 0.01 kg $N_2O$-N/kg N (IPCC/UNEP/OECD/IEA 1997). These emission estimates are presented in (Table M-9).

#### *Step 4b: Indirect Emissions Due to Leaching and Runoff.*

To estimate these emissions, first the amounts of commercial fertilizer nitrogen and sewage sludge nitrogen applied, and the total amount of manure nitrogen applied or deposited, were each multiplied by the IPCC default fraction of nitrogen that is assumed to leach and runoff (30 percent for all nitrogen). Next, the leached/runoff amounts of nitrogen were summed, and then the total nitrogen was multiplied by the IPCC default emission factor of 0.025 kg $N_2O$-N/kg N (IPCC/UNEP/OECD/IEA 1997). These emission estimates are presented in (Table M-9).

**Table M-7: Direct $N_2O$ Emissions from Managed Soils (Tg $CO_2$ Eq.)**

| Activity | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Commercial Fertilizers* | 55 | 56 | 57 | 59 | 61 | 59 | 61 | 61 | 61 | 62 | 62 |
| Livestock Manure | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 14 | 14 | 14 |
| Sewage Sludge | + | + | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Nitrogen Fixation | 58 | 60 | 61 | 57 | 66 | 62 | 64 | 68 | 69 | 68 | 69 |
| Crop Residue | 23 | 22 | 26 | 21 | 28 | 23 | 27 | 29 | 29 | 28 | 29 |
| Histosol Cultivation | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **Total** | **153** | **155** | **161** | **154** | **172** | **161** | **169** | **175** | **177** | **176** | **177** |

+ Less than 0.5 Tg $CO_2$ Eq.
Note: Totals may not sum due to independent rounding.
* These data do not include sewage sludge and livestock manure used as commercial fertilizers, to avoid double counting.

**Table M-8: Direct $N_2O$ Emissions from Pasture, Range, and Paddock Livestock Manure (Tg $CO_2$ Eq.)**

| Animal Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Beef Cattle | 35 | 35 | 36 | 37 | 38 | 39 | 39 | 38 | 37 | 37 | 36 |
| Dairy Cows | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| Swine | + | 1 | 1 | + | + | + | + | + | + | + | + |
| Sheep | + | + | + | + | + | + | + | + | + | + | + |
| Goats | + | + | + | + | + | + | + | + | + | + | + |
| Poultry | + | + | + | + | + | + | + | + | + | + | + |
| Horses | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **Total** | **40** | **41** | **42** | **42** | **43** | **44** | **44** | **42** | **41** | **41** | **40** |

+ Less than 0.5 Tg $CO_2$ Eq.
Note: Totals may not sum due to independent rounding.

**Table M-9: Indirect $N_2O$ Emissions (Tg $CO_2$ Eq.)**

| Activity | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Volatil. & Atm. Deposition** | **12** | **12** | **12** | **12** | **13** | **12** | **13** | **13** | **13** | **13** | **13** |
| Comm. Fertilizers | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Livestock Manure | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Sewage Sludge | + | + | + | + | + | + | + | + | + | + | + |
| **Surface Leaching & Runoff** | **62** | **63** | **64** | **65** | **67** | **66** | **68** | **67** | **67** | **67** | **67** |
| Comm. Fertilizers | 37 | 38 | 38 | 39 | 41 | 39 | 41 | 41 | 41 | 41 | 41 |
| Livestock Manure | 25 | 25 | 25 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |
| Sewage Sludge | + | + | + | + | + | + | + | + | + | 1 | 1 |
| **Total** | **74** | **75** | **76** | **78** | **80** | **79** | **80** | **80** | **80** | **80** | **80** |

+ Less than 0.5 Tg $CO_2$ Eq.
Note: Totals may not sum due to independent rounding.

### Step 5: Estimate Total $N_2O$ Emissions

In this step, total emissions are calculated by summing direct emissions from managed soils, direct emissions from pasture, range, and paddock livestock manure, and indirect emissions (Table M-10).

**Table M-10: Total $N_2O$ Emissions (Tg $CO_2$ Eq.)**

| Activity | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Direct Emissions from Managed Soils | 153 | 155 | 161 | 154 | 172 | 161 | 169 | 175 | 177 | 176 | 177 |
| Direct Emissions from Pasture, Range, and Paddock Livestock | 40 | 41 | 42 | 42 | 43 | 44 | 44 | 42 | 41 | 41 | 40 |
| Indirect Emissions | 74 | 75 | 76 | 78 | 80 | 79 | 80 | 80 | 80 | 80 | 80 |
| **Total** | **267** | **270** | **278** | **273** | **295** | **283** | **292** | **297** | **298** | **296** | **297** |

Note: Totals may not sum due to independent rounding.

# ANNEX N

## Methodology for Estimating Net Changes in Forest Carbon Stocks

This annex presents a discussion of the methodology used to calculate net changes in carbon stocks in trees, understory, forest floor, down dead wood, forest soils, and harvested wood (i.e., wood products and landfilled wood). More detailed discussions of selected topics may be found in the references cited in this annex.

The details of carbon conversion factors and step-by-step details of calculating net $CO_2$ flux for forests are given in three steps. In addition, the modeling projection system is briefly described.

### Step 1: Estimate Forest Carbon Stocks and Net Changes in Forest Carbon Stocks

#### *Step 1a: Obtain Forest Inventory Data*

Forest survey data in the United States by broad forest type and region for 1987 and 1997 were obtained from U.S. Forest Service, Forest Inventory & Analysis (FIA) estimates of forest resources, published in Waddell et al. (1989) and Smith et al. (2001). The FIA data include: (1) growing stock volume per acre by forest type (referred to hereinafter as "growing stock volumes"); and (2) area by Timberland and other forest land, for general forest types by region (referred to hereinafter as "forest areas"). For 2001, the same variables were obtained from model results as described in Haynes et al. (2001b). (See The Forest Sector Modeling Projection System below). This information was combined with separate estimates of carbon density (carbon mass per unit area) to compile estimates of carbon stocks.

#### *Step 1b: Estimate Carbon in Living and Standing Dead Trees*

To estimate live tree biomass, equations that convert forest tree volumes to total live tree dry biomass (Smith et al. in review) were applied to the growing stock volumes by forest type and region (obtained in Step 1a). Tree biomass includes aboveground biomass and belowground biomass of coarse roots. The minimum size tree is one-inch diameter at diameter breast height (1.3 meter). Trees less than one-inch diameter are counted as carbon in understory vegetation. Biomass estimates were divided by two to obtain estimates of carbon in living trees (i.e., it was assumed that dry biomass is 50 percent carbon). Standing dead tree biomass was calculated by applying equations that estimate biomass for standing dead trees (Smith et al. in review) from growing stock volumes. Again, standing dead tree biomass was divided by two to estimate carbon in standing dead trees. Table N-1 lists the average living and standing dead tree carbon densities by forest type, as calculated by applying the equations to the 1997 data.

**Table N-1: Average U.S. Carbon Densities of Forest Components* (metric tons C/ha)**

| Region[a]/Forest Type | Live and Standing Dead Tree Carbon | Forest Floor Carbon | Soil Organic Carbon[b] |
|---|---|---|---|
| Eastern | | | |
| White-red-jack pine | 77.1 | 13.8 | 196.1 |
| Spruce-fir | 59.8 | 40.2 | 192.9 |
| Longleaf-slash pine | 42.4 | 9.2 | 136.3 |
| Loblolly-shortleaf pine | 49.3 | 9.1 | 91.7 |
| Oak-pine | 57.3 | 11.6 | 82.3 |
| Oak-hickory | 76.3 | 6.6 | 85.0 |
| Oak-gum-cypress | 86.0 | 6.0 | 152.2 |
| Elm-ash-cottonwood | 67.6 | 23.0 | 118.1 |
| Maple-beech-birch | 82.5 | 28.0 | 139.5 |
| Aspen-birch | 56.0 | 7.6 | 237.0 |
| Other forest types | 1.8 | 2.1 | 99.6 |
| Nonstocked | 3.7 | 3.5 | 99.6 |
| Western | | | |
| Douglas-fir | 110.8 | 30.7 | 89.6 |
| Ponderosa pine | 66.3 | 20.3 | 70.4 |
| Western white pine | 69.2 | 25.8 | 68.3 |
| Fir-spruce | 113.0 | 37.4 | 137.5 |
| Hemlock-Sitka spruce | 152.4 | 34.1 | 157.1 |
| Larch | 97.0 | 30.2 | 65.6 |
| Lodgepole pine | 67.8 | 23.9 | 62.7 |
| Redwood | 186.6 | 26.9 | 85.8 |
| Hardwoods | 89.0 | 9.9 | 79.5 |
| Other forest types | 55.4 | 28.2 | 90.1 |
| Pinyon-juniper | 20.8 | 21.1 | 56.3 |
| Chaparral | 17.5 | 25.7 | 58.7 |
| Nonstocked | 18.1 | 24.4 | 90.1 |

* Based on 1997 data for major forest types of the conterminous United States.
[a]Eastern United States is defined as states east of, and including North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas. Western United States includes the remaining conterminous States.
[b]Soil includes both mineral soils and organic soils (i.e., histosols); carbon densities are to a depth of 1 meter.

### *Step 1c: Estimate Carbon in Understory Vegetation*

To estimate carbon in understory vegetation, equations based on Birdsey (1992) were applied to the database that was used to produce the compiled forest statistics in Smith et al. (2001). Understory vegetation is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than one-inch diameter, measured at breast height. A ratio of understory carbon to live tree carbon was calculated, and multiplied by 100 to display the percent that understory carbon is as related to live tree carbon. The average percent understory carbon to live tree carbon was calculated by region and forest type. This percent was multiplied by the live tree carbon data in 1987 and 1997 to calculate understory carbon. These percentages are given in Table N-2. This procedure was used instead of applying the Birdsey equations directly, because detailed databases are not available for inventory years prior to 1987. Using average estimates results in consistent historical carbon estimates for all survey years.

**Table N-2: Ratios of Understory and Down Dead Wood Carbon to Live Tree Carbon* (percent)**

| Region/Forest Type | Ratio of Understory Carbon to Live Tree Carbon | Ratio of Down Dead Wood Carbon to Live Tree Carbon |
|---|---|---|
| Northeast | | |
| White-red-jack pine | 2.5 | 10.8 |
| Spruce-fir | 2.6 | 13.3 |
| Longleaf-Slash pine | 2.5 | 10.8 |
| Loblolly-shortleaf pine | 2.5 | 10.8 |
| Oak-pine | 2.8 | 12.9 |

| | | |
|---|---|---|
| Oak-hickory | 2.4 | 10.9 |
| Oak-gum-cypress | 2.6 | 11.1 |
| Elm-ash-cottonwood | 2.6 | 11.1 |
| Maple-beech-birch | 1.9 | 11.1 |
| Aspen-birch | 2.7 | 13.6 |
| Other Forest Types | 8.9 | 3.8 |
| Nonstocked | 8.9 | 3.8 |
| **North Central** | | |
| White-red-jack pine | 1.8 | 9.8 |
| Spruce-fir | 2.2 | 17.4 |
| Longleaf-Slash pine | 2.4 | 7.4 |
| Loblolly-shortleaf pine | 2.4 | 7.4 |
| Oak-pine | 1.9 | 7.2 |
| Oak-hickory | 2.3 | 9.6 |
| Oak-gum-cypress | 2.3 | 9.6 |
| Elm-ash-cottonwood | 2.2 | 10.8 |
| Maple-beech-birch | 2.2 | 10.8 |
| Aspen-birch | 2.8 | 13.3 |
| Other Forest Types | 5.5 | 4.1 |
| Nonstocked | 5.5 | 4.1 |
| **Southeast** | | |
| White-red-jack pine | 6.8 | 23.9 |
| Spruce-fir | 6.8 | 23.9 |
| Longleaf-Slash pine | 6.8 | 23.9 |
| Loblolly-shortleaf pine | 6.8 | 23.9 |
| Oak-pine | 5.2 | 28.0 |
| Oak-hickory | 4.4 | 24.2 |
| Oak-gum-cypress | 2.2 | 21.8 |
| Elm-ash-cottonwood | 2.2 | 21.8 |
| Maple-beech-birch | 4.4 | 24.2 |
| Aspen-birch | 2.2 | 21.8 |
| Other Forest Types | 11.9 | 2.0 |
| Nonstocked | 11.9 | 2.0 |
| **South Central** | | |
| White-red-jack pine | 5.9 | 18.6 |
| Spruce-fir | 5.9 | 18.6 |
| Longleaf-Slash pine | 5.9 | 18.6 |
| Loblolly-shortleaf pine | 5.9 | 18.6 |
| Oak-pine | 4.4 | 17.3 |
| Oak-hickory | 3.7 | 15.0 |
| Oak-gum-cypress | 2.2 | 15.7 |
| Elm-ash-cottonwood | 2.2 | 15.7 |
| Maple-beech-birch | 3.7 | 15.0 |
| Aspen-birch | 2.2 | 15.7 |
| Other Forest Types | 16.9 | 1.7 |
| Nonstocked | 16.9 | 1.7 |
| **Pacific Northwest Eastside of Cascades** | | |
| Douglas-fir | 1.6 | 10.0 |
| Ponderosa Pine | 2.5 | 12.6 |
| Western White Pine | 1.6 | 10.0 |
| Fir-Spruce | 1.1 | 15.7 |
| Hemlock-Sitka spruce | 1.6 | 10.0 |
| Larch | 1.6 | 10.0 |
| Lodgepole pine | 2.6 | 21.3 |
| Redwood | 1.9 | 25.8 |
| Other hardwoods | 1.4 | 8.9 |
| Unclassified & other | 2.5 | 12.6 |
| Pinyon-Juniper | 10.7 | 3.7 |
| Chaparral | 9.7 | 2.1 |
| Nonstocked | 9.7 | 2.1 |
| **Pacific Northwest Westside of Cascades** | | |
| Douglas-fir | 2.0 | 11.9 |

| | | |
|---|---|---|
| Ponderosa Pine | 2.5 | 18.1 |
| Western White Pine | 2.5 | 18.1 |
| Fir-Spruce | 1.0 | 13.7 |
| Hemlock-Sitka spruce | 1.0 | 13.7 |
| Larch | 2.0 | 11.9 |
| Lodgepole pine | 1.7 | 16.4 |
| Redwood | 2.0 | 11.9 |
| Other hardwoods | 4.5 | 3.9 |
| Unclassified & other | 1.7 | 16.4 |
| Pinyon-Juniper | 20.2 | 3.7 |
| Chaparral | 14.2 | 3.0 |
| Nonstocked | 14.2 | 3.0 |
| **Rocky Mountain, Northern** | | |
| Douglas-fir | 2.6 | 19.2 |
| Ponderosa Pine | 2.4 | 19.6 |
| Western White Pine | 2.2 | 9.7 |
| Fir-Spruce | 1.7 | 14.8 |
| Hemlock-Sitka spruce | 2.0 | 18.7 |
| Larch | 2.2 | 9.7 |
| Lodgepole pine | 2.4 | 19.6 |
| Redwood | 2.2 | 9.7 |
| Other hardwoods | 1.9 | 14.2 |
| Unclassified & other | 2.2 | 9.7 |
| Pinyon-Juniper | 16.1 | 3.2 |
| Chaparral | 16.1 | 3.2 |
| Nonstocked | 16.1 | 3.2 |
| **Rocky Mountain, Southern** | | |
| Douglas-fir | 2.8 | 19.4 |
| Ponderosa Pine | 4.1 | 21.6 |
| Western White Pine | 2.8 | 19.4 |
| Fir-Spruce | 2.2 | 17.4 |
| Hemlock-Sitka spruce | 2.8 | 19.4 |
| Larch | 2.8 | 19.4 |
| Lodgepole pine | 3.1 | 12.8 |
| Redwood | 2.8 | 19.4 |
| Other hardwoods | 9.2 | 26.7 |
| Unclassified & other | 10.7 | 3.3 |
| Pinyon-Juniper | 9.8 | 3.9 |
| Chaparral | 9.8 | 3.9 |
| Nonstocked | 2.6 | 15.2 |
| **Pacific Southwest** | | |
| Douglas-fir | 2.3 | 15.5 |
| Ponderosa Pine | 2.6 | 15.2 |
| Western White Pine | 2.2 | 11.5 |
| Fir-Spruce | 2.6 | 15.2 |
| Hemlock-Sitka spruce | 2.6 | 15.2 |
| Larch | 4.6 | 10.8 |
| Lodgepole pine | 2.6 | 15.2 |
| Redwood | 4.4 | 9.7 |
| Other hardwoods | 2.8 | 11.5 |
| Unclassified & other | 9.9 | 3.1 |
| Pinyon-Juniper | 15.3 | 3.5 |
| Chaparral | 15.3 | 3.5 |
| Nonstocked | 2.5 | 10.8 |

* Based on data from 1997. Regions are defined in Figure 6-2 of the Land-Use Change and Forestry Chapter.

### *Step 1d: Estimate Carbon in Forest Floor*

To estimate forest floor carbon, the forest floor equations (Smith and Heath, in review) were applied to the dataset described in Step 1a. Forest floor carbon is the pool of organic carbon (litter, duff, humus, and small woody

debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. Table N-1 shows the average forest floor carbon densities by forest type, as calculated by applying the equations to the 1997 data.

#### *Step 1e: Estimate Carbon in Down Dead Wood*

To estimate carbon in down dead wood, a procedure similar to estimating carbon in understory vegetation was used. Down dead wood is defined as dead wood pieces not attached to trees, greater than 7.5 cm diameter, including stumps and roots of harvested trees. Down dead wood was estimated in the projections by using decay rates applied to logging residue, along with equations that estimate down dead wood not related to harvesting. The ratio of down dead wood carbon to live tree carbon was calculated, and multiplied by 100 to display the ratio as a percentage. The average percentage of down dead wood carbon as compared to live tree carbon was calculated by region and forest type. The percent was multiplied by the live tree carbon data based on the dataset described in step 1a to calculate down dead wood carbon. These percentages are given in Table N-2. This procedure was used because detailed databases are not available for older data. By using average estimates, carbon estimates from historical data are consistent with carbon estimates from current FIA data.

#### *Step 1f: Estimate Forest Soil Carbon*

To estimate forest soil carbon, soil carbon estimates for 1 meter depth were obtained from the STATSGO database (USDA 1991). A forest type coverage (Powell et al. 1993) was overlaid onto the soil carbon estimates derived from STATSGO. An average soil carbon estimate was then calculated by forest type. Soil organic carbon of both mineral soils and organic soils (histosol soil order, characterized as soils that develop in wetland areas, and have greater than 20 to 30 percent organic matter by weight, depending on clay content) was included. Coarse roots were included with tree carbon estimates rather than with soils. The soil carbon estimates are given in Table N-1. These estimates were multiplied by the area of forest land in each forest type for all years. Thus, any change in soil carbon is purely a reflection of the changing forest land base.

#### *Step 1g: Calculate Net Carbon Stock Changes*

The next step was to calculate the average annual net carbon stock change for each forest carbon pool for the years from 1990 through 2000. The net annual stock change for each pool for 1987 through 1997 was derived by subtracting the 1987 stock from the 1992 stock, and dividing by the number of years between estimates (10 years). The stocks, by definition, correspond to the stock as of January 1 of the given year. The net annual stock changes for 1997 through 2000 were derived in the same way using the 1997 and 2001 stocks.

### Step 2: Estimate Harvested Wood Carbon Fluxes

The first step in estimating harvested wood (i.e., wood products and landfilled wood) carbon flux estimates was to compile historical data on: the production of lumber, plywood and veneer, pulp and other products; product and log imports and exports; and fuelwood (in terms of million cubic feet of roundwood equivalent beginning in the year 1900, as described in Skog and Nicholson 1998). Data were obtained from USDA (1964), Ulrich (1989), and Howard (2001). Projected products and roundwood use were obtained from the models used for the USDA Forest Service 2000 Resource Planning Act Assessment (Haynes et al. 2001b, Ince 1994). Roundwood products include logs, bolts, and other round timber generated from harvesting trees for industrial or consumer use. The harvested wood-to-carbon conversion factors (as listed in Skog and Nicholson 1998) were applied to annual estimates and projections to produce an estimate for carbon in roundwood in products. Roundwood consumed was categorized according to product, such as lumber, railroad ties, and paper, because the time carbon remains in those products differs substantially. The dynamics of carbon loss through decay or through disposal of the product is summarized as the half-life of each product (Skog and Nicholson 1998). The resulting estimates can be applied to products to derive the net carbon change in wood products and landfills. Note that, unlike forest carbon stock estimates, carbon in harvested wood products estimates are derived as a carbon stock change. In other words, the annual roundwood production is a change variable already before it is converted to carbon.

### Step 3: Sum the Results from Step 1 and Step 2 for the Total Net Flux from U.S. Forests

In the final step, net changes in forest carbon stocks are added to net changes in harvested wood carbon stocks, to obtain estimates of total net forest flux (see Table N-3).

**Table N-3: Net $CO_2$ Flux from U.S. Forest Carbon Stocks (Tg $CO_2$ Eq.)**

| Description | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Forests** | **(773.7)** | **(773.7)** | **(773.7)** | **(773.7)** | **(773.7)** | **(773.7)** | **(773.7)** | **(546.3)** | **(546.3)** | **(546.3)** | **(546.3)** |
| Trees | (469.3) | (469.3) | (469.3) | (469.3) | (469.3) | (469.3) | (469.3) | (447.3) | (447.3) | (447.3) | (447.3) |
| Understory | (11.0) | (11.0) | (11.0) | (11.0) | (11.0) | (11.0) | (11.0) | (14.7) | (14.7) | (14.7) | (14.7) |
| Forest Floor | (25.7) | (25.7) | (25.7) | (25.7) | (25.7) | (25.7) | (25.7) | 29.3 | 29.3 | 29.3 | 29.3 |
| Down Dead Wood | (55.0) | (55.0) | (55.0) | (55.0) | (55.0) | (55.0) | (55.0) | (58.7) | (58.7) | (58.7) | (58.7) |
| Forest Soils | (212.7) | (212.7) | (212.7) | (212.7) | (212.7) | (212.7) | (212.7) | (55.0) | (55.0) | (55.0) | (55.0) |
| **Harvested Wood** | **(209.0)** | **(198.0)** | **(202.8)** | **(203.9)** | **(210.5)** | **(205.3)** | **(205.3)** | **(212.7)** | **(205.3)** | **(216.3)** | **(223.7)** |
| Wood Products | (47.7) | (40.7) | (46.6) | (54.6) | (60.9) | (55.0) | (55.0) | (58.7) | (51.3) | (62.3) | (66.0) |
| Landfilled Wood | (161.3) | (157.3) | (156.2) | (149.2) | (149.6) | (150.3) | (150.3) | (154.0) | (154.0) | (154.0) | (157.7) |
| **Total** | **(982.7)** | **(971.7)** | **(976.4)** | **(977.5)** | **(984.1)** | **(979.0)** | **(979.0)** | **(759.0)** | **(751.7)** | **(762.7)** | **(770.0)** |

Note: Parentheses indicate net carbon "sequestration" (i.e., accumulation into the carbon pool minus emissions or stock removal from the carbon pool). The sum of the net stock changes in this table (i.e., total net flux) is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Lightly shaded areas indicate values based on a combination of historical data and projections. Forest values are based on periodic measurements; harvested wood estimates are based on annual surveys. Totals may not sum due to independent rounding.

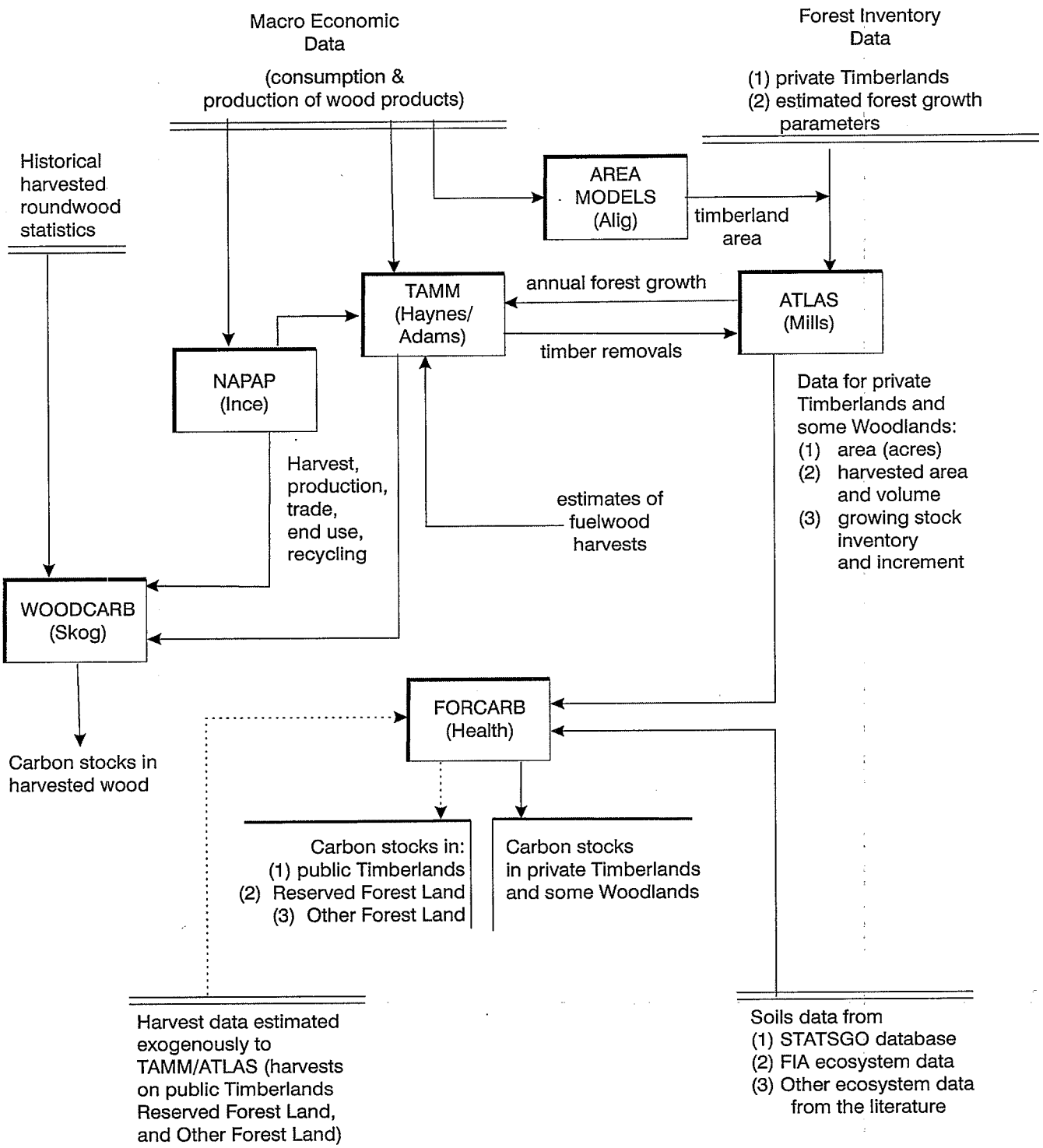
## The Forest Sector Modeling Projection System

The modeling projection system is a set of models that has been used for the USDA Forest Service, Resource Planning Act Assessment since the late 1980's (see Figure N-1). The models include an area change model (Alig 1985), a timber market model (TAMM; Adams and Haynes 1980), a pulp and paper model (NAPAP; Ince 1994) and an inventory model (ATLAS; Mills and Kincaid 1992). Many of these models are econometric models, designed to project the demand and supply and prices in the forest sector. Results of the projection include timber volume, forest areas, harvests, and primary product production. To see all the assumptions and results of the modeling system for 2001, see Haynes et al. (2001b).

The FORCARB model (Plantinga and Birdsey 1993, Heath and Birdsey 1993, and Heath et al. 1996) uses data on timber volume, forest areas, and harvests from the modeling system to estimate carbon in trees using biometrical relationships between carbon and live tree volume. FORCARB estimates carbon in all other forest ecosystem components, producing carbon density estimates similar to those in Table N-1 and Table N-2. The model WOODCARB (Skog and Nicholson 1998) uses harvested roundwood product statistics, along with end-use, decay rate, and duration information to estimate carbon in harvested wood.

This figure illustrates the models, data inputs, and data outputs that compose the forest sector modeling projection system. Names of model authors are in parentheses in each model box to facilitate identification of model citations. Data that are external to the models are marked with double lines.

# Figure N-1: Forest Sector Modeling Projection System



# ANNEX O

## Methodology for Estimating $CH_4$ Emissions from Landfills

Landfill methane ($CH_4$) is produced from a complex process of waste decomposition and subsequent fermentation under anaerobic conditions. The amount and rate of methane production depends upon the characteristics of the landfilled material and the surrounding environment. To estimate the amount of methane produced in a landfill in a given year, the following information is needed: the quantity of waste in the landfill, the landfill characteristics, the residence time of the waste in the landfill, and the landfill capacity.

The amount of methane emitted from a landfill is less than the amount generated. If no measures are taken to extract the methane, a portion of it will oxidize as it travels through the top layer of the landfill cover. The portion of the methane that oxidizes turns primarily to carbon dioxide ($CO_2$). If the methane is extracted and combusted (e.g., flared or used for energy), then that portion of the methane produced in the landfill will not be emitted as methane, but again, would be oxidized to $CO_2$. In general, landfill-related $CO_2$ emissions are of biogenic origin and primarily result from the decomposition, either aerobic or anaerobic, of organic matter such as food or yard wastes.[1]

Methane emissions are primarily driven by the quantity of waste in landfills. From an analysis of the population of municipal solid waste (MSW) landfills, landfill-specific data were extracted and used in an emissions model to estimate the amount of methane produced by municipal solid waste. Although not explicitly modeled, methane emissions from industrial landfills were assumed to be seven percent of the total methane generated from MSW at landfills. Total methane emissions were estimated by adding the methane from MSW landfills, subtracting the amount recovered or used for energy or flared, subtracting the amount oxidized in the soil, and adding emissions from industrial landfills. The steps taken to estimate emissions from U.S. landfills for the years 1990 through 2000 are discussed in greater detail below.

### Step 1: Estimate Municipal Solid Waste-in-Place Contributing to Methane Emissions

First, landfills were characterized as of 1990 based on a landfill survey (EPA 1988). Each landfill was characterized in terms of its year of opening, waste acceptance during operation, year of closure, and design capacity. Following characterization of the landfill population, waste was simulated to be placed in these landfills. For 1990 through 2000, waste disposal estimates were based on annual *BioCycle* (2001) data. Landfills were simulated to open and close based on waste disposal rates. If landfills reached their design capacity, they were simulated to close. New landfills were simulated to open when a significant shortfall in disposal capacity was predicted. Simulated new landfills were assumed to be larger, on average, reflecting the trend toward fewer and more centralized facilities. The analysis updated the landfill characteristics each year, calculating the total waste-in-place and the profile of waste disposal over time. Table O-1 shows the amount of waste landfilled each year and the total estimated waste-in-place contributing to methane emissions.

### Step 2: Estimate Landfill Methane Production

Emissions for each landfill were estimated by applying the emissions model (EPA 1993) to the landfill waste-in-place contributing to methane production. The model estimates that landfilled waste generates methane for 30 years after disposal. Total emissions were then calculated as the sum of emissions from all landfills, open and closed.

### Step 3: Estimate Industrial Landfill Methane Production

Industrial landfills receive waste from factories, processing plants, and other manufacturing activities. Because no data were available on methane generation at industrial landfills, emissions from industrial landfills were assumed to equal seven percent of the total methane emitted from MSW landfills (EPA 1993). The EPA

[1] Emissions and sinks of biogenic carbon are accounted for in the Land-Use Change and Forestry chapter.

landfill survey contained estimates of industrial waste (EPA 1988). The organic content of industrial waste represents seven percent of the methane producing capacity of MSW. These emissions are shown in Table O-2.

### Step 4: Estimate Methane Emissions Avoided

The estimate of methane emissions avoided was based on landfill-specific data on flares and landfill gas-to-energy (LFGTE) projects.

#### *Step 4a: Estimate Methane Emissions Avoided through Flaring*

The quantity of methane flared was based on data collected from flaring equipment vendors, including information on the quantity of flares, landfill gas flow rates, and year of installation. To avoid double counting, flares associated with landfills that had an LFGTE project were excluded from the flaring analysis. Total methane recovered was estimated by summing the median landfill gas flow rate for each remaining flare. However, several vendors provided information on the size of the flare rather than the landfill gas flow rate. To estimate a median flare rate for flares associated with these vendors, the size of the flare was matched with the size and corresponding flow rate provided by the other vendors.

#### *Step 4b: Estimate Methane Emissions Avoided through Landfill gas-to-energy (LFGTE) projects*

The quantity of methane avoided due to LFGTE systems was estimated based on information in a database compiled by EPA's Landfill Methane Outreach Program (LMOP). Using data on landfill gas flow and energy generation, the total direct methane emissions avoided were estimated.

To avoid double counting flares associated with LFGTE projects, the flare estimates were adjusted to account for LFGTE projects for which an associated flare could not be identified.

### Step 5: Estimate Methane Oxidation

As discussed above, a portion of the methane escaping from a landfill through its cover oxidizes in the top layer of the soil. The amount of oxidation that occurs is uncertain and depends upon the characteristics of the soil and the environment. For purposes of this analysis, it was assumed that ten percent of the methane produced, minus the amount of gas recovered for flaring or LFGTE projects, was oxidized in the soil (Liptay et al. 1998).

### Step 6: Estimate Total Methane Emissions

Total methane emissions were calculated by adding emissions from MSW and industrial waste, and subtracting methane recovered and oxidized, as shown in Table O-2.

**Table O-1: Municipal Solid Waste (MSW) Contributing to Methane Emissions (Tg unless otherwise noted)**

| Description | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total MSW Generated[a] | 266 | 255 | 265 | 278 | 293 | 296 | 297 | 309 | 340 | 347 | 371 |
| Percent of MSW Landfilled[a] | 77% | 76% | 72% | 71% | 67% | 63% | 62% | 61% | 61% | 60% | 61% |
| Total MSW Landfilled | 205 | 194 | 191 | 198 | 196 | 187 | 184 | 188 | 207 | 208 | 226 |
| MSW Contributing to Emissions[b] | 4,926 | 5,027 | 5,162 | 5,292 | 5,428 | 5,559 | 5,676 | 5,790 | 5,906 | 6,035 | 6,147 |

[a] Source: *BioCycle* (2001). The data, originally reported in short tons, are converted to metric tons.
[b] The emissions model (EPA 1993) defines all waste that has been in place for less than 30 years as contributing to methane emissions.

## Table O-2: Methane Emissions from Landfills (Gg)

| Activity | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **MSW Generation** | **11,599** | **11,837** | **12,168** | **12,499** | **12,847** | **13,218** | **13,490** | **13,774** | **14,015** | **14,348** | **14,617** |
| Large Landfills | 4,780 | 4,817 | 4,883 | 4,950 | 5,038 | 5,129 | 5,199 | 5,280 | 5,351 | 5,453 | 5,520 |
| Medium Landfills | 5,545 | 5,720 | 5,954 | 6,190 | 6,424 | 6,682 | 6,868 | 7,057 | 7,211 | 7,424 | 7,614 |
| Small Landfills | 1,273 | 1,300 | 1,332 | 1,359 | 1,385 | 1,407 | 1,423 | 1,438 | 1,453 | 1,471 | 1,483 |
| **Industrial Generation** | **731** | **746** | **767** | **787** | **809** | **833** | **850** | **868** | **883** | **904** | **921** |
| **Potential Emissions** | **12,330** | **12,582** | **12,935** | **13,286** | **13,657** | **14,051** | **14,340** | **14,642** | **14,898** | **15,252** | **15,538** |
| **Emissions Avoided** | **(1,119)** | **(1,387)** | **(1,601)** | **(1,848)** | **(2,225)** | **(2,682)** | **(3,244)** | **(3,820)** | **(4,362)** | **(4,607)** | **(4,874)** |
| Landfill Gas-to-Energy | (692) | (728) | (784) | (855) | (977) | (1,017) | (1,171) | (1,415) | (1,729) | (1,984) | (2,196) |
| Flare | (427) | (659) | (817) | (994) | (1,248) | (1,665) | (2,073) | (2,405) | (2,633) | (2,623) | (2,678) |
| **Oxidation** | **(1,048)** | **(1,045)** | **(1,057)** | **(1,065)** | **(1,062)** | **(1,054)** | **(1,025)** | **(995)** | **(965)** | **(974)** | **(974)** |
| **Net Emissions** | **10,162** | **10,150** | **10,277** | **10,373** | **10,370** | **10,315** | **10,072** | **9,827** | **9,571** | **9,671** | **9,690** |

Note: Totals may not sum due to independent rounding.
Note: MSW generation in Table O-2 represents emissions before oxidation. In other tables throughout the text, MSW generation estimates account for oxidation.

# ANNEX P

## Key Source Analysis

This Annex provides an analysis of key sources of emissions found in this report in keeping with the IPCC's *Good Practice Guidance* (IPCC 2000). In order to ensure accuracy and reliability of inventory estimates, quality assurance and quality control (QA/QC) resources and activities should be directed to the key source categories in a given country's greenhouse gas emissions inventory. A key source category is defined as a "[source 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."[1] By definition, key source categories are sources that have the greatest contribution to the absolute overall level of national emissions. In addition, when an entire time series of emission estimates is prepared, a thorough investigation of key source categories must also include accounting for the influence of trends of individual source categories. Therefore, a trend assessment is also conducted based on an attempt to identify source categories for which significant uncertainty in the estimate would have considerable effects on overall emission trends. This analysis culls out source categories that diverge from the overall trend in national emissions. Finally, a qualitative evaluation of key source categories should be performed, in order to capture any key source categories that were not identified in either of the quantitative analyses.

The methodology for conducting a key source analysis, as defined by IPCC's *Good Practice Guidance* (IPCC 2000), includes:

- Tier 1 approach (including both level and trend assessments);
- Tier 2 approach (including both level and trend assessments, and incorporating uncertainty analysis); and
- Qualitative approach.

Following this introduction, the Annex will present and analyze key source categories; discuss Tier 1, Tier 2, and qualitative approaches to identifying key sources; provide level and trend assessment equations; and provide a brief statistical evaluation of IPCC's quantitative methodologies for defining key sources.

Table P-1 presents the key source categories for the United States using emissions data in this report, and ranked according to their sector and global warming potential-weighted emissions in 2000. The table also identifies the criteria used in identifying these source categories (i.e., level, trend, and/or qualitative assessments).

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

**Table P-1: Key Source Categories for the United States (1990-2000) Based on Tier 1 Approach**

| IPCC Source Categories | Gas | Criteria | | | 2000 Emissions ($Tg CO_2 Eq.$) |
|---|---|---|---|---|---|
| | | Level | Trend | Qual.[a] | |
| **Energy** | | | | | |
| $CO_2$ Emissions from Stationary Combustion - Coal | $CO_2$ | ✓ | ✓ | C,T,Q | 2,030.1 |
| $CO_2$ Emissions from Stationary Combustion - Oil | $CO_2$ | ✓ | ✓ | | 640.7 |
| Mobile Combustion: Road & Other | $CO_2$ | ✓ | ✓ | | 1,503.2 |
| $CO_2$ Emissions from Stationary Combustion - Gas | $CO_2$ | ✓ | ✓ | | 1,162.9 |
| Mobile Combustion: Aviation | $CO_2$ | ✓ | | | 196.5 |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | ✓ | ✓ | | 138.2 |
| Mobile Combustion: Marine | $CO_2$ | ✓ | ✓ | | 89.9 |
| Fugitive Emissions from Coal Mining & Handling | $CH_4$ | ✓ | ✓ | | 61.0 |
| Mobile Combustion: Road & Other | $N_2O$ | ✓ | | | 55.7 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | | ✓ | | 26.3 |
| International Bunker Fuels[b] | Several | | | ✓ | 101.2 |
| Non-Energy Use of Fossil Fuels[b] | $CO_2$ | | | ✓ | 409.6 |
| **Industrial Processes** | | | | | |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | ✓ | ✓ | | 107.6 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | ✓ | ✓ | | 57.8 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | ✓ | | | 41.1 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | ✓ | ✓ | | 29.8 |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | | ✓ | ✓ | 14.4 |
| PFC Emissions from Aluminum Production | PFCs | | ✓ | | 7.9 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | | ✓ | ✓ | 8.1 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacturing | Several | | | ✓ | 7.4 |
| **Agriculture** | | | | | |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | ✓ | | | 217.8 |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | ✓ | ✓ | | 123.9 |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | ✓ | | | 79.8 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | ✓ | | ✓ | 37.5 |
| **Waste** | | | | | |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | ✓ | ✓ | | 203.5 |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | | ✓ | | 22.5 |
| **Subtotal** | | | | | **6,843.4** |
| **Total** | | | | | **7,001.2** |
| **Percent of Total** | | | | | **98.0%** |

[a] Qualitative criteria.

[b] Emissions from these sources not included in totals.

Notes: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis. The Tier 1 approach for identifying key source categories does not directly include assessment of uncertainty in emissions estimates.

Table P-2 provides a complete listing of source categories by IPCC sector and with additional comments on the criteria used in identifying key source categories. Specifically, the level assessment was performed for each year that inventory data was available (i.e., 1990 to 2000). As the emissions change over time, categories may fall under or over the threshold for being key. The following points should be noted regarding the key sources identified.

Due to the relative quantity of $CO_2$ emissions from fossil fuel combustion—particularly from mobile source and stationary combustion of coal, gas, and oil—these sources contributed most to each year's level assessment. Additionally, the following sources were the largest contributors to the level assessments for each year (listed in descending order):

- $CH_4$ from solid waste disposal sites;
- $N_2O$ from agricultural soils;
- $CO_2$ emissions from mobile combustion in the aviation and marine sectors;
- Fugitive emissions from oil and gas operations;
- $CH_4$ from enteric fermentation in domestic livestock;
- $CO_2$ emissions from other industrial processes;

- Fugitive emissions from coal mining; and
- $N_2O$ emissions from mobile road source emissions.

The remaining key sources identified under the level assessment varied by year. The following four source categories were determined to be key using the level assessment for only part of the complete times series:

- $CO_2$ emissions from cement production (1991, 1993 to 1996);
- HFC and PFC emissions from substitutes for ozone depleting substances (1997 to 2000);
- HFC-23 emissions from HCFC-22 manufacture (1990, 1992, 1996, 1998); and
- $CH_4$ emissions from manure management (1995).

Although other sources have fluctuated by greater percentages since 1990, by virtue of their size, $CO_2$ emissions from stationary combustion of coal, gas, and oil, and from mobile combustion from road vehicles are the greatest contributors to the overall trend for 2000.

Another large contributor to the overall trend is emissions of substitutes for ozone depleting substances, which are growing quickly with the Montreal Protocol phase-out of ozone depleting substances. Fugitive emissions from coal mining and PFC emissions from aluminum manufacturing have decreased by approximately 30 and 56 percent, respectively from 1990 through 2000.

Six other source categories were determined to be key using the qualitative criteria. A brief discussion of the reasoning for the qualitative designation is given below:

- 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 source 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.
- Non-energy uses of fossil fuels represent a significant percentage of the total carbon inventory, and the idea that small changes in storage factors for these non-energy uses may result in large changes in storage and emissions qualifies this source category as key.
- Nitrous oxide emissions from adipic acid plants have been dramatically reduced due to the installation of emission control technologies on 3 of the 4 production facilities in the United States. These changes in addition to the uncertainty in this emission source category suggest that it should be treated as key, although it has also been identified using the trend assessment.
- Estimates of $SF_6$ emissions from electrical equipment have been made using only a limited amount of data; therefore, there is a significant degree of uncertainty associated with them. Although future inventories are expected to incorporate improvements, the current lack of data and small margin under which the category missed both the trend and level assessment thresholds suggests that it should be treated as key.
- Emissions of HFCs, PFCs and $SF_6$ from semiconductor manufacturing have increased significantly from 1990 through 1999, almost tripling in size. This source category's potential future growth—in addition to historical growth that has already led to list listing as key using the trend assessment—suggests that it should be treated as key.
- Estimated $CH_4$ emissions from manure management have been significantly revised relative to the previous greenhouse gas inventory. This revision is due to both changes in the estimation methodology and data sources. The reduction in estimated emissions for the entire time series have by approximately 50 to 60 percent, suggests that it should be treated as key, although it has also been identified using the trend assessment.

Following the text of this Annex, Table P-3 through Table P-13 contain each individual year's level assessment and contain further detail on where each source falls within the analysis. Table P-14 details the trend assessment for 1990 through 2000.

## Table P-2: U.S Greenhouse Gas Inventory Source Categories Based on Tier 1 Approach

| IPCC Source Categories | Direct GHG | 2000 Emissions (Tg $CO_2$ Eq.) | Key Source Category Flag? | Criteria[a] | Comments |
|---|---|---|---|---|---|
| **Energy** | | | | | |
| $CO_2$ Emissions from Stationary Combustion - Coal | $CO_2$ | 2,030.1 | ✓ | L, T | All years |
| $CO_2$ Emissions from Stationary Combustion - Oil | $CO_2$ | 640.7 | ✓ | L, T | All years |
| $CO_2$ Emissions from Stationary Combustion - Gas | $CO_2$ | 1,162.9 | ✓ | L, T | All years |
| $CO_2$ Emissions from Stationary Combustion – Geothermal | $CO_2$ | + | | | |
| $CO_2$ Emissions from Natural Gas Flaring | $CO_2$ | 6.1 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion | $CH_4$ | 7.5 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion | $N_2O$ | 14.9 | | | |
| Mobile Combustion: Road & Other | $CO_2$ | 1,503.2 | ✓ | L, T | All years |
| Mobile Combustion: Road & Other | $CH_4$ | 4.1 | | | |
| Mobile Combustion: Road & Other | $N_2O$ | 55.7 | ✓ | L | All years |
| Mobile Combustion: Aviation | $CO_2$ | 196.5 | ✓ | L | All years |
| Mobile Combustion: Aviation | $CH_4$ | 0.2 | | | |
| Mobile Combustion: Aviation | $N_2O$ | 1.9 | | | |
| Mobile Combustion: Marine | $CO_2$ | 89.9 | ✓ | L, T | All years |
| Mobile Combustion: Marine | $CH_4$ | 0.1 | | | |
| Mobile Combustion: Marine | $N_2O$ | 0.6 | | | |
| Fugitive Emissions from Coal Mining & Handling | $CH_4$ | 61.0 | ✓ | L, T | All years |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | 138.2 | ✓ | L, T | All years |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | 26.3 | ✓ | T | |
| International Bunker Fuels[b] | Several | 101.2 | ✓ | Q | |
| Non-Energy Use of Fossil Fuels[b] | $CO_2$ | 409.6 | ✓ | Q | |
| **Industrial Processes** | | | | | |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 41.1 | ✓ | L | Level in 1991, 1993- 1997 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 13.3 | | | |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | 107.6 | ✓ | L, T | All years |
| $CH_4$ Emissions from Other Industrial Processes | $CH_4$ | 1.7 | | | |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 8.1 | ✓ | T, Q | |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 19.8 | | | |
| PFC Emissions from Aluminum Production | PFCs | 7.9 | ✓ | T | |
| $SF_6$ Emissions from Magnesium Production | $SF_6$ | 4.0 | | | |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | 14.4 | ✓ | T, Q | |
| HFC, PFC, and $SF_6$ Emissions from Semiconductor Mfg. | Several | 7.4 | ✓ | Q | |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 57.8 | ✓ | L, T | Level from 1997 - 2000 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | 29.8 | ✓ | L, T | Level in 1990, 1992, 1996, 1998 |
| **Agriculture** | | | | | |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | 123.9 | ✓ | L, T | All years |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 37.5 | ✓ | L, Q | Level in 1995 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 17.5 | | | |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | 217.8 | ✓ | L | All years |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | 79.8 | ✓ | L | All years |
| $CH_4$ Emissions from Rice Production | $CH_4$ | 7.5 | | | |
| $CH_4$ Emissions from Agricultural Residue Burning | $CH_4$ | 0.8 | | | |
| $N_2O$ Emissions from Agricultural Residue Burning | $N_2O$ | 0.5 | | | |
| **Waste** | | | | | |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | 203.5 | ✓ | L, T | All years |
| $CH_4$ Emissions from Wastewater Handling | $CH_4$ | 28.7 | | | |
| $N_2O$ Emissions from Wastewater Handling | $N_2O$ | 8.5 | | | |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | 22.5 | ✓ | T | |
| $N_2O$ Emissions from Waste Incineration | $N_2O$ | 0.2 | | | |

+ Does not exceed 0.05 Tg $CO_2$ Eq.

[a] Qualitative criteria.

[b] Emissions from these sources not included in totals.

Notes: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis. The Tier 1 approach for identifying key source categories does not directly include assessment of uncertainty in emissions estimates.

## Tier 1 Approach

The Tier 1 method for identifying key source categories assesses the impacts of all IPCC-defined source categories on the level and trend of the national emission inventory for the 1990 through 2000 time-series, but works independently of any formal uncertainty analysis. However, it is important to mention that although conducting a key source analysis can be very valuable in improving the U.S. inventory, it would be ideal to undertake a full uncertainty analysis in order to accurately identify all key sources and to be able to take into account the level of uncertainty associated with each estimate.

When using a Tier 1 approach for the *level*, a pre-determined cumulative emissions threshold is used to identify key source categories. When source categories are sorted in order of decreasing emissions, those that fall at the top of the list and cumulatively account for 95 percent of emissions are considered key source categories. The 95 percent threshold was established based on an evaluation of several inventories, and was designed to establish a general level where the key source category analysis covers 90 percent of inventory uncertainty. The Tier 1 approach for the *trend* uses a 95 percent contribution threshold of the cumulative contribution to the trend assessment metric, which was also designed to establish a general level where the key source category analysis covers 90 percent of inventory uncertainty. The Tier 1 method is completed using a simple spreadsheet analysis based on equations for both level and trend assessments that are described in detail below. It is the current approach that the United States is taking to identify key source categories of greenhouse gas emissions until a rigorous uncertainty analysis is completed.

### Level and Trend Assessments of Key Source Categories

#### Level Assessment

A level assessment was performed for years 1990 to 2000. Key sources were identified as any source category which, when summed in descending order of magnitude for a given year, cumulatively add up to 95 percent of the total level assessment for that year. Level estimates are based upon the following equation:

$$\text{Source Category Level Assessment} = \text{Source Category} / \text{Total Estimate}$$

$$L_{x,t} = E_{x,t} / E_t$$

Where,

$L_{x,t}$ = level assessment for source x in year t

$E_{x,t}$ = emissions estimate for source x in year t

$E_t$ = total emissions estimate for year t

#### Trend Assessment

A trend assessment was then conducted to evaluate how significantly the difference between the source category's trend and the overall inventory trend affect the overall trend. This assessment was done by multiplying the difference between the source category trend and the total inventory trend by the source category level assessment. Trend assessments were based upon the following equation:

$$\text{Source Category Trend Assessment} = (\text{Source Category Level Assessment}) \times \left|(\text{Source Category Trend} - \text{Total Trend})\right|$$

$$T_{x,t} = L_{x,t} \times \left| [((E_{x,t} - E_{x,o}) / E_{x,t}) - ((E_t - E_o) / E_t)] \right|$$

Where,

$T_{x,t}$ = trend assessment for source x in year t

$L_{x,t}$ = level assessment for source x in year t

$E_{x,t}$ and $E_{x,0}$ = emissions estimates for source x in year t and year 0, respectively

$E_t$ and $E_0$ = total emissions estimate for year t and year 0, respectively

0 = base year (e.g., 1990)

The following section of this annex evaluates these key source category analyses. The remainder of the annex summarizes the key source categories identified by these analyses, and quantifies their contribution to total level and trend assessments.

## Tier 2 Approach

IPCC recommends that inventory agencies use the Tier 2 method for identifying key source categories if nationally derived source-level uncertainties are measured. The Tier 2 approach is a more detailed analysis that builds on the Tier 1 approach by multiplying the results of the Tier 1 analysis by the relative uncertainty of each source category. This method is likely to reduce the number of key source categories under consideration. Using the Tier 2 approach, key source categories represent 90 percent of the quantified uncertainty contribution, as opposed to those that sum to the pre-determined cumulative emissions or trend threshold. A simple spreadsheet version accounts for the uncertainty contribution by applying the source category percentage uncertainty estimates to the Tier 1 level and trend assessments.

A detailed, more complete assessment of uncertainty uses Monte Carlo uncertainty modeling. The U.S. EPA is currently working on preparing such an analysis using procedures for gathering necessary data inputs and estimating uncertainty using a Monte Carlo model developed with @Risk© software. The project, which is in the initial phase of developing the uncertainty model, has as its goal developing a simulation model to estimate uncertainty for all source categories of the U.S. Inventory, and in total. The Monte Carlo model develops estimates of uncertainty for inventory source categories based on (a) mathematical models used to estimate emissions for each source category; (b) source category specific input parameters and emission estimates; and (c) the statistical properties underlying the input parameters and estimates.

## Qualitative Approach

In addition to conducting a quantitative assessment like the ones described above, a variety of qualitative criteria could be applied to identify additional key source categories. The following qualitative criteria for identifying key source categories have been outlined in the *Good Practice Guidance* (IPCC 2000). A source category should be identified as a key source if:

- Mitigation techniques and technologies are being implemented to reduce emissions from the source category that are expected to be reflected in the inventory estimates;
- Significant changes in emissions (i.e., growth or decline) from the source category is expected in the future;
- High uncertainty is evident for the source category;
- Unexpectedly low or high emissions, or other order of magnitude discrepancies, are apparent for the source category; and
- Major changes in estimation methodology or data have occurred.

In many cases, the results of this qualitative approach to identifying key source categories will overlap with source categories already defined as key source categories through the quantitative analysis. However, the qualitative method may illuminate a few additional key source categories, which should then be included in the final list of key source categories. The application of such qualitative criteria are primarily intended to identify any additional source categories that were "just under" the threshold criteria for the level assessment and not for extremely minor source categories.

Six source categories are also considered key from a qualitative standpoint, these include:

- International Bunker Fuels,

- Non-Energy Use of Fossil Fuels,
- $N_2O$ from adipic acid production,
- $SF_6$ from electrical equipment,
- HFCs, PFCs, and $SF_6$ from semiconductor manufacturing, and
- $CH_4$ from manure management.

Of these sources, $N_2O$ from adipic acid production, $SF_6$ from electrical equipment, and $CH_4$ from manure management are also considered key sources in either the level or the trend assessments. Semiconductor manufacture is not considered a key source in either the level or the trend assessments, but the rapid growth rate of this industry identifies it as a qualitative key. Both international bunker fuels and non-fuel use of fossil fuels are considered unique in that they are not included as a part of the inventory totals. Therefore they require additional explanation in this analysis. International bunker fuel emissions are not included in national totals, and are not considered in the level or trend analyses mentioned above, but are considered key from a qualitative standpoint due to their unique position within the emissions accounting framework. Additionally, non-fuel use of fossil fuels is also not included in the level or trend analyses. However, due to the significant quantity of fossil fuels consumed in the United States that are not used to produce energy (generically referred to as feedstocks), it is imperative to understand their fate and to determine how much of the consumption results in emissions, versus in stored carbon.

### International Bunker Fuels

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 source according to the Tier 1 approach, as emissions for 2000 are estimated at 101.2 Tg $CO_2$ Eq. An additional reason to treat bunker fuels as a key source lies in the amount of uncertainty in these emission estimates. Difficulties in collecting this data and the use of varying definitions of bunker fuels are a few of the uncertainties that could have a significant effect on total emission trends.

### Non-Energy Use of Fossil Fuel

Fossil fuel feedstocks including naphthas, liquefied petroleum gases, and natural gas are used in the manufacture of a wide variety of man-made chemicals and products, in addition to their use as fuels. Non-fuel feedstock uses of fossil fuels include manufacture of plastics, rubber, synthetic fibers, solvents, paints, fertilizers, pharmaceuticals, and food additives. Subsequent use or disposal of these products may result in either carbon storage or carbon emissions. Industrial coking coal, petroleum coke, distillate and residual fuel oils, and other fossil fuels are also used for non-energy uses. Because non-fuel uses of these fuel types are diverse, the carbon storage and carbon emissions from these non-fuel uses are difficult to characterize.

Non-energy uses of fossil fuels represent a significant percentage of the total carbon inventory. Potential emissions of carbon from non-energy use increased from 319.9 Tg $CO_2$ Eq. (87.25 Tg C) in 1990 to 409.6 Tg $CO_2$ Eq. (111.70 Tg C) in 2000, an increase of 28 percent. In the same time frame, carbon stored in products from non-energy use increased from 221.0 Tg $CO_2$ Eq. (60.26 Tg C) to 283.2 Tg $CO_2$ Eq. (77.23 Tg C), an increase of 28 percent. Small changes in storage factors for these non-energy uses may result in large changes in storage and emissions. Therefore, non-energy use of fossil fuels is considered to be a key source from a qualitative standpoint.

## Evaluation of Key Source Identification Methodologies

### Level Assessment

The Tier 1 approach for level assessment defines the source category contribution as the percentage of total inventory emissions from that source category. Only emission source categories are considered.[2] To determine key source categories, the level assessments are sorted in decreasing order, so that the source categories with the highest

[2] The level assessment is intended to be applied to sources and to exclude sinks. Although the assessment would still be valid if sinks were included (as unsigned values), the 95 percent threshold by which sources are deemed "key" would lose significance because it is based on an analysis (Flusgrud et al. 1999) of selected inventories where sinks were excluded.

level assessments appear first. The level assessments are summed until the threshold of 95 percent is reached; all source categories that fall within that cumulative 95 percent are considered key source categories.

Since the Tier 1 approach does not explicitly incorporate uncertainties, the level assessment key source categories will be the largest contributors to total emissions but will not necessarily have large contributions to the total uncertainty. Focusing resources on improving the methodologies for estimating emissions from the source categories with the largest emissions is undesirable if those emissions are estimated relatively precisely using the current methodologies. Nevertheless, the analysis (reported in IPCC 2000) of several inventories that have source category uncertainties showed that about 90 percent of the total uncertainty could be covered by the source categories in the top 95 percent of emissions.

It is important to note that this key source category analysis can be very sensitive to the definitions of the source categories. If a large source category is split into many subcategories, then the subcategories may have contributions to the total inventory that are too small for those source categories to be considered key. Similarly, a collection of small, non-key source categories adding up to less than 5 percent of total emissions could become key source categories if those source categories were aggregated into a single source category. A consistent approach to addressing this issue is available in the *Good Practice Guidance*. Table 7.1 in IPCC (2000) provides guidance and a suggested list of source categories for analysis, although countries are given some discretion based upon their national circumstances.

Some important components of other source categories were not included in the list of IPCC source categories in the key source category chapter of IPCC's *Good Practice Guidance* (IPCC 2000). These source categories include fossil fuel feedstocks, international bunkers, and emissions from territories. They are potentially large source categories that often are derived from unique data sources, have a significant impact on the uncertainty of the estimates, and therefore ought to be considered as potential key source categories.

### Trend Assessment

The Tier 1 approach for trend assessment is defined as the product of the source category level assessment (i.e., source category emissions as a fraction, or percentage, of total emissions) and the absolute difference between the source category trend and the total trend. In turn, the source category trend is defined as the change in source category emissions from the base year to the current year, as a percentage of current year emissions from that source category. The total trend is the percentage change in total inventory emissions from the base year to the current year. Thus, the *source category trend assessment* will be large if the source category represents a large percentage of emissions and/or has a trend that is quite different from the overall inventory trend. Only emissions source categories are considered.[3] To determine key source categories, the trend assessments are sorted in decreasing order, so that the source categories with the highest trend assessments appear first. The trend assessments are summed until the threshold of 95 percent is reached; all source categories that fall within that cumulative 95 percent are considered key source categories.

It is important to note that the trend assessment calculation assumes that the base and current year source category emission uncertainties are the same. Therefore, the trend assessment is a useful measure in cases where the percentage uncertainties of the base and current year source category emission levels are thought to be the same. However, its usefulness diminishes when individual source category uncertainties are different between the base year and the current year. Such time series inconsistencies could result from changes in data quality or availability over time. As more rigorous methods to determine uncertainties in emission estimates are applied, it may be necessary to revisit the results of the trend assessments.

Another important caveat to the identification of key source categories through the trend assessment is that, while each individual source category's trend assessment provides a measure of how sensitive the overall trend in the inventory is to the trend of a particular source category, the sum of a number of trend assessments does not yield the total sensitivity of the overall trend to changes in all of those source categories. In other words, the cumulative percentages should not be considered a measure of the percentage contributions to the trend from those source categories.

---

[3] The trend assessment is intended to be applied to sources and to exclude sinks. Although the assessment would still be valid if sinks were included (as unsigned values), the 95 percent threshold by which sources are deemed "key" would lose significance because it is based on an analysis (Flusgrud et al. 1999) of selected inventories where sinks were excluded.

The trend assessment key source categories are also sensitive to the level of aggregation of the source categories; and the IPCC list of source categories may exclude some important, potentially key source category components.

## References

Flugsrud, K., W. Irving, and K. Rypdal (1999) *Methodological Choice in Inventory Preparation. Suggestions for Good Practice Guidance.* Statistics Norway Department of Economic Statistics. 1999/19.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme.

## Table P-3: 1990 Key Source Tier 1 Analysis - Level Assessment

| IPCC Source Categories | Direct Greenhouse Gas | Base Year Estimate (Tg $CO_2$ Eq.) | Current Year Estimate (Tg $CO_2$ Eq.) | Level Assessment | Cumulative Total |
|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal | $CO_2$ | 1,692.60 | 1,692.60 | 0.28 | 0.28 |
| Mobile Combustion: Road & Other | $CO_2$ | 1,235.49 | 1,235.49 | 0.20 | 0.48 |
| $CO_2$ Emissions from Stationary Combustion - Gas | $CO_2$ | 952.76 | 952.76 | 0.16 | 0.63 |
| $CO_2$ Emissions from Stationary Combustion - Oil | $CO_2$ | 662.46 | 662.46 | 0.11 | 0.74 |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | 213.41 | 213.41 | 0.03 | 0.78 |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | 193.49 | 193.49 | 0.03 | 0.81 |
| Mobile Combustion: Aviation | $CO_2$ | 176.88 | 176.88 | 0.03 | 0.84 |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | 147.64 | 147.64 | 0.02 | 0.86 |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | 127.88 | 127.88 | 0.02 | 0.88 |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | 123.65 | 123.65 | 0.02 | 0.90 |
| Fugitive Emissions from Coal Mining and Handling | $CH_4$ | 87.12 | 87.12 | 0.01 | 0.92 |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | 73.60 | 73.60 | 0.01 | 0.93 |
| Mobile Combustion: Marine | $CO_2$ | 59.43 | 59.43 | 0.01 | 0.94 |
| Mobile Combustion: Road & Other | $N_2O$ | 48.86 | 48.86 | 0.01 | 0.95 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | 34.98 | 34.98 | 0.01 | 0.95 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.28 | 33.28 | 0.01 | 0.96 |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | 31.23 | 31.23 | 0.01 | 0.96 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | 30.90 | 30.90 | 0.01 | 0.97 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 29.19 | 29.19 | <0.01 | 0.97 |
| $CH_4$ Emissions from Wastewater Handling | $CH_4$ | 24.25 | 24.25 | <0.01 | 0.98 |
| PFC Emissions from Aluminum Production | PFCs | 18.11 | 18.11 | <0.01 | 0.98 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.85 | 17.85 | <0.01 | 0.98 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 16.03 | 16.03 | <0.01 | 0.98 |
| Non-$CO_2$ Emissions from Stationary Combustion | $N_2O$ | 12.82 | 12.82 | <0.01 | 0.99 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 14.89 | 14.89 | <0.01 | 0.99 |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | 14.09 | 14.09 | <0.01 | 0.99 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.24 | 11.24 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $CH_4$ | 7.90 | 7.90 | <0.01 | 0.99 |
| $CH_4$ Emissions from Rice Production | $CH_4$ | 7.12 | 7.12 | <0.01 | 0.99 |
| $N_2O$ Emissions from Wastewater Handling | $N_2O$ | 7.04 | 7.04 | <0.01 | 1.00 |
| $SF_6$ Emissions from Magnesium Production | $SF_6$ | 5.50 | 5.50 | <0.01 | 1.00 |
| $CO_2$ Emissions from Natural Gas Flaring | $CO_2$ | 5.51 | 5.51 | <0.01 | 1.00 |
| Mobile Combustion: Road & Other | $CH_4$ | 4.67 | 4.67 | <0.01 | 1.00 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacturing | $SF_6$ | 2.86 | 2.86 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $N_2O$ | 1.71 | 1.71 | <0.01 | 1.00 |
| $CH_4$ Emissions from Other Industrial Processes | $CH_4$ | 1.19 | 1.19 | <0.01 | 1.00 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.94 | 0.94 | <0.01 | 1.00 |
| $CH_4$ Emissions from Agricultural Residue Burning | $CH_4$ | 0.68 | 0.68 | <0.01 | 1.00 |
| $N_2O$ Emissions from Agricultural Residue Burning | $N_2O$ | 0.37 | 0.37 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $N_2O$ | 0.36 | 0.36 | <0.01 | 1.00 |
| $N_2O$ Emissions from Waste Incineration | $N_2O$ | 0.29 | 0.29 | <0.01 | 1.00 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.22 | 0.22 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $CH_4$ | 0.16 | 0.16 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $CH_4$ | 0.07 | 0.07 | <0.01 | 1.00 |
| **TOTAL** | | **6,130.72** | **6,130.72** | **1.00** | |

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

## Table P-4: 1991 Key Source Tier 1 Analysis - Level Assessment

| IPCC Source Categories | Direct Greenhouse Gas | Base Year Estimate (Tg $CO_2$ Eq.) | Current Year Estimate (Tg $CO_2$ Eq.) | Level Assessment | Cumulative Total |
|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal | $CO_2$ | 1,692.60 | 1,684.05 | 0.28 | 0.28 |
| Mobile Combustion: Road & Other | $CO_2$ | 1,235.49 | 1,215.58 | 0.20 | 0.48 |
| $CO_2$ Emissions from Stationary Combustion - Gas | $CO_2$ | 952.76 | 973.29 | 0.16 | 0.64 |
| $CO_2$ Emissions from Stationary Combustion - Oil | $CO_2$ | 662.46 | 637.75 | 0.10 | 0.74 |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | 213.41 | 213.16 | 0.04 | 0.78 |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | 193.49 | 195.30 | 0.03 | 0.81 |
| Mobile Combustion: Aviation | $CO_2$ | 176.88 | 169.34 | 0.03 | 0.84 |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | 147.64 | 149.51 | 0.02 | 0.86 |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | 127.88 | 127.23 | 0.02 | 0.88 |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | 123.65 | 114.51 | 0.02 | 0.90 |
| Fugitive Emissions from Coal Mining and Handling | $CH_4$ | 87.12 | 83.68 | 0.01 | 0.92 |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | 73.60 | 74.76 | 0.01 | 0.93 |
| Mobile Combustion: Marine | $CO_2$ | 59.43 | 52.82 | 0.01 | 0.94 |
| Mobile Combustion: Road & Other | $N_2O$ | 48.86 | 51.21 | 0.01 | 0.95 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.28 | 32.54 | 0.01 | 0.95 |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | 31.23 | 32.48 | 0.01 | 0.96 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | 34.98 | 30.77 | 0.01 | 0.96 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | 30.90 | 30.70 | 0.01 | 0.97 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 29.19 | 31.14 | 0.01 | 0.97 |
| $CH_4$ Emissions from Wastewater Handling | $CH_4$ | 24.25 | 24.60 | <0.01 | 0.98 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.85 | 17.83 | <0.01 | 0.98 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 16.03 | 16.53 | <0.01 | 0.98 |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | 14.09 | 15.78 | <0.01 | 0.98 |
| PFC Emissions from Aluminum Production | PFCs | 18.11 | 15.68 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $N_2O$ | 12.82 | 12.68 | <0.01 | 0.99 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 14.89 | 14.69 | <0.01 | 0.99 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.24 | 11.01 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $CH_4$ | 7.90 | 8.03 | <0.01 | 0.99 |
| $N_2O$ Emissions from Wastewater Handling | $N_2O$ | 7.04 | 7.21 | <0.01 | 0.99 |
| $CH_4$ Emissions from Rice Production | $CH_4$ | 7.12 | 7.00 | <0.01 | 1.00 |
| $CO_2$ Emissions from Natural Gas Flaring | $CO_2$ | 5.51 | 5.59 | <0.01 | 1.00 |
| $SF_6$ Emissions from Magnesium Production | $SF_6$ | 5.50 | 5.50 | <0.01 | 1.00 |
| Mobile Combustion: Road & Other | $CH_4$ | 4.67 | 4.64 | <0.01 | 1.00 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacturing | $SF_6$ | 2.86 | 2.86 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $N_2O$ | 1.71 | 1.64 | <0.01 | 1.00 |
| $CH_4$ Emissions from Other Industrial Processes | $CH_4$ | 1.19 | 1.21 | <0.01 | 1.00 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.94 | 0.84 | <0.01 | 1.00 |
| $CH_4$ Emissions from Agricultural Residue Burning | $CH_4$ | 0.68 | 0.64 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $N_2O$ | 0.36 | 0.38 | <0.01 | 1.00 |
| $N_2O$ Emissions from Agricultural Residue Burning | $N_2O$ | 0.37 | 0.36 | <0.01 | 1.00 |
| $N_2O$ Emissions from Waste Incineration | $N_2O$ | 0.29 | 0.24 | <0.01 | 1.00 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.22 | 0.21 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $CH_4$ | 0.16 | 0.15 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $CH_4$ | 0.07 | 0.07 | <0.01 | 1.00 |
| **TOTAL** | | **6,130.72** | **6,075.18** | **1.00** | |

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

## Table P-5: 1992 Key Source Tier 1 Analysis - Level Assessment

| IPCC Source Categories | Direct Greenhouse Gas | Base Year Estimate ($Tg CO_2 Eq.$) | Current Year Estimate ($Tg CO_2 Eq.$) | Level Assessment | Cumulative Total |
|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal | $CO_2$ | 1,692.60 | 1,702.18 | 0.27 | 0.27 |
| Mobile Combustion: Road & Other | $CO_2$ | 1,235.49 | 1,238.29 | 0.20 | 0.47 |
| $CO_2$ Emissions from Stationary Combustion - Gas | $CO_2$ | 952.76 | 1,002.81 | 0.16 | 0.64 |
| $CO_2$ Emissions from Stationary Combustion - Oil | $CO_2$ | 662.46 | 657.85 | 0.11 | 0.74 |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | 213.41 | 215.82 | 0.03 | 0.78 |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | 193.49 | 202.46 | 0.03 | 0.81 |
| Mobile Combustion: Aviation | $CO_2$ | 176.88 | 167.01 | 0.03 | 0.84 |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | 147.64 | 150.35 | 0.02 | 0.86 |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | 127.88 | 130.16 | 0.02 | 0.88 |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | 123.65 | 113.82 | 0.02 | 0.90 |
| Fugitive Emissions from Coal Mining and Handling | $CH_4$ | 87.12 | 81.37 | 0.01 | 0.91 |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | 73.60 | 75.58 | 0.01 | 0.93 |
| Mobile Combustion: Marine | $CO_2$ | 59.43 | 67.68 | 0.01 | 0.94 |
| Mobile Combustion: Road & Other | $N_2O$ | 48.86 | 54.35 | 0.01 | 0.95 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | 34.98 | 34.87 | 0.01 | 0.95 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.28 | 32.79 | 0.01 | 0.96 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | 30.90 | 30.51 | <0.01 | 0.96 |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | 31.23 | 30.16 | <0.01 | 0.97 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 29.19 | 30.72 | <0.01 | 0.97 |
| $CH_4$ Emissions from Wastewater Handling | $CH_4$ | 24.25 | 25.22 | <0.01 | 0.98 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.85 | 18.30 | <0.01 | 0.98 |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | 14.09 | 16.32 | <0.01 | 0.98 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 16.03 | 16.31 | <0.01 | 0.98 |
| Non-$CO_2$ Emissions from Stationary Combustion | $N_2O$ | 12.82 | 12.94 | <0.01 | 0.99 |
| PFC Emissions from Aluminum Production | PFCs | 18.11 | 14.55 | <0.01 | 0.99 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 14.89 | 12.63 | <0.01 | 0.99 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.24 | 11.39 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $CH_4$ | 7.90 | 8.30 | <0.01 | 0.99 |
| $CH_4$ Emissions from Rice Production | $CH_4$ | 7.12 | 7.87 | <0.01 | 0.99 |
| $N_2O$ Emissions from Wastewater Handling | $N_2O$ | 7.04 | 7.34 | <0.01 | 1.00 |
| $CO_2$ Emissions from Natural Gas Flaring | $CO_2$ | 5.51 | 5.06 | <0.01 | 1.00 |
| $SF_6$ Emissions from Magnesium Production | $SF_6$ | 5.50 | 5.50 | <0.01 | 1.00 |
| Mobile Combustion: Road & Other | $CH_4$ | 4.67 | 4.67 | <0.01 | 1.00 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacturing | $SF_6$ | 2.86 | 2.86 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $N_2O$ | 1.71 | 1.62 | <0.01 | 1.00 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.94 | 1.52 | <0.01 | 1.00 |
| $CH_4$ Emissions from Other Industrial Processes | $CH_4$ | 1.19 | 1.28 | <0.01 | 1.00 |
| $CH_4$ Emissions from Agricultural Residue Burning | $CH_4$ | 0.68 | 0.75 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $N_2O$ | 0.36 | 0.43 | <0.01 | 1.00 |
| $N_2O$ Emissions from Agricultural Residue Burning | $N_2O$ | 0.37 | 0.41 | <0.01 | 1.00 |
| $N_2O$ Emissions from Waste Incineration | $N_2O$ | 0.29 | 0.27 | <0.01 | 1.00 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.22 | 0.21 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $CH_4$ | 0.16 | 0.15 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $CH_4$ | 0.07 | 0.08 | <0.01 | 1.00 |
| **TOTAL** | | **6,130.72** | **6,194.77** | **1.00** | |

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

## Table P-6: 1993 Key Source Tier 1 Analysis - Level Assessment

| IPCC Source Categories | Direct Greenhouse Gas | Base Year Estimate (Tg $CO_2$ Eq.) | Current Year Estimate (Tg $CO_2$ Eq.) | Level Assessment | Cumulative Total |
|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion – Coal | $CO_2$ | 1,692.60 | 1,764.15 | 0.28 | 0.28 |
| Mobile Combustion: Road & Other | $CO_2$ | 1,235.49 | 1,271.16 | 0.20 | 0.48 |
| $CO_2$ Emissions from Stationary Combustion – Gas | $CO_2$ | 952.76 | 1,036.28 | 0.16 | 0.65 |
| $CO_2$ Emissions from Stationary Combustion – Oil | $CO_2$ | 662.46 | 647.74 | 0.10 | 0.75 |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | 213.41 | 217.83 | 0.03 | 0.78 |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | 193.49 | 195.55 | 0.03 | 0.81 |
| Mobile Combustion: Aviation | $CO_2$ | 176.88 | 168.04 | 0.03 | 0.84 |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | 147.64 | 154.01 | 0.02 | 0.87 |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | 127.88 | 128.47 | 0.02 | 0.89 |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | 123.65 | 106.89 | 0.02 | 0.90 |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | 73.60 | 77.49 | 0.01 | 0.92 |
| Fugitive Emissions from Coal Mining and Handling | $CH_4$ | 87.12 | 69.68 | 0.01 | 0.93 |
| Mobile Combustion: Marine | $CO_2$ | 59.43 | 63.38 | 0.01 | 0.94 |
| Mobile Combustion: Road & Other | $N_2O$ | 48.86 | 56.45 | 0.01 | 0.95 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.28 | 34.62 | 0.01 | 0.95 |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | 31.23 | 34.09 | 0.01 | 0.96 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | 34.98 | 31.82 | 0.01 | 0.96 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | 30.90 | 29.48 | <0.01 | 0.97 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 29.19 | 31.64 | 0.01 | 0.97 |
| $CH_4$ Emissions from Wastewater Handling | $CH_4$ | 24.25 | 25.59 | <0.01 | 0.97 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.85 | 18.57 | <0.01 | 0.98 |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | 14.09 | 17.18 | <0.01 | 0.98 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 16.03 | 16.73 | <0.01 | 0.98 |
| Non-$CO_2$ Emissions from Stationary Combustion | $N_2O$ | 12.82 | 13.14 | <0.01 | 0.99 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 14.89 | 13.92 | <0.01 | 0.99 |
| PFC Emissions from Aluminum Production | PFCs | 18.11 | 13.86 | <0.01 | 0.99 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.24 | 11.64 | <0.01 | 0.99 |
| $CO_2$ Emissions from Natural Gas Flaring | $CO_2$ | 5.51 | 6.55 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $CH_4$ | 7.90 | 7.82 | <0.01 | 0.99 |
| $N_2O$ Emissions from Wastewater Handling | $N_2O$ | 7.04 | 7.45 | <0.01 | 1.00 |
| $CH_4$ Emissions from Rice Production | $CH_4$ | 7.12 | 7.02 | <0.01 | 1.00 |
| $SF_6$ Emissions from Magnesium Production | $SF_6$ | 5.50 | 5.37 | <0.01 | 1.00 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.94 | 5.24 | <0.01 | 1.00 |
| Mobile Combustion: Road & Other | $CH_4$ | 4.67 | 4.65 | <0.01 | 1.00 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacturing | $SF_6$ | 2.86 | 3.58 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $N_2O$ | 1.71 | 1.63 | <0.01 | 1.00 |
| $CH_4$ Emissions from Other Industrial Processes | $CH_4$ | 1.19 | 1.40 | <0.01 | 1.00 |
| $CH_4$ Emissions from Agricultural Residue Burning | $CH_4$ | 0.68 | 0.60 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $N_2O$ | 0.36 | 0.43 | <0.01 | 1.00 |
| $N_2O$ Emissions from Agricultural Residue Burning | $N_2O$ | 0.37 | 0.34 | <0.01 | 1.00 |
| $N_2O$ Emissions from Waste Incineration | $N_2O$ | 0.29 | 0.26 | <0.01 | 1.00 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.22 | 0.19 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $CH_4$ | 0.16 | 0.14 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $CH_4$ | 0.07 | 0.08 | <0.01 | 1.00 |
| **TOTAL** | | **6,130.72** | **6,302.16** | **1.00** | |

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

## Table P-7: 1994 Key Source Tier 1 Analysis - Level Assessment

| IPCC Source Categories | Direct Greenhouse Gas | Base Year Estimate (Tg $CO_2$ Eq.) | Current Year Estimate (Tg $CO_2$ Eq.) | Level Assessment | Cumulative Total |
|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal | $CO_2$ | 1,692.60 | 1,782.55 | 0.28 | 0.28 |
| Mobile Combustion: Road & Other | $CO_2$ | 1,235.49 | 1,313.34 | 0.20 | 0.48 |
| $CO_2$ Emissions from Stationary Combustion - Gas | $CO_2$ | 952.76 | 1,056.23 | 0.16 | 0.65 |
| $CO_2$ Emissions from Stationary Combustion - Oil | $CO_2$ | 662.46 | 656.85 | 0.10 | 0.75 |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | 213.41 | 217.77 | 0.03 | 0.78 |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | 193.49 | 215.16 | 0.03 | 0.81 |
| Mobile Combustion: Aviation | $CO_2$ | 176.88 | 175.85 | 0.03 | 0.84 |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | 147.64 | 151.91 | 0.02 | 0.87 |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | 127.88 | 130.12 | 0.02 | 0.89 |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | 123.65 | 111.86 | 0.02 | 0.90 |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | 73.60 | 79.95 | 0.01 | 0.92 |
| Fugitive Emissions from Coal Mining and Handling | $CH_4$ | 87.12 | 70.32 | 0.01 | 0.93 |
| Mobile Combustion: Marine | $CO_2$ | 59.43 | 62.18 | 0.01 | 0.94 |
| Mobile Combustion: Road & Other | $N_2O$ | 48.86 | 57.88 | 0.01 | 0.95 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.28 | 36.09 | 0.01 | 0.95 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | 34.98 | 31.59 | <0.01 | 0.96 |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | 31.23 | 31.42 | <0.01 | 0.96 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 29.19 | 33.82 | 0.01 | 0.97 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | 30.90 | 29.30 | <0.01 | 0.97 |
| $CH_4$ Emissions from Wastewater Handling | $CH_4$ | 24.25 | 26.21 | <0.01 | 0.97 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.85 | 19.60 | <0.01 | 0.98 |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | 14.09 | 17.87 | <0.01 | 0.98 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 16.03 | 16.72 | <0.01 | 0.98 |
| Non-$CO_2$ Emissions from Stationary Combustion | $N_2O$ | 12.82 | 13.38 | <0.01 | 0.98 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 14.89 | 15.39 | <0.01 | 0.99 |
| PFC Emissions from Aluminum Production | PFCs | 18.11 | 12.17 | <0.01 | 0.99 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.24 | 12.05 | <0.01 | 0.99 |
| $CO_2$ Emissions from Natural Gas Flaring | $CO_2$ | 5.51 | 6.62 | <0.01 | 0.99 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.94 | 8.45 | <0.01 | 0.99 |
| $CH_4$ Emissions from Rice Production | $CH_4$ | 7.12 | 8.21 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $CH_4$ | 7.90 | 7.82 | <0.01 | 1.00 |
| $N_2O$ Emissions from Wastewater Handling | $N_2O$ | 7.04 | 7.74 | <0.01 | 1.00 |
| $SF_6$ Emissions from Magnesium Production | $SF_6$ | 5.50 | 5.19 | <0.01 | 1.00 |
| Mobile Combustion: Road & Other | $CH_4$ | 4.67 | 4.61 | <0.01 | 1.00 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacturing | $SF_6$ | 2.86 | 3.93 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $N_2O$ | 1.71 | 1.71 | <0.01 | 1.00 |
| $CH_4$ Emissions from Other Industrial Processes | $CH_4$ | 1.19 | 1.50 | <0.01 | 1.00 |
| $CH_4$ Emissions from Agricultural Residue Burning | $CH_4$ | 0.68 | 0.81 | <0.01 | 1.00 |
| $N_2O$ Emissions from Agricultural Residue Burning | $N_2O$ | 0.37 | 0.45 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $N_2O$ | 0.36 | 0.41 | <0.01 | 1.00 |
| $N_2O$ Emissions from Waste Incineration | $N_2O$ | 0.29 | 0.27 | <0.01 | 1.00 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.22 | 0.18 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $CH_4$ | 0.16 | 0.15 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $CH_4$ | 0.07 | 0.08 | <0.01 | 1.00 |
| **TOTAL** | | **6,130.72** | **6,435.71** | **1.00** | |

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

## Table P-8: 1995 Key Source Tier 1 Analysis - Level Assessment

| IPCC Source Categories | Direct Greenhouse Gas | Base Year Estimate (Tg $CO_2$ Eq.) | Current Year Estimate (Tg $CO_2$ Eq.) | Level Assessment | Cumulative Total |
|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal | $CO_2$ | 1,692.60 | 1,792.70 | 0.28 | 0.28 |
| Mobile Combustion: Road & Other | $CO_2$ | 1,235.49 | 1,340.99 | 0.21 | 0.48 |
| $CO_2$ Emissions from Stationary Combustion - Gas | $CO_2$ | 952.76 | 1,102.94 | 0.17 | 0.65 |
| $CO_2$ Emissions from Stationary Combustion - Oil | $CO_2$ | 662.46 | 609.93 | 0.09 | 0.75 |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | 213.41 | 216.62 | 0.03 | 0.78 |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | 193.49 | 204.77 | 0.03 | 0.81 |
| Mobile Combustion: Aviation | $CO_2$ | 176.88 | 171.45 | 0.03 | 0.84 |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | 147.64 | 149.89 | 0.02 | 0.86 |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | 127.88 | 133.18 | 0.02 | 0.88 |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | 123.65 | 114.41 | 0.02 | 0.90 |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | 73.60 | 78.64 | 0.01 | 0.91 |
| Fugitive Emissions from Coal Mining and Handling | $CH_4$ | 87.12 | 73.54 | 0.01 | 0.92 |
| Mobile Combustion: Marine | $CO_2$ | 59.43 | 66.92 | 0.01 | 0.93 |
| Mobile Combustion: Road & Other | $N_2O$ | 48.86 | 58.28 | 0.01 | 0.94 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.28 | 36.85 | 0.01 | 0.95 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 29.19 | 34.79 | 0.01 | 0.95 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | 30.90 | 29.46 | <0.01 | 0.96 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | 34.98 | 27.03 | <0.01 | 0.96 |
| $CH_4$ Emissions from Wastewater Handling | $CH_4$ | 24.25 | 26.79 | <0.01 | 0.97 |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | 31.23 | 26.49 | <0.01 | 0.97 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.94 | 21.82 | <0.01 | 0.97 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.85 | 19.89 | <0.01 | 0.98 |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | 14.09 | 18.61 | <0.01 | 0.98 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 14.89 | 17.88 | <0.01 | 0.98 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 16.03 | 16.37 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $N_2O$ | 12.82 | 13.48 | <0.01 | 0.99 |
| $CO_2$ Emissions from Natural Gas Flaring | $CO_2$ | 5.51 | 8.73 | <0.01 | 0.99 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.24 | 12.80 | <0.01 | 0.99 |
| PFC Emissions from Aluminum Production | PFCs | 18.11 | 11.81 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $CH_4$ | 7.90 | 8.23 | <0.01 | 0.99 |
| $N_2O$ Emissions from Wastewater Handling | $N_2O$ | 7.04 | 7.69 | <0.01 | 1.00 |
| $CH_4$ Emissions from Rice Production | $CH_4$ | 7.12 | 7.62 | <0.01 | 1.00 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacturing | $SF_6$ | 2.86 | 5.90 | <0.01 | 1.00 |
| $SF_6$ Emissions from Magnesium Production | $SF_6$ | 5.50 | 5.49 | <0.01 | 1.00 |
| Mobile Combustion: Road & Other | $CH_4$ | 4.67 | 4.54 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $N_2O$ | 1.71 | 1.67 | <0.01 | 1.00 |
| $CH_4$ Emissions from Other Industrial Processes | $CH_4$ | 1.19 | 1.53 | <0.01 | 1.00 |
| $CH_4$ Emissions from Agricultural Residue Burning | $CH_4$ | 0.68 | 0.66 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $N_2O$ | 0.36 | 0.46 | <0.01 | 1.00 |
| $N_2O$ Emissions from Agricultural Residue Burning | $N_2O$ | 0.37 | 0.38 | <0.01 | 1.00 |
| $N_2O$ Emissions from Waste Incineration | $N_2O$ | 0.29 | 0.28 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $CH_4$ | 0.16 | 0.15 | <0.01 | 1.00 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.22 | 0.12 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $CH_4$ | 0.07 | 0.09 | <0.01 | 1.00 |
| **TOTAL** | | **6,130.72** | **6,481.81** | **1.00** | |

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

## Table P-9: 1996 Key Source Tier 1 Analysis - Level Assessment

| IPCC Source Categories | Direct Greenhouse Gas | Base Year Estimate ($Tg CO_2 Eq.$) | Current Year Estimate ($Tg CO_2 Eq.$) | Level Assessment | Cumulative Total |
|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal | $CO_2$ | 1,692.60 | 1,878.38 | 0.28 | 0.28 |
| Mobile Combustion: Road & Other | $CO_2$ | 1,235.49 | 1,374.75 | 0.21 | 0.49 |
| $CO_2$ Emissions from Stationary Combustion - Gas | $CO_2$ | 952.76 | 1,123.44 | 0.17 | 0.66 |
| $CO_2$ Emissions from Stationary Combustion - Oil | $CO_2$ | 662.46 | 645.98 | 0.10 | 0.75 |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | 193.49 | 212.29 | 0.03 | 0.78 |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | 213.41 | 211.50 | 0.03 | 0.82 |
| Mobile Combustion: Aviation | $CO_2$ | 176.88 | 180.16 | 0.03 | 0.84 |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | 147.64 | 150.67 | 0.02 | 0.87 |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | 127.88 | 129.58 | 0.02 | 0.89 |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | 123.65 | 109.78 | 0.02 | 0.90 |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | 73.60 | 80.28 | 0.01 | 0.91 |
| Fugitive Emissions from Coal Mining and Handling | $CH_4$ | 87.12 | 68.36 | 0.01 | 0.92 |
| Mobile Combustion: Marine | $CO_2$ | 59.43 | 63.78 | 0.01 | 0.93 |
| Mobile Combustion: Road & Other | $N_2O$ | 48.86 | 57.94 | 0.01 | 0.94 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.28 | 37.08 | 0.01 | 0.95 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | 34.98 | 31.12 | <0.01 | 0.95 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 29.19 | 34.20 | 0.01 | 0.96 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.94 | 30.62 | <0.01 | 0.96 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | 30.90 | 28.89 | <0.01 | 0.97 |
| $CH_4$ Emissions from Wastewater Handling | $CH_4$ | 24.25 | 27.04 | <0.01 | 0.97 |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | 31.23 | 26.77 | <0.01 | 0.97 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.85 | 20.71 | <0.01 | 0.98 |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | 14.09 | 19.57 | <0.01 | 0.98 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 14.89 | 17.75 | <0.01 | 0.98 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 16.03 | 16.79 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $N_2O$ | 12.82 | 14.06 | <0.01 | 0.99 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.24 | 13.49 | <0.01 | 0.99 |
| $CO_2$ Emissions from Natural Gas Flaring | $CO_2$ | 5.51 | 8.23 | <0.01 | 0.99 |
| PFC Emissions from Aluminum Production | PFCs | 18.11 | 12.47 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $CH_4$ | 7.90 | 8.41 | <0.01 | 0.99 |
| $N_2O$ Emissions from Wastewater Handling | $N_2O$ | 7.04 | 7.79 | <0.01 | 1.00 |
| $CH_4$ Emissions from Rice Production | $CH_4$ | 7.12 | 6.97 | <0.01 | 1.00 |
| $SF_6$ Emissions from Magnesium Production | $SF_6$ | 5.50 | 5.47 | <0.01 | 1.00 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacturing | $SF_6$ | 2.86 | 5.44 | <0.01 | 1.00 |
| Mobile Combustion: Road & Other | $CH_4$ | 4.67 | 4.44 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $N_2O$ | 1.71 | 1.76 | <0.01 | 1.00 |
| $CH_4$ Emissions from Other Industrial Processes | $CH_4$ | 1.19 | 1.60 | <0.01 | 1.00 |
| $CH_4$ Emissions from Agricultural Residue Burning | $CH_4$ | 0.68 | 0.75 | <0.01 | 1.00 |
| $N_2O$ Emissions from Agricultural Residue Burning | $N_2O$ | 0.37 | 0.42 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $N_2O$ | 0.36 | 0.42 | <0.01 | 1.00 |
| $N_2O$ Emissions from Waste Incineration | $N_2O$ | 0.29 | 0.28 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $CH_4$ | 0.16 | 0.15 | <0.01 | 1.00 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.22 | 0.13 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $CH_4$ | 0.07 | 0.08 | <0.01 | 1.00 |
| **TOTAL** | | **6,130.72** | **6,669.76** | **1.00** | |

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

## Table P-10: 1997 Key Source Tier 1 Analysis - Level Assessment

| IPCC Source Categories | Direct Greenhouse Gas | Base Year Estimate (Tg $CO_2$ Eq.) | Current Year Estimate (Tg $CO_2$ Eq.) | Level Assessment | Cumulative Total |
|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal | $CO_2$ | 1,692.60 | 1,930.51 | 0.29 | 0.29 |
| Mobile Combustion: Road & Other | $CO_2$ | 1,235.49 | 1,399.71 | 0.21 | 0.49 |
| $CO_2$ Emissions from Stationary Combustion - Gas | $CO_2$ | 952.76 | 1,125.23 | 0.17 | 0.66 |
| $CO_2$ Emissions from Stationary Combustion - Oil | $CO_2$ | 662.46 | 654.86 | 0.10 | 0.76 |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | 193.49 | 217.50 | 0.03 | 0.79 |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | 213.41 | 206.37 | 0.03 | 0.82 |
| Mobile Combustion: Aviation | $CO_2$ | 176.88 | 178.94 | 0.03 | 0.85 |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | 147.64 | 146.76 | 0.02 | 0.87 |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | 127.88 | 126.77 | 0.02 | 0.89 |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | 123.65 | 119.15 | 0.02 | 0.90 |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | 73.60 | 79.99 | 0.01 | 0.92 |
| Fugitive Emissions from Coal Mining and Handling | $CH_4$ | 87.12 | 68.13 | 0.01 | 0.93 |
| Mobile Combustion: Road & Other | $N_2O$ | 48.86 | 57.61 | 0.01 | 0.94 |
| Mobile Combustion: Marine | $CO_2$ | 59.43 | 50.17 | 0.01 | 0.94 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.28 | 38.32 | 0.01 | 0.95 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.94 | 37.99 | 0.01 | 0.95 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 29.19 | 35.85 | 0.01 | 0.96 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | 34.98 | 29.99 | <0.01 | 0.96 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | 30.90 | 28.35 | <0.01 | 0.97 |
| $CH_4$ Emissions from Wastewater Handling | $CH_4$ | 24.25 | 27.54 | <0.01 | 0.97 |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | 31.23 | 24.49 | <0.01 | 0.98 |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | 14.09 | 21.34 | <0.01 | 0.98 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.85 | 21.22 | <0.01 | 0.98 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 16.03 | 17.08 | <0.01 | 0.98 |
| Non-$CO_2$ Emissions from Stationary Combustion | $N_2O$ | 12.82 | 14.24 | <0.01 | 0.99 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.24 | 13.69 | <0.01 | 0.99 |
| $CO_2$ Emissions from Natural Gas Flaring | $CO_2$ | 5.51 | 7.57 | <0.01 | 0.99 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 14.89 | 11.50 | <0.01 | 0.99 |
| PFC Emissions from Aluminum Production | PFCs | 18.11 | 10.99 | <0.01 | 0.99 |
| $N_2O$ Emissions from Wastewater Handling | $N_2O$ | 7.04 | 7.94 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $CH_4$ | 7.90 | 7.48 | <0.01 | 1.00 |
| $CH_4$ Emissions from Rice Production | $CH_4$ | 7.12 | 7.48 | <0.01 | 1.00 |
| $SF_6$ Emissions from Magnesium Production | $SF_6$ | 5.50 | 6.91 | <0.01 | 1.00 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacturing | $SF_6$ | 2.86 | 6.55 | <0.01 | 1.00 |
| Mobile Combustion: Road & Other | $CH_4$ | 4.67 | 4.35 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $N_2O$ | 1.71 | 1.74 | <0.01 | 1.00 |
| $CH_4$ Emissions from Other Industrial Processes | $CH_4$ | 1.19 | 1.63 | <0.01 | 1.00 |
| $CH_4$ Emissions from Agricultural Residue Burning | $CH_4$ | 0.68 | 0.76 | <0.01 | 1.00 |
| $N_2O$ Emissions from Agricultural Residue Burning | $N_2O$ | 0.37 | 0.45 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $N_2O$ | 0.36 | 0.30 | <0.01 | 1.00 |
| $N_2O$ Emissions from Waste Incineration | $N_2O$ | 0.29 | 0.26 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $CH_4$ | 0.16 | 0.15 | <0.01 | 1.00 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.22 | 0.14 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $CH_4$ | 0.07 | 0.06 | <0.01 | 1.00 |
| **TOTAL** | | **6,130.72** | **6,748.06** | **1.00** | |

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

## Table P-11: 1998 Key Source Tier 1 Analysis - Level Assessment

| IPCC Source Categories | Direct Greenhouse Gas | Base Year Estimate (Tg $CO_2$ Eq.) | Current Year Estimate (Tg $CO_2$ Eq.) | Level Assessment | Cumulative Total |
|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal | $CO_2$ | 1,692.60 | 1,949.67 | 0.29 | 0.29 |
| Mobile Combustion: Road & Other | $CO_2$ | 1,235.49 | 1,424.19 | 0.21 | 0.50 |
| $CO_2$ Emissions from Stationary Combustion - Gas | $CO_2$ | 952.76 | 1,090.90 | 0.16 | 0.66 |
| $CO_2$ Emissions from Stationary Combustion - Oil | $CO_2$ | 662.46 | 660.47 | 0.10 | 0.76 |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | 193.49 | 218.59 | 0.03 | 0.79 |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | 213.41 | 200.98 | 0.03 | 0.82 |
| Mobile Combustion: Aviation | $CO_2$ | 176.88 | 182.97 | 0.03 | 0.85 |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | 147.64 | 145.61 | 0.02 | 0.87 |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | 127.88 | 124.90 | 0.02 | 0.89 |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | 123.65 | 111.11 | 0.02 | 0.90 |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | 73.60 | 79.81 | 0.01 | 0.92 |
| Fugitive Emissions from Coal Mining and Handling | $CH_4$ | 87.12 | 67.94 | 0.01 | 0.93 |
| Mobile Combustion: Road & Other | $N_2O$ | 48.86 | 57.08 | 0.01 | 0.93 |
| Mobile Combustion: Marine | $CO_2$ | 59.43 | 47.83 | 0.01 | 0.94 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.94 | 44.87 | 0.01 | 0.95 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | 34.98 | 40.15 | 0.01 | 0.95 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.28 | 39.22 | 0.01 | 0.96 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 29.19 | 38.03 | 0.01 | 0.97 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | 30.90 | 28.18 | <0.01 | 0.97 |
| $CH_4$ Emissions from Wastewater Handling | $CH_4$ | 24.25 | 27.85 | <0.01 | 0.97 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.85 | 20.89 | <0.01 | 0.98 |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | 14.09 | 20.25 | <0.01 | 0.98 |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | 31.23 | 20.15 | <0.01 | 0.98 |
| Non-$CO_2$ Emissions from Stationary Combustion | $N_2O$ | 12.82 | 14.32 | <0.01 | 0.99 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 16.03 | 17.12 | <0.01 | 0.99 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.24 | 13.91 | <0.01 | 0.99 |
| PFC Emissions from Aluminum Production | PFCs | 18.11 | 9.04 | <0.01 | 0.99 |
| $N_2O$ Emissions from Wastewater Handling | $N_2O$ | 7.04 | 8.08 | <0.01 | 0.99 |
| $CH_4$ Emissions from Rice Production | $CH_4$ | 7.12 | 7.90 | <0.01 | 0.99 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 14.89 | 7.71 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $CH_4$ | 7.90 | 7.01 | <0.01 | 1.00 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacturing | $SF_6$ | 2.86 | 7.26 | <0.01 | 1.00 |
| $SF_6$ Emissions from Magnesium Production | $SF_6$ | 5.50 | 6.18 | <0.01 | 1.00 |
| Mobile Combustion: Road & Other | $CH_4$ | 4.67 | 4.25 | <0.01 | 1.00 |
| $CO_2$ Emissions from Natural Gas Flaring | $CO_2$ | 5.51 | 6.25 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $N_2O$ | 1.71 | 1.78 | <0.01 | 1.00 |
| $CH_4$ Emissions from Other Industrial Processes | $CH_4$ | 1.19 | 1.66 | <0.01 | 1.00 |
| $CH_4$ Emissions from Agricultural Residue Burning | $CH_4$ | 0.68 | 0.78 | <0.01 | 1.00 |
| $N_2O$ Emissions from Agricultural Residue Burning | $N_2O$ | 0.37 | 0.45 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $N_2O$ | 0.36 | 0.26 | <0.01 | 1.00 |
| $N_2O$ Emissions from Waste Incineration | $N_2O$ | 0.29 | 0.24 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $CH_4$ | 0.16 | 0.15 | <0.01 | 1.00 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.22 | 0.13 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $CH_4$ | 0.07 | 0.05 | <0.01 | 1.00 |
| **TOTAL** | | **6,130.72** | **6,756.19** | **1.00** | |

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

## Table P-12: 1999 Key Source Tier 1 Analysis - Level Assessment

| IPCC Source Categories | Direct Greenhouse Gas | Base Year Estimate (Tg $CO_2$ Eq.) | Current Year Estimate (Tg $CO_2$ Eq.) | Level Assessment | Cumulative Total |
|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal | $CO_2$ | 1,692.60 | 1,956.91 | 0.29 | 0.29 |
| Mobile Combustion: Road & Other | $CO_2$ | 1,235.49 | 1,478.53 | 0.22 | 0.50 |
| $CO_2$ Emissions from Stationary Combustion - Gas | $CO_2$ | 952.76 | 1,105.01 | 0.16 | 0.66 |
| $CO_2$ Emissions from Stationary Combustion - Oil | $CO_2$ | 662.46 | 658.39 | 0.10 | 0.76 |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | 193.49 | 216.49 | 0.03 | 0.79 |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | 213.41 | 203.09 | 0.03 | 0.82 |
| Mobile Combustion: Aviation | $CO_2$ | 176.88 | 186.69 | 0.03 | 0.85 |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | 147.64 | 140.84 | 0.02 | 0.87 |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | 127.88 | 124.51 | 0.02 | 0.89 |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | 123.65 | 107.90 | 0.02 | 0.90 |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | 73.60 | 79.79 | 0.01 | 0.92 |
| Fugitive Emissions from Coal Mining and Handling | $CH_4$ | 87.12 | 63.69 | 0.01 | 0.93 |
| Mobile Combustion: Marine | $CO_2$ | 59.43 | 63.02 | 0.01 | 0.93 |
| Mobile Combustion: Road & Other | $N_2O$ | 48.86 | 56.44 | 0.01 | 0.94 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.94 | 51.28 | 0.01 | 0.95 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.28 | 39.99 | 0.01 | 0.96 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 29.19 | 37.56 | 0.01 | 0.96 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | 34.98 | 30.41 | <0.01 | 0.97 |
| $CH_4$ Emissions from Wastewater Handling | $CH_4$ | 24.25 | 28.35 | <0.01 | 0.97 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | 30.90 | 27.00 | <0.01 | 0.97 |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | 14.09 | 21.84 | <0.01 | 0.98 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.85 | 20.12 | <0.01 | 0.98 |
| Non-$CO_2$ Emissions from Stationary Combustion | $N_2O$ | 12.82 | 14.60 | <0.01 | 0.98 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 16.03 | 17.15 | <0.01 | 0.99 |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | 31.23 | 15.51 | <0.01 | 0.99 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.24 | 13.47 | <0.01 | 0.99 |
| PFC Emissions from Aluminum Production | PFCs | 18.11 | 8.94 | <0.01 | 0.99 |
| $N_2O$ Emissions from Wastewater Handling | $N_2O$ | 7.04 | 8.36 | <0.01 | 0.99 |
| $CH_4$ Emissions from Rice Production | $CH_4$ | 7.12 | 8.29 | <0.01 | 0.99 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacturing | $SF_6$ | 2.86 | 7.73 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $CH_4$ | 7.90 | 7.34 | <0.01 | 1.00 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 14.89 | 7.68 | <0.01 | 1.00 |
| $SF_6$ Emissions from Magnesium Production | $SF_6$ | 5.50 | 6.11 | <0.01 | 1.00 |
| Mobile Combustion: Road & Other | $CH_4$ | 4.67 | 4.15 | <0.01 | 1.00 |
| $CO_2$ Emissions from Natural Gas Flaring | $CO_2$ | 5.51 | 6.68 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $N_2O$ | 1.71 | 1.82 | <0.01 | 1.00 |
| $CH_4$ Emissions from Other Industrial Processes | $CH_4$ | 1.19 | 1.68 | <0.01 | 1.00 |
| $CH_4$ Emissions from Agricultural Residue Burning | $CH_4$ | 0.68 | 0.76 | <0.01 | 1.00 |
| $N_2O$ Emissions from Agricultural Residue Burning | $N_2O$ | 0.37 | 0.44 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $N_2O$ | 0.36 | 0.43 | <0.01 | 1.00 |
| $N_2O$ Emissions from Waste Incineration | $N_2O$ | 0.29 | 0.23 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $CH_4$ | 0.16 | 0.15 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $CH_4$ | 0.07 | 0.08 | <0.01 | 1.00 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.22 | 0.04 | <0.01 | 1.00 |
| **TOTAL** | | **6,130.72** | **6,829.49** | **1.00** | |

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

## Table P-13: 2000 Key Source Tier 1 Analysis - Level Assessment

| IPCC Source Categories | Direct Greenhouse Gas | Base Year Estimate (Tg $CO_2$ Eq.) | Current Year Estimate (Tg $CO_2$ Eq.) | Level Assessment | Cumulative Total |
|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal | $CO_2$ | 1692.60 | 2,030.09 | 0.29 | 0.29 |
| Mobile Combustion: Road & Other | $CO_2$ | 1235.49 | 1,503.16 | 0.21 | 0.50 |
| $CO_2$ Emissions from Stationary Combustion - Gas | $CO_2$ | 952.76 | 1,162.91 | 0.17 | 0.67 |
| $CO_2$ Emissions from Stationary Combustion - Oil | $CO_2$ | 662.46 | 640.72 | 0.09 | 0.76 |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | 193.49 | 217.75 | 0.03 | 0.79 |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | 213.41 | 203.48 | 0.03 | 0.82 |
| Mobile Combustion: Aviation | $CO_2$ | 176.88 | 196.45 | 0.03 | 0.85 |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | 147.64 | 138.22 | 0.02 | 0.87 |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | 127.88 | 123.86 | 0.02 | 0.89 |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | 123.65 | 107.56 | 0.02 | 0.90 |
| Mobile Combustion: Marine | $CO_2$ | 59.43 | 89.91 | 0.01 | 0.92 |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | 73.60 | 79.81 | 0.01 | 0.93 |
| Fugitive Emissions from Coal Mining and Handling | $CH_4$ | 87.12 | 60.97 | 0.01 | 0.94 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.94 | 57.78 | 0.01 | 0.94 |
| Mobile Combustion: Road & Other | $N_2O$ | 48.86 | 55.74 | 0.01 | 0.95 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.28 | 41.07 | 0.01 | 0.96 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 29.19 | 37.46 | 0.01 | 0.96 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | 34.98 | 29.79 | <0.01 | 0.97 |
| $CH_4$ Emissions from Wastewater Handling | $CH_4$ | 24.25 | 28.70 | <0.01 | 0.97 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | 30.90 | 26.30 | <0.01 | 0.98 |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | 14.09 | 22.47 | <0.01 | 0.98 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.85 | 19.79 | <0.01 | 0.98 |
| Non-$CO_2$ Emissions from Stationary Combustion | $N_2O$ | 12.82 | 14.93 | <0.01 | 0.98 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 16.03 | 17.52 | <0.01 | 0.99 |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | 31.23 | 14.45 | <0.01 | 0.99 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.24 | 13.32 | <0.01 | 0.99 |
| $N_2O$ Emissions from Wastewater Handling | $N_2O$ | 7.04 | 8.46 | <0.01 | 0.99 |
| PFC Emissions from Aluminum Production | PFCs | 18.11 | 7.95 | <0.01 | 0.99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $CH_4$ | 7.90 | 7.50 | <0.01 | 0.99 |
| $CH_4$ Emissions from Rice Production | $CH_4$ | 7.12 | 7.50 | <0.01 | 0.99 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 14.89 | 8.11 | <0.01 | 1.00 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacturing | $SF_6$ | 2.86 | 7.37 | <0.01 | 1.00 |
| Mobile Combustion: Road & Other | $CH_4$ | 4.67 | 4.09 | <0.01 | 1.00 |
| $SF_6$ Emissions from Magnesium Production | $SF_6$ | 5.50 | 4.00 | <0.01 | 1.00 |
| $CO_2$ Emissions from Natural Gas Flaring | $CO_2$ | 5.51 | 6.06 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $N_2O$ | 1.71 | 1.92 | <0.01 | 1.00 |
| $CH_4$ Emissions from Other Industrial Processes | $CH_4$ | 1.19 | 1.67 | <0.01 | 1.00 |
| $CH_4$ Emissions from Agricultural Residue Burning | $CH_4$ | 0.68 | 0.79 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $N_2O$ | 0.36 | 0.63 | <0.01 | 1.00 |
| $N_2O$ Emissions from Agricultural Residue Burning | $N_2O$ | 0.37 | 0.46 | <0.01 | 1.00 |
| $N_2O$ Emissions from Waste Incineration | $N_2O$ | 0.29 | 0.23 | <0.01 | 1.00 |
| Mobile Combustion: Aviation | $CH_4$ | 0.16 | 0.16 | <0.01 | 1.00 |
| Mobile Combustion: Marine | $CH_4$ | 0.07 | 0.12 | <0.01 | 1.00 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.22 | 0.02 | <0.01 | 1.00 |
| **TOTAL** | | **6,130.72** | **7,001.22** | **1.00** | |

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

## Table P-14: 1990-2000 Key Source Tier 1 Analysis - Trend Assessment

| IPCC Source Categories | Direct Greenhouse Gas | Base Year Estimate (Tg $CO_2$ Eq.) | Current Year Estimate (Tg $CO_2$ Eq.) | Trend Assessment | Percent Contribution to Trend | Cumulative Total |
|---|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Oil | $CO_2$ | 662.46 | 640.72 | 0.01 | 16 | 16 |
| $CO_2$ Emissions from Stationary Combustion - Coal | $CO_2$ | 1,692.60 | 2,030.09 | 0.01 | 13 | 29 |
| Mobile Combustion: Road & Other | $CO_2$ | 1,235.49 | 1,503.16 | 0.01 | 13 | 42 |
| $CO_2$ Emissions from Stationary Combustion - Gas | $CO_2$ | 952.76 | 1,162.91 | 0.01 | 10 | 52 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.94 | 57.78 | 0.01 | 8 | 60 |
| $CH_4$ Emissions from Solid Waste Disposal Sites | $CH_4$ | 213.41 | 203.48 | 0.01 | 6 | 66 |
| Fugitive Emissions from Coal Mining and Handling | $CH_4$ | 87.12 | 60.97 | <0.01 | 5 | 71 |
| $CO_2$ Emissions from Other Industrial Processes | $CO_2$ | 123.65 | 107.56 | <0.01 | 5 | 76 |
| Fugitive Emissions from Oil & Gas Operations | $CH_4$ | 147.64 | 138.22 | <0.01 | 4 | 80 |
| $CH_4$ Emissions from Enteric Fermentation in Domestic Livestock | $CH_4$ | 127.88 | 123.86 | <0.01 | 3 | 83 |
| Mobile Combustion: Marine | $CO_2$ | 59.43 | 89.91 | <0.01 | 3 | 86 |
| $SF_6$ Emissions from Electrical Equipment | $SF_6$ | 31.23 | 14.45 | <0.01 | 3 | 89 |
| PFC Emissions from Aluminum Production | PFCs | 18.11 | 7.95 | <0.01 | 2 | 90 |
| HFC-23 Emissions from HCFC-22 Manufacture | HFCs | 34.98 | 29.79 | <0.01 | 1 | 92 |
| Indirect $CO_2$ Emissions from $CH_4$ Oxidation | $CO_2$ | 30.90 | 26.30 | <0.01 | 1 | 93 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 14.89 | 8.11 | <0.01 | 1 | 94 |
| $CO_2$ Emissions from Waste Incineration | $CO_2$ | 14.09 | 22.47 | <0.01 | 1 | 95 |
| Mobile Combustion: Aviation | $CO_2$ | 176.88 | 196.45 | <0.01 | 1 | 96 |
| Indirect $N_2O$ Emissions from Nitrogen Used in Agriculture | $N_2O$ | 73.60 | 79.81 | <0.01 | 1 | 97 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 29.19 | 37.46 | <0.01 | 1 | 97 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacturing | $SF_6$ | 2.86 | 7.37 | <0.01 | 1 | 98 |
| Direct $N_2O$ Emissions from Agricultural Soils | $N_2O$ | 193.49 | 217.75 | <0.01 | 0 | 98 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.28 | 41.07 | <0.01 | 0 | 99 |
| $SF_6$ Emissions from Magnesium Production | $SF_6$ | 5.50 | 4.00 | <0.01 | 0 | 99 |
| Non-$CO_2$ Emissions from Stationary Combustion | $CH_4$ | 7.90 | 7.50 | <0.01 | 0 | 99 |
| Mobile Combustion: Road & Other | $CH_4$ | 4.67 | 4.09 | <0.01 | 0 | 99 |
| $CH_4$ Emissions from Wastewater Handling | $CH_4$ | 24.25 | 28.70 | <0.01 | 0 | 99 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 16.03 | 17.52 | <0.01 | 0 | 99 |
| $CH_4$ Emissions from Rice Production | $CH_4$ | 7.12 | 7.50 | <0.01 | 0 | 100 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.85 | 19.79 | <0.01 | 0 | 100 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.24 | 13.32 | <0.01 | 0 | 100 |
| $N_2O$ Emissions from Wastewater Handling | $N_2O$ | 7.04 | 8.46 | <0.01 | 0 | 100 |
| $CH_4$ Emissions from Other Industrial Processes | $CH_4$ | 1.19 | 1.67 | <0.01 | 0 | 100 |
| Non-$CO_2$ Emissions from Stationary Combustion | $N_2O$ | 12.82 | 14.93 | <0.01 | 0 | 100 |
| $CO_2$ Emissions from Natural Gas Flaring | $CO_2$ | 5.51 | 6.06 | <0.01 | 0 | 100 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.22 | 0.02 | <0.01 | 0 | 100 |
| Mobile Combustion: Marine | $N_2O$ | 0.36 | 0.63 | <0.01 | 0 | 100 |
| $N_2O$ Emissions from Waste Incineration | $N_2O$ | 0.29 | 0.23 | <0.01 | 0 | 100 |
| Mobile Combustion: Road & Other | $N_2O$ | 48.86 | 55.74 | <0.01 | 0 | 100 |
| Mobile Combustion: Marine | $CH_4$ | 0.07 | 0.12 | <0.01 | 0 | 100 |
| Mobile Combustion: Aviation | $N_2O$ | 1.71 | 1.92 | <0.01 | 0 | 100 |
| $N_2O$ Emissions from Agricultural Residue Burning | $N_2O$ | 0.37 | 0.46 | <0.01 | 0 | 100 |
| Mobile Combustion: Aviation | $CH_4$ | 0.16 | 0.16 | <0.01 | 0 | 100 |
| $CH_4$ Emissions from Agricultural Residue Burning | $CH_4$ | 0.68 | 0.79 | <0.01 | 0 | 100 |
| **TOTAL** | | **6,130.72** | **7,001.22** | **0.09** | **100** | |

Note: Sinks (e.g., LUCF, Landfill Carbon Storage) are not included in this analysis.

# ANNEX Q

## Global Warming Potential Values

Global Warming Potentials (GWPs) are intended as a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas. It is defined as the cumulative radiative forcing—both direct and indirect effects—integrated over a period of time from the emission of a unit mass of gas relative to some reference gas (IPCC 1996). Carbon dioxide ($CO_2$) was chosen as this reference gas. Direct effects occur when the gas itself is a greenhouse gas. 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 relationship between gigagrams (Gg) of a gas and Tg $CO_2$ Eq. can be expressed as follows:

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

Where,

Tg $CO_2$ Eq. = Teragrams of Carbon Dioxide Equivalents

Gg = Gigagrams (equivalent to a thousand metric tons)

GWP = Global Warming Potential

Tg = Teragrams

GWP values allow policy makers to compare the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of roughly ±35 percent, though some GWPs have larger uncertainty than others, especially those in which lifetimes have not yet been ascertained. In the following decision, the parties to the UNFCCC have agreed to use consistent GWPs from the IPCC Second Assessment Report (SAR), based upon a 100 year time horizon, although other time horizon values are available (see Table Q-1).

> *In addition to communicating emissions in units of mass, Parties may choose also to use global warming potentials (GWPs) to reflect their inventories and projections in carbon dioxide-equivalent terms, using information provided by the Intergovernmental Panel on Climate Change (IPCC) in its Second Assessment Report. Any use of GWPs should be based on the effects of the greenhouse gases over a 100-year time horizon. In addition, Parties may also use other time horizons.*[1]

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, other ambient air pollutants (e.g., $NO_x$, and NMVOCs), and tropospheric aerosols (e.g., $SO_2$ products and black carbon), however, vary spatially, and consequently it is difficult to quantify their global radiative forcing impacts. GWP values are generally not attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere.

---

[1] Framework Convention on Climate Change; FCCC/CP/1996/15/Add.1; 29 October 1996; Report of the Conference of the Parties at its second session; held at Geneva from 8 to 19 July 1996; Addendum; Part Two: Action taken by the Conference of the Parties at its second session; Decision 9/CP.2; Communications from Parties included in Annex I to the Convention: guidelines, schedule and process for consideration; Annex: Revised Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention; p. 18. FCCC (1996)

**Table Q-1: Global Warming Potentials (GWP) and Atmospheric Lifetimes (Years) of Gases Used in this Report**

| Gas | Atmospheric Lifetime | 100-year GWP[a] | 20-year GWP | 500-year GWP |
|---|---|---|---|---|
| Carbon dioxide ($CO_2$) | 50-200 | 1 | 1 | 1 |
| Methane ($CH_4$)[b] | 12±3 | 21 | 56 | 6.5 |
| Nitrous oxide ($N_2O$) | 120 | 310 | 280 | 170 |
| HFC-23 | 264 | 11,700 | 9,100 | 9,800 |
| HFC-125 | 32.6 | 2,800 | 4,600 | 920 |
| HFC-134a | 14.6 | 1,300 | 3,400 | 420 |
| HFC-143a | 48.3 | 3,800 | 5,000 | 1,400 |
| HFC-152a | 1.5 | 140 | 460 | 42 |
| HFC-227ea | 36.5 | 2,900 | 4,300 | 950 |
| HFC-236fa | 209 | 6,300 | 5,100 | 4,700 |
| HFC-4310mee | 17.1 | 1,300 | 3,000 | 400 |
| $CF_4$ | 50,000 | 6,500 | 4,400 | 10,000 |
| $C_2F_6$ | 10,000 | 9,200 | 6,200 | 14,000 |
| $C_4F_{10}$ | 2,600 | 7,000 | 4,800 | 10,100 |
| $C_6F_{14}$ | 3,200 | 7,400 | 5,000 | 10,700 |
| $SF_6$ | 3,200 | 23,900 | 16,300 | 34,900 |

Source: IPCC (1996)

[a] GWPs used in this report are calculated over 100 year time horizon

[b] The methane 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.

Table Q-2 presents direct and net (i.e., direct and indirect) GWPs for ozone-depleting substances (ODSs). Ozone-depleting substances directly absorb infrared radiation and contribute to positive radiative forcing; however, their effect as ozone-depleters also leads to a negative radiative forcing because ozone itself is a potent greenhouse gas. There is considerable uncertainty regarding this indirect effect; therefore, a range of net GWPs is provided for ozone depleting substances.

**Table Q-2: Net 100-year Global Warming Potentials for Select Ozone Depleting Substances***

| Gas | Direct | $Net_{min}$ | $Net_{max}$ |
|---|---|---|---|
| CFC-11 | 4,600 | (600) | 3,600 |
| CFC-12 | 10,600 | 7,300 | 9,900 |
| CFC-113 | 6,000 | 2,200 | 5,200 |
| HCFC-22 | 1,700 | 1,400 | 1,700 |
| HCFC-123 | 120 | 20 | 100 |
| HCFC-124 | 620 | 480 | 590 |
| HCFC-141b | 700 | (5) | 570 |
| HCFC-142b | 2,400 | 1,900 | 2,300 |
| $CHCl_3$ | 140 | (560) | 0 |
| $CCl_4$ | 1,800 | (3,900) | 660 |
| $CH_3Br$ | 5 | (2,600) | (500) |
| Halon-1211 | 1,300 | (24,000) | (3,600) |
| Halon-1301 | 6,900 | (76,000) | (9,300) |

Source: IPCC (2001)

* Because these compounds have been shown to deplete stratospheric ozone, they are typically referred to as ozone depleting substances (ODSs). However, they are also potent greenhouse gases. Recognizing the harmful effects of these compounds on the ozone layer, in 1987 many governments signed the *Montreal Protocol on Substances that Deplete the Ozone Layer* to limit the production and importation of a number of CFCs and other halogenated compounds. The United States furthered its commitment to phase-out ODSs by signing and ratifying the Copenhagen Amendments to the *Montreal Protocol* in 1992. Under these amendments, the United States committed to ending the production and importation of halons by 1994, and CFCs by 1996. The IPCC Guidelines and the UNFCCC do not include reporting instructions for estimating emissions of ODSs because their use is being phased-out under the *Montreal Protocol*. The effects of these compounds on radiative forcing are not addressed in this report.

The IPCC recently published its Third Assessment Report (TAR), providing the most current and comprehensive scientific assessment of climate change (IPCC 2001). Within this report, the GWPs of several gases were revised relative to the IPCC's Second Assessment Report (SAR) (IPCC 1996), 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 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. However, there were some instances in which other variables, such as the radiative efficiency or the chemical lifetime, were altered that resulted in further increases or decreases in particular GWP values. In addition, the values for radiative forcing and lifetimes have been calculated for a variety of halocarbons, which were not presented in the SAR. The changes are described in the TAR as follows:

> *New categories of gases include fluorinated organic molecules, many of which are ethers that are proposed as halocarbon substitutes. Some of the GWPs have larger uncertainties than that of others, particularly for those gases where detailed laboratory data on lifetimes are not yet available. The direct GWPs have been calculated relative to $CO_2$ using an improved calculation of the $CO_2$ radiative forcing, the SAR response function for a $CO_2$ pulse, and new values for the radiative forcing and lifetimes for a number of halocarbons.*

Table Q-3 compares the lifetimes and GWPs for the SAR and TAR. As can be seen in Table Q-3, GWPs changed anywhere from a decrease of 15 percent to an increase of 49 percent.

**Table Q-3: Comparison of GWPs and lifetimes used in the SAR and the TAR**

| Gas | Lifetime (years) SAR | Lifetime (years) TAR | GWP (100 year) SAR | GWP (100 year) TAR | Difference | |
|---|---|---|---|---|---|---|
| Carbon dioxide ($CO_2$) | 50-200 | 5-200[a] | 1 | 1 | NC | NC |
| Methane ($CH_4$)[b] | 12±3 | 8.4/12[c] | 21 | 23 | 2 | 10% |
| Nitrous oxide ($N_2O$) | 120 | 120/114[c] | 310 | 296 | (14) | -5% |
| Hydrofluorocarbons | | | | | | |
| HFC-23 | 264 | 260 | 11,700 | 12,000 | 300 | 3% |
| HFC-32 | 5.6 | 5.0 | 650 | 550 | (100) | -15% |
| HFC-41 | 3.7 | 2.6 | 150 | 97 | (53) | -35% |
| HFC-125 | 32.6 | 29 | 2,800 | 3,400 | 600 | 21% |
| HFC-134 | 10.6 | 9.6 | 1,000 | 1,100 | 100 | 10% |
| HFC-134a | 14.6 | 13.8 | 1,300 | 1,300 | NC | NC |
| HFC-143 | 3.8 | 3.4 | 300 | 330 | 30 | 10% |
| HFC-143a | 48.3 | 52 | 3,800 | 4,300 | 500 | 13% |
| HFC-152 | NA | 0.5 | NA | 43 | NA | NA |
| HFC-152a | 1.5 | 1.4 | 140 | 120 | (20) | -14% |
| HFC-161 | NA | 0.3 | NA | 12 | NA | NA |
| HFC-227ea | 36.5 | 33.0 | 2,900 | 3,500 | 600 | 21% |
| HFC-236cb | NA | 13.2 | NA | 1,300 | NA | NA |
| HFC-236ea | NA | 10 | NA | 1,200 | NA | NA |
| HFC-236fa | 209 | 220 | 6,300 | 9,400 | 3,100 | 49% |
| HFC-245ca | 6.6 | 5.9 | 560 | 640 | 80 | 14% |
| HFC-245fa | NA | 7.2 | NA | 950 | NA | NA |
| HFC-365mfc | NA | 9.9 | NA | 890 | NA | NA |
| HFC-4310mee | 17.1 | 15 | 1,300 | 1,500 | 200 | 15% |
| Iodocarbons | | | | | | |
| FIC-1311 | <0.005 | 0.005 | <1 | 1 | NC | NC |
| Fully Fluorinated Species | | | | | | |
| $SF_6$ | 3,200 | 3,200 | 23,900 | 22,000 | (1,900) | -8% |
| $CF_4$ | 50,000 | 50,000 | 6,500 | 5,700 | (800) | -12% |
| $C_2F_6$ | 10,000 | 10,000 | 9,200 | 11,900 | 2,700 | 29% |
| $C_3F_8$ | 2,600 | 2,600 | 7,000 | 8,600 | 1,600 | 23% |
| $C_4F_{10}$ | 2,600 | 2,600 | 7,000 | 8,600 | 1,600 | 23% |
| c-$C_4F_8$ | 3,200 | 3,200 | 8,700 | 10,000 | 1,300 | 15% |
| $C_5F_{12}$ | 4,100 | 4,100 | 7,500 | 8,900 | 1,400 | 19% |
| $C_6F_{14}$ | 3,200 | 3,200 | 7,400 | 9,000 | 1,600 | 22% |
| Ethers and Halogenated Ethers | | | | | | |
| $CH_3OCH_3$ | NA | 0.015 | NA | 1 | NA | NA |
| $(CF_3)_2CFOCH_3$ | NA | 3.4 | NA | 330 | NA | NA |
| $(CF_3)CH_2OH$ | NA | 0.5 | NA | 57 | NA | NA |
| $CF_3CF_2CH_2OH$ | NA | 0.4 | NA | 40 | NA | NA |
| $(CF_3)_2CHOH$ | NA | 1.8 | NA | 190 | NA | NA |
| HFE-125 | NA | 150 | NA | 14,900 | NA | NA |
| HFE-134 | NA | 26.2 | NA | 6,100 | NA | NA |
| HFE-143a | NA | 4.4 | NA | 750 | NA | NA |
| HCFE-235da2 | NA | 2.6 | NA | 340 | NA | NA |
| HFE-245cb2 | NA | 4.3 | NA | 580 | NA | NA |
| HFE-245fa2 | NA | 4.4 | NA | 570 | NA | NA |
| HFE-254cb2 | NA | 0.22 | NA | 30 | NA | NA |
| HFE-347mcc3 | NA | 4.5 | NA | 480 | NA | NA |
| HFE-356pcf3 | NA | 3.2 | NA | 430 | NA | NA |

| | | | | | | |
|---|---|---|---|---|---|---|
| HFE-374pcf2 | NA | 5.0 | NA | 540 | NA | NA |
| HFE-7100 | NA | 5.0 | NA | 390 | NA | NA |
| HFE-7200 | NA | 0.77 | NA | 55 | NA | NA |
| H-Galden 1040x | NA | 6.3 | NA | 1,800 | NA | NA |
| HG-10 | NA | 12.1 | NA | 2,700 | NA | NA |
| HG-01 | NA | 6.2 | NA | 1,500 | NA | NA |
| **Others**[d] | | | | | | |
| $NF_3$ | NA | 740 | NA | 10,800 | NA | NA |
| $SF_5CF_3$ | NA | >1,000 | NA | >17,500 | NA | NA |
| c-$C_3F_6$ | NA | >1,000 | NA | >16,800 | NA | NA |
| HFE-227ea | NA | 11 | NA | 1,500 | NA | NA |
| HFE-236ea2 | NA | 5.8 | NA | 960 | NA | NA |
| HFE-236fa | NA | 3.7 | NA | 470 | NA | NA |
| HFE-245fa1 | NA | 2.2 | NA | 280 | NA | NA |
| HFE-263fb2 | NA | 0.1 | NA | 11 | NA | NA |
| HFE-329mcc2 | NA | 6.8 | NA | 890 | NA | NA |
| HFE-338mcf2 | NA | 4.3 | NA | 540 | NA | NA |
| HFE-347-mcf2 | NA | 2.8 | NA | 360 | NA | NA |
| HFE-356mec3 | NA | 0.94 | NA | 98 | NA | NA |
| HFE-356pcc3 | NA | 0.93 | NA | 110 | NA | NA |
| HFE-356pcf2 | NA | 2.0 | NA | 260 | NA | NA |
| HFE-365mcf3 | NA | 0.11 | NA | 11 | NA | NA |
| $(CF_3)_2CHOCHF_2$ | NA | 3.1 | NA | 370 | NA | NA |
| $(CF_3)_2CHOCH_3$ | NA | 0.25 | NA | 26 | NA | NA |
| -$(CF_2)_4CH(OH)$- | NA | 0.85 | NA | 70 | NA | NA |

[a] No single lifetime can be determined for carbon dioxide. (See IPCC 2001)

[b] The methane 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.

[c] Methane and nitrous oxide have chemical feedback systems that can alter the length of the atmospheric response, in these cases, global mean atmospheric lifetime (LT) is given first, followed by perturbation time (PT).

[d] Gases whose lifetime has been deterined only via indirect means of for whom there is uncertainty over the loss process.

Source: IPCC (2001)

NC (No Change)

NA (Not Applicable)

When the GWPs from the TAR are applied to the emission estimates presented in this report, total emissions for the year 2000 are 7,044.3 Tg $CO_2$ Eq., as compared to 7,001.2 Tg $CO_2$ Eq. when the GWPs from the SAR are used (a 0.6 percent difference). Table Q-4 provides a detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 2000, using the GWPs from the TAR. The adjusted greenhouse gas emissions are shown for each gas in units of Tg $CO_2$ Eq. in Table Q-5. The correlating percent change in emissions of each gas is shown in Table Q-6. The percent change in emissions is equal to the percent change in the GWP, however, in cases where multiple gases are emitted in varying amounts the percent change is variable over the years, such as with substitutes for ozone depleting substances. Table Q-7 summarizes the emissions and resulting change in emissions using GWPs from the SAR or the TAR for 1990 and 2000.

## Table Q-4: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks using the TAR GWPs (Tg $CO_2$ Eq.)

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **$CO_2$** | **4,998.5** | **5,305.9** | **5,483.7** | **5,568.0** | **5,575.1** | **5,665.5** | **5,840.0** |
| Fossil Fuel Combustion | 4,779.8 | 5,085.0 | 5,266.6 | 5,339.6 | 5,356.2 | 5,448.6 | 5,623.3 |
| Natural Gas Flaring | 5.5 | 8.7 | 8.2 | 7.6 | 6.3 | 6.7 | 6.1 |
| Cement Manufacture | 33.3 | 36.8 | 37.1 | 38.3 | 39.2 | 40.0 | 41.1 |
| Lime Manufacture | 11.2 | 12.8 | 13.5 | 13.7 | 13.9 | 13.5 | 13.3 |
| Limestone and Dolomite Use | 5.2 | 7.0 | 7.4 | 8.4 | 8.2 | 9.1 | 9.2 |
| Soda Ash Manufacture and Consumption | 4.1 | 4.3 | 4.2 | 4.4 | 4.3 | 4.2 | 4.2 |
| Carbon Dioxide Consumption | 0.8 | 1.0 | 1.1 | 1.3 | 1.4 | 1.6 | 1.4 |
| Waste Combustion | 14.1 | 18.6 | 19.6 | 21.3 | 20.3 | 21.8 | 22.5 |
| Titanium Dioxide Production | 1.3 | 1.7 | 1.7 | 1.8 | 1.8 | 1.9 | 2.0 |
| Aluminum Production | 6.3 | 5.3 | 5.6 | 5.6 | 5.8 | 5.9 | 5.4 |
| Iron and Steel Production | 85.4 | 74.4 | 68.3 | 76.1 | 67.4 | 64.4 | 65.7 |
| Ferroalloys | 2.0 | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 | 1.7 |
| Indirect $CO_2$ | 30.9 | 29.5 | 28.9 | 28.4 | 28.2 | 27.0 | 26.3 |
| Ammonia Manufacture | 18.5 | 18.9 | 19.5 | 19.5 | 20.1 | 18.9 | 18.0 |
| Land-Use Change and Forestry (Sink)[a] | (1,097.7) | (1,110.0) | (1,108.1) | (887.5) | (885.9) | (896.4) | (902.5) |
| International Bunker Fuels[b] | 113.9 | 101.0 | 102.3 | 109.9 | 112.9 | 105.3 | 100.2 |
| **$CH_4$** | **713.3** | **720.2** | **705.0** | **693.7** | **686.8** | **679.6** | **673.0** |
| Stationary Sources | 8.6 | 9.0 | 9.2 | 8.2 | 7.7 | 8.0 | 8.2 |
| Mobile Sources | 5.4 | 5.2 | 5.1 | 5.0 | 4.9 | 4.8 | 4.8 |
| Coal Mining | 95.4 | 80.5 | 74.9 | 74.6 | 74.4 | 69.8 | 66.8 |
| Natural Gas Systems | 132.8 | 137.6 | 138.7 | 134.4 | 133.9 | 129.9 | 127.4 |
| Petroleum Systems | 28.9 | 26.5 | 26.3 | 26.3 | 25.6 | 24.4 | 23.9 |
| Petrochemical Production | 1.3 | 1.7 | 1.7 | 1.8 | 1.8 | 1.8 | 1.8 |
| Silicon Carbide Production | + | + | + | + | + | + | + |
| Enteric Fermentation | 140.1 | 145.9 | 141.9 | 138.8 | 136.8 | 136.4 | 135.7 |
| Manure Management | 32.0 | 38.1 | 37.5 | 39.3 | 41.6 | 41.1 | 41.0 |
| Rice Cultivation | 7.8 | 8.3 | 7.6 | 8.2 | 8.7 | 9.1 | 8.2 |
| Agricultural Residue Burning | 0.7 | 0.7 | 0.8 | 0.8 | 0.9 | 0.8 | 0.9 |
| Landfills | 233.7 | 237.3 | 231.6 | 226.0 | 220.1 | 222.4 | 222.9 |
| Wastewater Treatment | 26.6 | 29.3 | 29.6 | 30.2 | 30.5 | 31.0 | 31.4 |
| International Bunker Fuels[b] | 0.2 | 0.1 | 0.1 | 0.2 | 0.2 | 0.1 | 0.1 |
| **$N_2O$** | **369.8** | **400.8** | **411.0** | **410.4** | **407.1** | **404.4** | **406.1** |
| Stationary Source | 12.2 | 12.9 | 13.4 | 13.6 | 13.7 | 13.9 | 14.3 |
| Mobile Sources | 48.6 | 57.7 | 57.4 | 57.0 | 56.5 | 56.0 | 55.7 |
| Adipic Acid | 14.2 | 17.1 | 17.0 | 11.0 | 7.4 | 7.3 | 7.7 |
| Nitric Acid | 17.0 | 19.0 | 19.8 | 20.3 | 19.9 | 19.2 | 18.9 |
| Manure Management | 15.3 | 15.6 | 16.0 | 16.3 | 16.3 | 16.4 | 16.7 |
| Agricultural Soil Management | 255.0 | 270.6 | 279.4 | 284.1 | 284.9 | 282.9 | 284.1 |
| Agricultural Residue Burning | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Human Sewage | 6.7 | 7.3 | 7.4 | 7.6 | 7.7 | 8.0 | 8.1 |
| Waste Combustion | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| International Bunker Fuels[b] | 0.9 | 0.8 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| **HFCs, PFCs, and $SF_6$** | **91.1** | **97.8** | **111.9** | **117.6** | **129.8** | **122.9** | **125.1** |
| Substitution of Ozone Depleting Substances | 0.9 | 22.6 | 32.3 | 39.9 | 47.4 | 54.4 | 61.5 |
| Aluminum Production | 16.8 | 10.9 | 11.5 | 10.1 | 8.3 | 8.2 | 7.3 |
| HCFC-22 Production[c] | 35.9 | 27.7 | 31.9 | 30.8 | 41.2 | 31.2 | 30.6 |
| Semiconductor Manufacture[d] | 3.3 | 6.8 | 6.3 | 7.6 | 8.4 | 9.0 | 8.5 |
| Electrical Transmission and Distribution[e] | 29.0 | 24.6 | 24.9 | 22.7 | 18.7 | 14.4 | 13.4 |
| Magnesium Production and Processing[e] | 5.1 | 5.1 | 5.1 | 6.4 | 5.7 | 5.7 | 3.7 |
| **Total** | **6,172.7** | **6,524.8** | **6,711.7** | **6,789.6** | **6,798.8** | **6,872.3** | **7,044.3** |

+ Does not exceed 0.05 Tg $CO_2$ Eq.

[a] Sinks are only included in net emissions total, and are based partially on projected activity data. Parentheses indicate negative values (or sequestration).

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

[c] HFC-23 emitted

[d] Emissions from HFC-23, $CF_4$, $C_2F_6$,$C_3F_8$ $SF_6$, and the addition of $NF_3$

[e] $SF_6$ emitted

Note: Totals may not sum due to independent rounding.

**Table Q-5: Change in U.S. Greenhouse Gas Emissions and Sinks Using TAR vs SAR GWPs (Tg $CO_2$ Eq.)**

| Gas | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| $CO_2$ | NC | NC | NC | NC | NC | NC | NC |
| $CH_4$ | 62.0 | 62.6 | 61.3 | 60.3 | 59.7 | 59.1 | 58.5 |
| $N_2O$ | (17.5) | (19.0) | (19.4) | (19.4) | (9.3) | (9.1) | (9.2) |
| HFCs, PFCs, and $SF_6$* | (2.6) | (0.7) | 0.1 | 0.6 | 2.1 | 2.9 | 3.8 |
| **Total** | **42.0** | **42.9** | **41.9** | **41.6** | **42.6** | **42.8** | **43.1** |

NC (No change)
*Includes $NF_3$
Note: Totals may not sum due to independent rounding.

**Table Q-6: Change in U.S. Greenhouse Gas Emissions Using TAR vs SAR GWPs (Percent)**

| Gas/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| $CO_2$ | NC | NC | NC | NC | NC | NC | NC |
| $CH_4$ | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 |
| $N_2O$ | (4.5) | (4.5) | (4.5) | (4.5) | (4.5) | (4.5) | (4.5) |
| HFCs, PFCs, and $SF_6$ | (2.7) | (0.7) | 0.1 | 0.6 | 1.6 | 2.4 | 3.1 |
| Substitution of Ozone Depleting Substances | (3.2) | 3.7 | 5.4 | 5.1 | 5.6 | 6.1 | 6.5 |
| Aluminum Production[a] | (7.0) | (7.7) | (7.8) | (7.9) | (7.9) | (7.9) | (8.0) |
| HCFC-22 Production[b] | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 |
| Semiconductor Manufacture[c] | 15.9 | 15.9 | 15.9 | 15.9 | 15.9 | 15.9 | 15.9 |
| Electrical Transmission and Distribution[d] | (7.1) | (7.1) | (7.1) | (7.1) | (7.1) | (7.1) | (7.1) |
| Magnesium Production and Processing[d] | (7.1) | (7.1) | (7.1) | (7.1) | (7.1) | (7.1) | (7.1) |
| **Total** | **0.7** | **0.7** | **0.6** | **0.6** | **0.6** | **0.6** | **0.6** |

NC (No change)
[a] PFC emissions from $CF_4$ and $C_2F_6$
[b] HFC-23 emitted
[c] Emissions from HFC-23, $CF_4$, $C_2F_6$,$C_3F_8$ $SF_6$, and the addition of $NF_3$
[d] $SF_6$ emitted
Note: Excludes Sinks.

**Table Q-7: Effects on U.S. Greenhouse Gas Emissions Using TAR vs SAR GWPs (Tg $CO_2$ Eq.)**

| Gas | Trend from 1990 to 2000 | | Revisions to Annual Estimates | |
|---|---|---|---|---|
| | SAR | TAR | 1990 | 2000 |
| $CO_2$ | 841.5 | 841.5 | NC | NC |
| $CH_4$ | (36.8) | (40.3) | 62.0 | 58.5 |
| $N_2O$ | 38.0 | 36.3 | (17.5) | (19.2) |
| HFCs, PFCs, and $SF_6$* | 27.7 | 34.0 | (2.6) | 3.8 |
| **Total** | **870.5** | **871.6** | **42.0** | **43.1** |
| **Percent Change** | **14.2%** | **14.1%** | **0.7%** | **0.6%** |

NC (No Change)
*Includes $NF_3$
Note: Totals may not sum due to independent rounding. Excludes Sinks.

Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends, as shown in Table Q-5 and Table Q-6. Table Q-8 below shows a comparison of total emissions estimates by sector using both the IPCC SAR and TAR GWP values. For most sectors, the change in emissions was minimal. The effect on emissions from waste was by far the greatest (9.1 percent), due the predominance of $CH_4$ emissions in this sector. Emissions from all other sectors were comprised of mainly $CO_2$ or a mix of gases, which moderated the effect of the changes.

**Table Q-8: Comparison of Emissions by Sector using IPCC SAR and TAR GWP Values (Tg $CO_2$ Eq.)**

| Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Energy** | | | | | | | |
| SAR GWP (Used in Inventory) | 5,141.9 | 5,452.4 | 5,629.9 | 5,697.9 | 5,709.5 | 5,793.9 | 5,962.6 |
| TAR GWP | 5,162.6 | 5,471.6 | 5,648.6 | 5,716.2 | 5,727.6 | 5,811.2 | 5,979.4 |
| Difference (%) | 0.4% | 0.4% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% |
| **Industrial Processes** | | | | | | | |
| SAR GWP (Used in Inventory) | 295.7 | 301.9 | 312.3 | 322.4 | 322.1 | 310.8 | 312.8 |
| TAR GWP | 291.8 | 299.6 | 310.8 | 321.7 | 323.1 | 312.6 | 315.5 |
| Difference (%) | -1.3% | -0.8% | -0.5% | -0.2% | 0.3% | 0.6% | 0.8% |
| **Agriculture** | | | | | | | |
| SAR GWP (Used in Inventory) | 448.4 | 476.4 | 481.3 | 485.9 | 487.6 | 485.0 | 485.1 |
| TAR GWP | 451.3 | 479.6 | 483.6 | 487.9 | 489.7 | 487.1 | 487.1 |
| Difference (%) | 0.6% | 0.7% | 0.5% | 0.4% | 0.4% | 0.4% | 0.4% |
| **Land-Use Change and Forestry** | | | | | | | |
| SAR GWP (Used in Inventory) | (1,097.7) | (1,110.0) | (1,108.1) | (887.5) | (885.9) | (896.4) | (902.5) |
| TAR GWP | (1,097.7) | (1,110.0) | (1,108.1) | (887.5) | (885.9) | (896.4) | (902.5) |
| Difference (%) | NC | NC | NC | NC | NC | NC | NC |
| **Waste** | | | | | | | |
| SAR GWP (Used in Inventory) | 244.7 | 251.1 | 246.3 | 241.9 | 236.9 | 239.8 | 240.6 |
| TAR GWP | 267.0 | 273.9 | 268.7 | 263.8 | 258.3 | 261.5 | 262.4 |
| Difference (%) | 9.1% | 9.1% | 9.1% | 9.1% | 9.0% | 9.0% | 9.0% |
| **Net Emisions (Sources and Sinks)** | | | | | | | |
| **SAR GWP (Used in Inventory)** | **5,033.0** | **5,371.8** | **5,561.7** | **5,860.5** | **5,870.3** | **5,933.1** | **6,098.7** |
| **TAR GWP** | **5,074.9** | **5,414.7** | **5,603.6** | **5,902.1** | **5,912.9** | **5,975.9** | **6,141.8** |
| **Difference (%)** | **0.8%** | **0.8%** | **0.7%** | **0.7%** | **0.7%** | **0.7%** | **0.7%** |

NC (No change)
Note: Totals may not sum due to independent rounding.

# ANNEX R

## Ozone Depleting Substance Emissions

Ozone is present in both the stratosphere,[1] where it shields the earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[2] where it is the main component of anthropogenic photochemical "smog." Chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs), along with certain other chlorine and bromine containing compounds, have been found to deplete the ozone levels in the stratosphere. These compounds are commonly referred to as ozone depleting substances (ODSs). If left unchecked, stratospheric ozone depletion could result in a dangerous increase of ultraviolet radiation reaching the earth's surface. In 1987, nations around the world signed the *Montreal Protocol on Substances that Deplete the Ozone Layer*. This landmark agreement created an international framework for limiting, and ultimately eliminating, the production of most ozone depleting substances. ODSs have historically been used in a variety of industrial applications, including refrigeration and air conditioning, foam blowing, fire extinguishing, as an aerosol propellant, sterilization, and solvent cleaning.

In the United States, the Clean Air Act Amendments of 1990 provide the legal instrument for implementation of the *Montreal Protocol* controls. The Clean Air Act classifies ozone depleting substances as either Class I or Class II, depending upon the ozone depletion potential (ODP) of the compound.[3] The production of CFCs, halons, carbon tetrachloride, and methyl chloroform—all Class I substances—has already ended in the United States. However, large amounts of these chemicals remain in existing equipment,[4] and stockpiles of the ODSs are used for maintaining the equipment. In addition, U.S. regulations require the recovery of ODSs in order to minimize "venting" to the atmosphere. As a result, emissions of Class I compounds will continue, albeit in ever decreasing amounts, into the early part of the next century. Class II designated substances, all of which are hydrochlorofluorocarbons (HCFCs), are being phased out at later dates because they have lower ozone depletion potentials. These compounds serve as interim replacements for Class I compounds in many industrial applications. The use and emissions of HCFCs in the United States is anticipated to increase over the next several years as equipment that use Class I substances are retired from use. Under current controls, however, the production for domestic use of all HCFCs in the United States will end by the year 2030.

In addition to contributing to ozone depletion, CFCs, halons, carbon tetrachloride, methyl chloroform, and HCFCs are also potent greenhouse gases. However, the depletion of the ozone layer has a cooling effect on the climate that counteracts the direct warming from tropospheric emissions of ODSs. Stratospheric ozone influences the earth's radiative balance by absorption and emission of longwave radiation from the troposphere as well as absorption of shortwave radiation from the sun.

The IPCC has prepared both direct GWPs and net (combined direct warming and indirect cooling) GWP ranges for some of the most common ozone depleting substances (IPCC 1996). See Annex Q for a listing of the net GWP values for ODS.

Although the IPCC emission inventory guidelines do not require the reporting of emissions of ozone depleting substances, the United States believes that no inventory is complete without the inclusion of these compounds. Emission estimates for several ozone depleting substances are provided in Table R-1.

---

[1] The stratosphere is the layer from the top of the troposphere up to about 50 kilometers. Approximately 90 percent of atmospheric ozone is within the stratosphere. The greatest concentration of ozone occurs in the middle of the stratosphere, in a region commonly called the ozone layer.

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

[3] Substances with an ozone depletion potential of 0.2 or greater are designated as Class I. All other substances that may deplete stratospheric ozone but which have an ODP of less than 0.2 are Class II.

[4] Older refrigeration and air-conditioning equipment, fire extinguishing systems, meter-dose inhalers, and foam products blown with CFCs/HCFCs may still contain ODS.

**Table R-1: Emissions of Ozone Depleting Substances (Gg)**

| Compound | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Class I** | | | | | | | | | | | |
| CFC-11 | 53.5 | 48.3 | 45.1 | 45.4 | 36.6 | 36.2 | 26.6 | 25.1 | 24.9 | 24.0 | 22.8 |
| CFC-12 | 112.6 | 103.5 | 80.5 | 79.3 | 57.6 | 51.8 | 35.5 | 23.1 | 21.0 | 14.0 | 17.2 |
| CFC-113 | 52.7 | 41.1 | 34.2 | 34.2 | 17.1 | 17.1 | + | + | + | + | + |
| CFC-114 | 4.7 | 3.6 | 3.0 | 3.0 | 1.6 | 1.6 | 0.3 | 0.1 | 0.1 | + | + |
| CFC-115 | 4.2 | 4.0 | 3.8 | 3.6 | 3.3 | 3.0 | 3.2 | 2.9 | 2.7 | 2.6 | 2.3 |
| Carbon Tetrachloride | 32.3 | + | 21.7 | 18.6 | 15.5 | 4.7 | + | + | + | + | + |
| Methyl Chloroform | 316.6 | 309.4 | 216.6 | 185.7 | 154.7 | 92.8 | + | + | + | + | + |
| Halon-1211 | 1.0 | 1.1 | 1.0 | 1.1 | 1.0 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Halon-1301 | 1.8 | 1.8 | 1.7 | 1.7 | 1.4 | 1.4 | 1.4 | 1.3 | 1.3 | 1.3 | 1.3 |
| **Class II** | | | | | | | | | | | |
| HCFC-22 | 34.0 | 35.4 | 35.2 | 35.3 | 37.7 | 39.3 | 41.0 | 42.4 | 43.8 | 74.1 | 79.1 |
| HCFC-123 | + | + | 0.1 | 0.3 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 |
| HCFC-124 | + | + | 0.2 | 2.7 | 5.3 | 5.6 | 5.9 | 6.2 | 6.4 | 6.5 | 6.5 |
| HCFC-141b | 1.3 | 1.7 | 1.7 | 2.9 | 6.2 | 9.9 | 9.9 | 8.8 | 9.7 | 10.9 | 10.9 |
| HCFC-142b | 0.8 | 1.4 | 1.9 | 2.6 | 3.3 | 3.6 | 4.0 | 4.3 | 4.7 | 5.0 | 5.4 |
| HCFC-225ca/cb | + | + | + | + | + | + | + | + | + | + | + |

+ Does not exceed 0.05 Gg

## Methodology and Data Sources

Emissions of ozone depleting substances were estimated using two simulation models: the Atmospheric and Health Effects Framework (AHEF) and the EPA's Vintaging Model. AHEF contains estimates of U.S. domestic use of each of the ozone depleting substances. These estimates were based upon data that industry reports to the EPA and other published material. The annual consumption of each compound was divided into various end-uses based upon historical trends and research into specific industrial applications. These end-uses include refrigerants, foam blowing agents, solvents, aerosol propellants, sterilants, and fire extinguishing agents.

With the exception of aerosols, solvents, and certain foam blowing agents, emissions of ozone depleting substances are not instantaneous, but instead occur gradually over time (i.e., emissions in a given year are the result of both ODS use in that year and use in previous years). Each end-use has a certain release profile, which gives the percentage of the compound that is released to the atmosphere each year until all releases have occurred. In refrigeration equipment, for example, the initial charge is released or leaked slowly over the lifetime of the equipment, which could be 20 or more years. In addition, not all of the refrigerant is ultimately emitted—some will be recovered when the equipment is retired from operation.

The AHEF model was used to estimate emissions of ODSs that were in use prior to the controls implemented under the *Montreal Protocol*. This included CFCs, halons, carbon tetrachloride, methyl chloroform, and HCFC-22. Certain HCFCs, such as HCFC-123, HCFC-124, HCFC-141b, HCFC-142b, HCFC-225ca and HCFC-225cb, have also entered the market as interim substitutes for ODSs. Emissions estimates for these compounds were taken from the EPA's Vintaging Model.

The Vintaging Model was used to estimate the use and emissions of various ODS substitutes, including HCFCs. The model, named for its method of tracking the emissions of annual "vintages" of new equipment that enter into service, is a "bottom-up" model. It models the consumption of chemicals based on estimates of the quantity of equipment or products sold, serviced, and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment. The Vintaging model makes use of this market information to build an inventory of the in-use stocks of the equipment in each of the end-uses. Emissions are estimated by applying annual leak rates, service emission rates, and disposal emission rates to each population of equipment, as in the AHEF. By aggregating the emission and consumption output from the different end-uses, the model produces estimates of total annual use and emissions of each chemical. Please see Annex J of this Inventory for a more detailed discussion of the Vintaging Model.

## Uncertainties

Uncertainties exist with regard to the levels of chemical production, equipment sales, equipment characteristics, and end-use emissions profiles that are used by these models.

# ANNEX S

## Sulfur Dioxide Emissions

Sulfur dioxide ($SO_2$) emitted into the atmosphere through natural and anthropogenic processes affects the Earth's radiative budget through photochemical transformation into sulfate aerosols that can (1) scatter sunlight back to space, thereby reducing the radiation reaching the Earth's surface; (2) affect cloud formation; and (3) affect atmospheric chemical composition (e.g., stratospheric ozone, by providing surfaces for heterogeneous chemical reactions). The overall effect of $SO_2$ derived aerosols on radiative forcing is believed to be negative (IPCC 1996). However, because $SO_2$ is short-lived and unevenly distributed through the atmosphere, its radiative forcing impacts are highly uncertain. Sulfur dioxide emissions have been provided below in Table S-1.

The major source of $SO_2$ emissions in the United States was the burning of sulfur containing fuels, mainly coal. Metal smelting and other industrial processes also released significant quantities of $SO_2$. As a result, the largest contributors to U.S. emissions of $SO_2$ were electric utilities, accounting for 63 percent in 2000 (see Table S-2). Coal combustion accounted for approximately 94 percent of $SO_2$ emissions from electric utilities in the same year. The second largest source was industrial fuel combustion, which produced 4 percent of 2000 $SO_2$ emissions. Overall, $SO_2$ emissions in the United States decreased by 23 percent from 1990 to 2000. The majority of this decline came from reductions from electric utilities, primarily due to increased consumption of low sulfur coal from surface mines in western states.

Sulfur dioxide is important for reasons other than its effect on radiative forcing. It is a major contributor to the formation of urban smog and acid rain. As a contributor to urban smog, high concentrations of $SO_2$ can cause significant increases in acute and chronic respiratory diseases. In addition, once $SO_2$ is emitted, it is chemically transformed in the atmosphere and returns to earth as the primary contributor to acid deposition, or acid rain. Acid rain has been found to accelerate the decay of building materials and paints, and to cause the acidification of lakes and streams and damage trees. As a result of these harmful effects, the United States has regulated the emissions of $SO_2$ under the Clean Air Act. The EPA has also developed a strategy to control these emissions via four programs: (1) the National Ambient Air Quality Standards program,[1] (2) New Source Performance Standards,[2] (3) the New Source Review/Prevention of Significant Deterioration Program,[3] and (4) the sulfur dioxide allowance program.[4]

### References

EPA (2001) *National Air Pollutant Emissions Trends Report, 1900-2000*, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

[1] [42 U.S.C § 7409, CAA § 109]
[2] [42 U.S.C § 7411, CAA § 111]
[3] [42 U.S.C § 7473, CAA § 163]
[4] [42 U.S.C § 7651, CAA § 401]

## Table S-1: $SO_2$ Emissions (Gg)

| Sector/Source | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| **Energy** | **20,136** | **16,247** | **16,641** | **17,052** | **17,157** | **16,517** | **15,435** |
| Stationary Combustion | 18,407 | 14,724 | 14,726 | 15,104 | 15,192 | 14,540 | 13,496 |
| Mobile Combustion | 1,339 | 1,189 | 1,612 | 1,636 | 1,655 | 1,668 | 1,626 |
| Oil and Gas Activities | 390 | 334 | 304 | 312 | 310 | 309 | 314 |
| **Industrial Processes** | **1,306** | **1,117** | **958** | **993** | **996** | **992** | **1,031** |
| Chemical Manufacturing | 269 | 260 | 231 | 235 | 237 | 238 | 243 |
| Metals Processing | 658 | 481 | 354 | 369 | 367 | 363 | 373 |
| Storage and Transport | 6 | 2 | 5 | 5 | 5 | 5 | 5 |
| Other Industrial Processes | 362 | 365 | 354 | 371 | 376 | 376 | 392 |
| Miscellaneous* | 11 | 9 | 15 | 14 | 11 | 11 | 19 |
| **Solvent Use** | **0** | **1** | **1** | **1** | **1** | **1** | **1** |
| Degreasing | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Graphic Arts | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Dry Cleaning | NA | 0 | 0 | 0 | 0 | 0 | 0 |
| Surface Coating | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Other Industrial | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| Non-industrial | NA | NA | NA | NA | NA | NA | NA |
| **Agriculture** | **NA** | **NA** | **NA** | **NA** | **NA** | **NA** | **NA** |
| Agricultural Burning | NA | NA | NA | NA | NA | NA | NA |
| **Waste** | **39** | **43** | **29** | **30** | **31** | **31** | **32** |
| Waste Combustion | 39 | 42 | 28 | 29 | 30 | 30 | 31 |
| Landfills | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| Wastewater Treatment | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Miscellaneous Waste | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | **21,481** | **17,408** | **17,629** | **18,076** | **18,185** | **17,541** | **16,499** |

Source: (EPA 2000)
* Miscellaneous includes other combustion and fugitive dust categories.
NA (Not Available)
Note: Totals may not sum due to independent rounding.

## Table S-2: $SO_2$ Emissions from Electric Utilities (Gg)

| Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Coal | 13,807 | 10,526 | 11,073 | 11,444 | 11,313 | 10,729 | 9,728 |
| Petroleum | 580 | 375 | 417 | 466 | 691 | 580 | 464 |
| Natural Gas | 1 | 8 | 6 | 5 | 5 | 6 | 8 |
| Misc. Internal Combustion | 45 | 50 | 48 | 51 | 52 | 53 | 54 |
| Other | NA | NA | 4 | 4 | 110 | 112 | 80 |
| **Total** | **14,432** | **10,959** | **11,549** | **11,971** | **12,171** | **11,479** | **10,333** |

Source: (EPA 2000)
Note: Totals may not sum due to independent rounding.

# ANNEX T

## Complete List of Source Categories

| Chapter/Source | Gas(es) |
|---|---|
| **Energy** | |
| Carbon Dioxide Emissions from Fossil Fuel Combustion | $CO_2$ |
| Carbon Stored in Products from Non-Energy Uses of Fossil Fuels | $CO_2$ |
| Stationary Combustion (excluding $CO_2$) | $CH_4$, $N_2O$, CO, $NO_x$, NMVOC |
| Mobile Combustion (excluding $CO_2$) | $CH_4$, $N_2O$, CO, $NO_x$, NMVOC |
| Coal Mining | $CH_4$ |
| Natural Gas Systems | $CH_4$ |
| Petroleum Systems | $CH_4$ |
| Municipal Solid Waste Combustion | $CO_2$, $N_2O$ |
| Natural Gas Flaring and Ambient Air Pollutant Emissions from Oil and Gas Activities | $CO_2$, CO, $NO_x$, NMVOC |
| Indirect $CO_2$ fom $CH_4$ Oxidation | $CO_2$ |
| International Bunker Fuels | $CO_2$, $CH_4$, $N_2O$, CO, $NO_x$, NMVOC |
| Wood Biomass and Ethanol Consumption | $CO_2$ |
| **Industrial Processes** | |
| Iron and Steel Production | $CO_2$ |
| Cement Manufacture | $CO_2$ |
| Ammonia Manufacture | $CO_2$ |
| Lime Manufacture | $CO_2$ |
| Limestone and Dolomite Use | $CO_2$ |
| Soda Ash Manufacture and Consumption | $CO_2$ |
| Ferroalloy Production | $CO_2$ |
| Titanium Dioxide Production | $CO_2$ |
| Carbon Dioxide Consumption | $CO_2$ |
| Petrochemical Production | $CH_4$ |
| Silicon Carbide Production | $CH_4$ |
| Adipic Acid Production | $N_2O$ |
| Nitric Acid Production | $N_2O$ |
| Substitution of Ozone Depleting Substances | HFCs, PFCs[a] |
| Aluminum Production | $CO_2$, $CF_4$, $C_2F_6$ |
| HCFC-22 Production | HFC-23 |
| Semiconductor Manufacture | HFCs, PFCs, $SF_6$[b] |
| Electrical Transmission and Distribution | $SF_6$ |
| Magnesium Production and Processing | $SF_6$ |
| Industrial Sources of Ambient Air Pollutants | CO, $NO_x$, NMVOC |
| **Solvent Use** | CO, $NO_x$, NMVOC |
| **Agriculture** | |
| Enteric Fermentation | $CH_4$ |
| Manure Management | $CH_4$, $N_2O$ |
| Rice Cultivation | $CH_4$ |
| Agricultural Soil Management | $N_2O$ |
| Agricultural Residue Burning | $CH_4$, $N_2O$, CO, $NO_x$ |
| **Land-Use Change and Forestry** | |
| Changes in Forest Carbon Stocks | $CO_2$ (sink) |
| Changes in Carbon Stocks in Urban Trees | $CO_2$ (sink) |
| Changes in Agricultural Soil Carbon Stocks | $CO_2$ (sink) |
| Changes in Yard Trimming Carbon Stocks in Landfills | $CO_2$ (sink) |
| **Waste** | |
| Landfills | $CH_4$ |
| Wastewater Treatment | $CH_4$ |
| Human Sewage | $N_2O$ |
| Waste Sources of Ambient Air Pollutants | CO, $NO_x$, NMVOC |

[a] In 1999, included HFC-23, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-4310mee, $C_4F_{10}$, $C_6F_{14}$, PFC/PFPEs

[b] Included such gases as HFC-23, $CF_4$, $C_2F_6$, $SF_6$

# ANNEX U

## IPCC Reference Approach for Estimating $CO_2$ Emissions from Fossil Fuel Combustion

It is possible to estimate carbon dioxide ($CO_2$) emissions from fossil fuel consumption using alternative methodologies and different data sources than those described in Annex A. For example, the UNFCCC reporting guidelines request that countries, in addition to their "bottom-up" sectoral methodology, to complete a "top-down" Reference Approach for estimating $CO_2$ emissions from fossil fuel combustion. Section 1.3 of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reporting Instructions* states, "If a detailed, Sectoral Approach for energy has been used for the estimation of $CO_2$ from fuel combustion you are still asked to complete...the Reference Approach...for verification purposes" (IPCC/UNEP/OECD/IEA 1997). This reference method estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys. The basic principle is 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. The following discussion provides the detailed calculations for estimating $CO_2$ emissions from fossil fuel combustion from the United States using the IPCC-recommended Reference Approach.

### Step 1: Collect and Assemble Data in Proper Format

To ensure the comparability of national inventories, the IPCC has recommended that countries report energy data using the International Energy Agency (IEA) reporting convention. National energy statistics were collected in physical units from several DOE/EIA documents in order to obtain the necessary data on production, imports, exports, and stock changes (EIA 2001a).

It was necessary to make a number of modifications to these data to generate more accurate apparent consumption estimates of these fuels. The first modification adjusts for consumption of fossil fuel feedstocks accounted for in the Industrial Processes chapter, which include unspecified coal for coal coke used in iron and steel production, natural gas used for ammonia production, and petroleum coke used in the production of aluminum, ferroalloys, and titanium dioxide. The second modification adjusts for consumption of bunker fuels, which refer to quantities of fuels used for international transportation estimated separately from U.S. totals. The third modification consists of the addition of U.S. territories data that are typically excluded from the national aggregate energy statistics. The territories include Puerto Rico, U.S. Virgin Islands, Guam, American Samoa, Wake Island, and U.S. Pacific Islands. These data, as well as the production, import, export, and stock change statistics, are presented in Table U-1.

The carbon content of fuel varies with the fuel's heat content. Therefore, for an accurate estimation of $CO_2$ emissions, fuel statistics were provided on an energy content basis (e.g., BTUs or joules). Because detailed fuel production statistics are typically provided in physical units (as in Table U-1), they were converted to units of energy before $CO_2$ emissions were calculated. Fuel statistics were converted to their energy equivalents by using conversion factors provided by DOE/EIA. These factors and their data sources are displayed in Table U-2. The resulting fuel type-specific energy data are provided in Table U-3.

### Step 2: Estimate Apparent Fuel Consumption

The next step of the IPCC Reference Approach is to estimate "apparent consumption" of fuels within the country. This requires a balance of primary fuels produced, plus imports, minus exports, and adjusting for stock changes. In this way, carbon enters an economy through energy production and imports (and decreases in fuel stocks) and is transferred out of the country through exports (and increases in fuel stocks). Thus, apparent consumption of primary fuels (including crude oil, natural gas liquids, anthracite, bituminous, subbituminous and lignite coal, and natural gas) can be calculated as follows:

*Apparent Consumption = Production + Imports - Exports - Stock Change*

Flows of secondary fuels (e.g., gasoline, residual fuel, coke) should be added to primary apparent consumption. The production of secondary fuels, however, should be ignored in the calculations of apparent consumption since the carbon contained in these fuels is already accounted for in the supply of primary fuels from which they were derived (e.g., the estimate for apparent consumption of crude oil already contains the carbon from which gasoline would be refined). Flows of secondary fuels should therefore be calculated as follows:

*Secondary Consumption = Imports - Exports - Stock Change*

Note that this calculation can result in negative numbers for apparent consumption of secondary fuels. This result is perfectly acceptable since it merely indicates a net export or stock increase in the country of that fuel when domestic production is not considered.

Next, the apparent consumption and secondary consumption need to be adjusted for feedstock uses of fuels accounted for in the Industrial Processes chapter, international bunker fuels, and U.S. territory fuel consumption. Bunker fuels and feedstocks accounted for in the Industrial Processes chapter are subtracted from these estimates, while fuel consuption in U.S. territories is added.

The IPCC Reference Approach calls for estimating apparent fuel consumption before converting to a common energy unit. However, certain primary fuels in the United States (e.g., natural gas and steam coal) have separate conversion factors for production, imports, exports, and stock changes. In these cases, it is not appropriate to multiply apparent consumption by a single conversion factor since each of its components have different heat contents. Therefore, United States fuel statistics were converted to their heat equivalents before estimating apparent consumption. Results are provided in Table U-2.

### Step 3: Estimate Carbon Emissions

Once apparent consumption is estimated, the remaining calculations are virtually identical to those for the "bottom-up" Sectoral Approach (see Annex A). That is:

- Potential $CO_2$ emissions were estimated using fuel-specific carbon coefficients (see Table U-3).[1]
- The carbon in products from non-energy uses of fossil fuels (e.g., plastics or asphalt) was then estimated and subtracted (see Table U-4).
- Finally, to obtain actual $CO_2$ emissions, net emissions were adjusted for any carbon that remained unoxidized as a result of incomplete combustion (e.g., carbon contained in ash or soot).[2]

### Step 4: Convert to $CO_2$ Emissions

Because the IPCC reporting guidelines recommend that countries report greenhouse gas emissions on a full molecular weight basis, the final step in estimating $CO_2$ emissions from fossil fuel consumption was converting from units of carbon to units of $CO_2$. Actual carbon emissions were multiplied by the molecular-to-atomic weight ratio of $CO_2$ to carbon (44/12) to obtain total carbon dioxide emitted from fossil fuel combustion in teragrams (Tg). The results are contained in Table U-5.

## Comparison Between Sectoral and Reference Approaches

These two alternative approaches can both produce reliable estimates that are comparable within a few percent. The major difference between methodologies employed by each approach lies in the energy data used to derive carbon emissions (i.e., the actual surveyed consumption for the Sectoral Approach versus apparent

---

[1] Carbon coefficients from EIA were used wherever possible. Because EIA did not provide coefficients for coal, the IPCC-recommended emission factors were used in the top-down calculations for these fuels. See notes in Table U-4 for more specific source information.

[2] For the portion of carbon that is unoxidized during coal combustion, the IPCC suggests a global average value of 2 percent. However, because combustion technologies in the United States are more efficient, the United States inventory uses 1 percent in its calculations for petroleum and coal and 0.5 percent for natural gas.

consumption derived for the Reference Approach). In theory, both approaches should yield identical results. In practice, however, slight discrepancies occur. For the United States, these differences are discussed below.

### Differences in Total Amount of Energy Consumed

Table U-7[3] summarizes the differences between the Reference and Sectoral approaches in estimating total energy consumption in the United States. Although theoretically the two methods should arrive at the same estimate for U.S. energy consumption, the Reference Approach provides an energy total that is 2.9 percent lower than the Sectoral Approach for 2000. The greatest difference lies in the higher estimate of petroleum consumption with the Sectoral Approach (3.5 percent).

There are several potential sources for the discrepancies in consumption estimates:

- *Product Definitions.* The fuel categories in the Reference Approach are different from those used in the Sectoral Approach, particularly for petroleum. For example, the Reference Approach estimates apparent consumption for crude oil. Crude oil is not typically consumed directly, but refined into other products. As a result, the United States does not focus on estimating the energy content of the various grades of crude oil, but rather estimating the energy content of the various products resulting from crude oil refining. The United States does not believe that estimating apparent consumption for crude oil, and the resulting energy content of the crude oil, is the most reliable method for the United States to estimate its energy consumption. Other differences in product definitions include using sector-specific coal statistics in the Sectoral Approach (i.e., residential, commercial, industrial coking, industrial other, and transportation coal), while the Reference Approach characterizes coal by rank (i.e. anthracite, bituminous, etc.). Also, the liquefied petroleum gas (LPG) statistics used in the bottom-up calculations are actually a composite category composed of natural gas liquids (NGL) and LPG.
- *Heat Equivalents.* It can be difficult to obtain heat equivalents for certain fuel types, particularly for categories such as "crude oil" where the key statistics are derived from thousands of producers in the United States and abroad. For heat equivalents by coal rank, it was necessary to refer back to EIA's *State Energy Data Report 1992* (1994) because this information is no longer published.
- *Possible inconsistencies in U.S. Energy Data.* The United States has not focused its energy data collection efforts on obtaining the type of aggregated information used in the Reference Approach. Rather, the United States believes that its emphasis on collection of detailed energy consumption data is a more accurate methodology for the United States to obtain reliable energy data. Therefore, top-down statistics used in the Reference Approach may not be as accurately collected as bottom-up statistics applied to the Sectoral Approach.
- *Balancing Item.* The Reference Approach uses *apparent* consumption estimates while the Sectoral Approach uses *reported* consumption estimates. While these numbers should be equal, there always seems to be a slight difference that is often accounted for in energy statistics as a "balancing item."

### Differences in Estimated $CO_2$ Emissions

Given these differences in energy consumption data, the next step for each methodology involved estimating emissions of $CO_2$. Table U-8 summarizes the differences between the two methods in estimated carbon emissions.

As mentioned above, for 2000, the Reference Approach resulted in a 2.9 percent lower estimate of energy consumption in the United States than the Sectoral Approach. However, the resulting emissions estimate for the Reference Approach was 0.6 percent lower. Both methods' estimates of natural gas emissions are almost exactly the same, but coal emission estimates from the Reference Approach are lower than the Sectoral Approach, while higher for petroleum. Potential reasons for these differences may include:

- *Product Definitions.* Coal data is aggregated differently in each methodology, as noted above. The format used for the Sectoral Approach likely results in more accurate estimates than in the Reference Approach. Also, the Reference Approach relies on a "crude oil" category for determining petroleum-related emissions.

[3] Although complete energy consumption data and calculations are not presented, comparison tables are also presented for 1996.

Given the many sources of crude oil in the United States, it is not an easy matter to track potential differences in carbon content between many different sources of crude, particularly since information on the carbon content of crude oil is not regularly collected.

- *Carbon Coefficients.* The Reference Approach relies on several default carbon coefficients by rank provided by IPCC (IPCC/UNEP/OECD/IEA 1997), while the Sectoral Approach uses annually updated category-specific coefficients by sector that are likely to be more accurate. Also, as noted above, the carbon coefficient for crude oil is more uncertain than that for specific secondary petroleum products, given the many sources and grades of crude oil consumed in the United States.

Although the two approaches produce similar results, the United States believes that the "bottom-up" Sectoral Approach provides a more accurate assessment of $CO_2$ emissions at the fuel level. This improvement in accuracy is largely a result of the data collection techniques used in the United States, where there has been more emphasis on obtaining the detailed products-based information used in the Sectoral Approach than obtaining the aggregated energy flow data used in the Reference Approach. The United States believes that it is valuable to understand both methods.

## References


EIA (2001a) *Annual Energy Review 2000* and other EIA data. Energy Information Administration, U.S. Department of Energy, Washington, DC. September, DOE/EIA- 0384(00)-annual.

EIA (2001b) *Monthly Energy Review*, Energy Information Administration, U.S. Department of Energy, Washington, DC. November. DOE/EIA 0035(00)-monthly.

EIA (2000) *Emissions of Greenhouse Gases in the United States 1999*. Energy Information Administration, U.S. Department of Energy, Washington, DC. Draft. October 5, 1999, DOE/EIA-0535(99)-annual.

EIA (1995-2001) *Petroleum Supply Annual*, Energy Information Administration, U.S. Department of Energy, Washington, DC, Volume I. DOE/EIA-0340.

EIA (1994) *State Energy Data Report 1992*, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA 0214(92)-annual.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

## Table U-1: 2000 U.S. Energy Statistics (Physical Units)

| Fuel Category (Units) | Fuel Type | Production | Imports | Exports | Stock Change | Adjustment | Bunkers | U.S. Territories |
|---|---|---|---|---|---|---|---|---|
| Solid Fuels (Thousand Short Tons) | Anthracite Coal | 4,508 | a | a | a | | | |
| | Bituminous Coal | 548,467 | a | a | a | | | |
| | Sub-bituminous Coal | 433,784 | a | a | a | | | |
| | Lignite | 88,740 | a | a | a | | | |
| | Coke | | 3,781 | 1,146 | 227 | | | |
| | Unspecified Coal | | 12,513 | 58,489 | (40,245) | 27,325 | | 441 |
| Gas Fuels (Million Cubic Feet) | Natural Gas | 18,377,829 | 3,726,290 | 237,035 | (845,082) | 330,653 | | 11,400 |
| Liquid Fuels (Thousand Barrels) | Crude Oil | 2,130,707 | 3,319,816 | 18,352 | (25,538) | | | |
| | Nat Gas Liquids and LRGs | 699,415 | 93,755 | 28,470 | (6,999) | | | 2,203 |
| | Other Liquids | 52,196 | 211,023 | 17,935 | 2,699 | | | |
| | Motor Gasoline | 85,938 | 156,230 | 52,539 | (1,089) | | | 35,408 |
| | Aviation Gasoline | | 336 | 0 | (309) | | | |
| | Kerosene | | 822 | 779 | (764) | | | 1,150 |
| | Jet Fuel | | 59,125 | 11,628 | 4,017 | | 143,769 | |
| | Distillate Fuel | | 107,919 | 63,198 | (7,436) | | 19,704 | 21,590 |
| | Residual Fuel | | 128,912 | 50,858 | 370 | | 70,634 | 16,071 |
| | Naptha for petrochemical feedstocks | | 43,357 | 0 | 488 | | | |
| | Petroleum Coke | | 394 | 116,589 | 1,360 | 13,966 | | |
| | Other Oil for petrochemical feedstocks | | 52,338 | 0 | 125 | | | |
| | Special Napthas | | 3,873 | 7,425 | (239) | | | |
| | Lubricants | | 4,950 | 9,472 | 279 | | | 223 |
| | Waxes | | 860 | 1,293 | 70 | | | |
| | Asphalt/Road Oil | | 10,300 | 2,104 | 8,183 | | | |
| | Still Gas | | 0 | 0 | 0 | | | |
| | Misc. Products | | 76 | 67 | (601) | | | 38,359 |

[a] Included in Unspecified Coal

Data Sources: Solid and Gas Fuels – EIA (2001a) Annual Energy Review 2000; Liquid Fuels - Petroleum Supply Annual 2000, Table 2.

## Table U-2: Conversion Factors to Energy Units (Heat Equivalents)

| Fuel Category (Units) | Fuel Type | Production | Imports | Exports | Stock Change | Adjustment | Bunkers | U.S. Territories |
|---|---|---|---|---|---|---|---|---|
| Solid Fuels (Million Btu/Short Ton) | Anthracite Coal | 22.57 | | | | | | |
| | Bituminous Coal | 23.89 | | | | | | |
| | Sub-bituminous Coal | 17.14 | | | | | | |
| | Lignite | 12.87 | | | | | | |
| | Coke | | 24.80 | 24.80 | 24.80 | | | |
| | Unspecified | | 25.00 | 26.24 | 21.07 | 27.43 | | 25.14 |
| Natural Gas (BTU/Cubic Foot) | | 1,027 | 1,022 | 1,006 | 1,027 | 1,027 | | |
| Liquid Fuels (Million Btu/Barrel) | Crude Oil | 5.80 | 5.96 | 5.80 | 5.80 | | 5.80 | 5.80 |
| | Nat Gas Liquids and LRGs | 3.73 | 3.73 | 3.73 | 3.73 | | 3.73 | 3.73 |
| | Other Liquids | 5.83 | 5.83 | 5.83 | 5.83 | | 5.83 | 5.83 |
| | Motor Gasoline | 5.21 | 5.21 | 5.21 | 5.21 | | 5.21 | 5.21 |
| | Aviation Gasoline | | 5.05 | 5.05 | 5.05 | | 5.05 | 5.05 |
| | Kerosene | | 5.67 | 5.67 | 5.67 | | 5.67 | 5.67 |
| | Jet Fuel | | 5.67 | 5.67 | 5.67 | | 5.67 | 5.67 |
| | Distillate Fuel | | 5.83 | 5.83 | 5.83 | | 5.83 | 5.83 |
| | Residual Oil | | 6.29 | 6.29 | 6.29 | | 6.29 | 6.29 |
| | Naptha for petrochemical feedstocks | | 5.25 | 5.25 | 5.25 | | 5.25 | 5.25 |
| | Petroleum Coke | | 6.02 | 6.02 | 6.02 | 6.02 | 6.02 | 6.02 |
| | Other Oil for petrochemical feedstocks | | 5.83 | 5.83 | 5.83 | | 5.83 | 5.83 |
| | Special Napthas | | 5.25 | 5.25 | 5.25 | | 5.25 | 5.25 |
| | Lubricants | | 6.07 | 6.07 | 6.07 | | 6.07 | 6.07 |
| | Waxes | | 5.54 | 5.54 | 5.54 | | 5.54 | 5.54 |
| | Asphalt/Road Oil | | 6.64 | 6.64 | 6.64 | | 6.64 | 6.64 |
| | Still Gas | | 6.00 | 6.00 | 6.00 | | 6.00 | 6.00 |
| | Misc. Products | | 5.80 | 5.80 | 5.80 | | 5.80 | 5.80 |

Data Sources: Coal and lignite production – EIA (1994) State Energy Data Report 1992; Unspecified Solid Fuels - EIA (2001b) Monthly Energy Review, Nov 2000; Coke, Natural Gas and Petroleum Products – EIA (2001b) Annual Energy Review 2000.

## Table U-3: 2000 Apparent Consumption of Fossil Fuels (TBtu)

| Fuel Category | Fuel Type | Production | Imports | Exports | Stock Change | Adjustment | Bunkers | U.S. Territories | Apparent Consumption |
|---|---|---|---|---|---|---|---|---|---|
| Solid Fuels | Anthracite Coal | 101.8 | | | | | | | **101.8** |
| | Bituminous Coal | 13,102.9 | | | | | | | **13,102.9** |
| | Sub-bituminous Coal | 7,435.1 | | | | | | | **7,435.1** |
| | Lignite | 1,141.7 | | | | | | | **1,141.7** |
| | Coke | | 93.8 | 28.4 | 5.6 | | | | **59.7** |
| | Unspecified | | 312.8 | 1,534.9 | (848.0) | 749.4 | | 11.1 | **(1,112.4)** |
| Gas Fuels | Natural Gas | 18,874.0 | 3,808.3 | 238.5 | (867.9) | 339.6 | | | **22,972.2** |
| Liquid Fuels | Crude Oil | 12,358.1 | 19,779.5 | 106.4 | (148.1) | | | | **32,179.2** |
| | Nat Gas Liquids and LRGs | 2,610.9 | 350.0 | 106.3 | (26.1) | | | 8.2 | **2,889.0** |
| | Other Liquids | 304.0 | 1,229.2 | 104.5 | 15.7 | | | | **1,413.1** |
| | Motor Gasoline | 447.7 | 814.0 | 273.7 | (5.7) | | | 184.5 | **1,178.1** |
| | Aviation Gasoline | | 1.7 | 0.0 | (1.6) | | | | **3.3** |
| | Kerosene | | 4.7 | 4.4 | (4.3) | | | 6.5 | **11.1** |
| | Jet Fuel | | 335.2 | 65.9 | 22.8 | | 815.2 | | **(568.6)** |
| | Distillate Fuel | | 628.6 | 368.1 | (43.3) | | 114.8 | 125.8 | **314.8** |
| | Residual Oil | | 810.5 | 319.7 | 2.3 | | 444.1 | 101.0 | **145.4** |
| | Naptha for petrochemical feedstocks | | 227.5 | 0.0 | 2.6 | | | | **225.0** |
| | Petroleum Coke | | 2.4 | 702.3 | 8.2 | 84.1 | | | **(792.3)** |
| | Other Oil for petrochemical feedstocks | | 304.9 | 0.0 | 0.7 | | | | **304.1** |
| | Special Napthas | | 20.3 | 39.0 | (1.3) | | | | **(17.4)** |
| | Lubricants | | 30.0 | 57.4 | 1.7 | | | 1.4 | **(27.8)** |
| | Waxes | | 4.8 | 7.2 | 0.4 | | | | **(2.8)** |
| | Asphalt/Road Oil | | 68.4 | 14.0 | 54.3 | | | | **0.1** |
| | Still Gas | | 0.0 | 0.0 | 0.0 | | | | **0.0** |
| | Misc. Products | | 0.4 | 0.4 | (3.5) | | | 222.3 | **225.9** |
| **Total** | | **56,376.3** | **28,826.8** | **3,971.2** | **(1,835.5)** | **1,173.1** | **1,374.0** | **660.8** | **81,181.0** |

Note: Totals may not sum due to independent rounding.

## Table U-4: 2000 Potential Carbon Dioxide Emissions

| Fuel Category | Fuel Type | Apparent Consumption (QBtu) | Carbon Coefficients (Tg Carbon/QBtu) | Potential Emissions (Tg $CO_2$ Eq.) |
|---|---|---|---|---|
| Solid Fuels | Anthracite Coal | 0.102 | 26.86 | **10.0** |
| | Bituminous Coal | 13.103 | 25.86 | **1,242.4** |
| | Sub-bituminous Coal | 7.435 | 26.26 | **715.9** |
| | Lignite | 1.142 | 27.66 | **115.8** |
| | Coke | 0.060 | 25.56 | **5.6** |
| | Unspecified | (1.112) | 25.34 | **(103.3)** |
| Gas Fuels | Natural Gas | 22.972 | 14.47 | **1,218.8** |
| Liquid Fuels | Crude Oil | 32.179 | 20.23 | **2,387.2** |
| | Nat Gas Liquids and LRGs | 2.889 | 16.99 | **180.0** |
| | Other Liquids | 1.413 | 20.23 | **104.8** |
| | Motor Gasoline | 1.178 | 19.34 | **83.5** |
| | Aviation Gasoline | 0.003 | 18.87 | **0.2** |
| | Kerosene | 0.011 | 19.72 | **0.8** |
| | Jet Fuel | (0.569) | 19.33 | **(40.3)** |
| | Distillate Fuel | 0.315 | 19.95 | **23.0** |
| | Residual Oil | 0.145 | 21.49 | **11.5** |
| | Naptha for petrochemical feedstocks | 0.225 | 18.14 | **15.0** |
| | Petroleum Coke | (0.792) | 27.85 | **(80.9)** |
| | Other Oil for petrochemical feedstocks | 0.304 | 19.95 | **22.2** |
| | Special Napthas | (0.017) | 19.86 | **(1.3)** |
| | Lubricants | (0.028) | 20.24 | **(2.1)** |
| | Waxes | (0.003) | 19.81 | **(0.2)** |
| | Asphalt/Road Oil | 0.000 | 20.62 | **0.0** |
| | Still Gas | 0.000 | 17.51 | **0.0** |
| | Misc. Products | 0.226 | 20.23 | **16.8** |
| **Total** | | | | **5,925.5** |

Data Sources: Coal and Lignite – IPCC (1997) Revised 1996 IPCC Guidelines Reference Manual, Table 1-1; Unspecified Solid Fuels - EIA (2001b) Monthly Energy Review, November 2001 Table C1 (U.S. Average); Natural Gas and Liquid Fuels - EIA (2000) *Emissions of Greenhouse Gases in the United States 1999.*
Note: Totals may not sum due to independent rounding.

## Table U-5: 2000 Non-Energy Carbon Stored in Products

| Fuel Type | Consumption for Non-Energy Use (TBtu) | Carbon Coefficients (Tg Carbon/QBtu) | Carbon Content (Tg Carbon) | Fraction Sequestered | Carbon Stored (Tg $CO_2$ Eq.) |
|---|---|---|---|---|---|
| Coal | 26.4 | 25.56 | 0.7 | 0.75 | **1.9** |
| Natural Gas | 342.4 | 14.47 | 5.0 | 0.63 | **11.5** |
| Asphalt & Road Oil | 1,275.7 | 20.62 | 26.3 | 1.00 | **96.5** |
| LPG | 1,707.3 | 16.88 | 28.8 | 0.63 | **66.8** |
| Lubricants | 370.6 | 20.24 | 7.5 | 0.09 | **2.5** |
| Pentanes Plus | 286.8 | 18.24 | 5.2 | 0.63 | **12.1** |
| Petrochemical Feedstocks | a | a | a | a | **54.9** |
| Petroleum Coke | 141.4 | 27.85 | 3.9 | 0.50 | **7.2** |
| Special Naptha | 97.4 | 19.86 | 1.9 | 0.00 | **0.0** |
| Waxes/Misc. | a | a | a | a | **13.5** |
| Misc. U.S. Territories Petroleum | a | a | a | a | **16.5** |
| **Total** | | | | | **283.4** |

[a] Values for Misc. U.S. Territories Petroleum, Petrochemical Feedstocks and Waxes/Misc. are not shown because these categories are aggregates of numerous smaller components.
Note: Totals may not sum due to independent rounding.

## Table U-6: 2000 Reference Approach $CO_2$ Emissions from Fossil Fuel Consumption (Tg $CO_2$ Eq. unless otherwise noted)

| Fuel Category | Potential Emissions | Carbon Sequestered | Net Emissions | Fraction Oxidized | Total Emissions |
|---|---|---|---|---|---|
| Coal | 1,986.4 | 1.9 | 1,984.5 | 99.0% | **1,964.7** |
| Petroleum | 2,720.3 | 270.0 | 2,450.3 | 99.0% | **2,425.8** |
| Natural Gas | 1,218.8 | 11.5 | 1,207.3 | 99.5% | **1,201.3** |
| **Total** | **5,925.5** | **283.4** | **5,642.2** | - | **5,591.8** |

Note: Totals may not sum due to independent rounding.

## Table U-7: Energy Consumption in the United States by Estimating Approach (TBtu)

| Approach | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sectoral** | **70,996.2** | **70,588.5** | **71,959.5** | **73,512.7** | **75,089.7** | **76,034.7** | **78,557.0** | **79,713.8** | **79,744.1** | **81,242.7** | **83,606.3** |
| Coal | 18,175.6 | 18,072.9 | 18,278.9 | 18,929.1 | 19,113.6 | 19,205.8 | 20,126.9 | 20,670.7 | 20,872.0 | 20,949.9 | 21,732.3 |
| Natural Gas | 18,912.2 | 19,233.6 | 19,755.5 | 20,437.1 | 20,921.5 | 21,813.1 | 22,212.5 | 22,307.8 | 21,532.4 | 21,907.9 | 23,038.0 |
| Petroleum | 33,908.4 | 33,282.0 | 33,925.2 | 34,146.6 | 35,054.6 | 35,015.8 | 36,217.6 | 36,735.2 | 37,339.8 | 38,384.9 | 38,836.0 |
| **Reference (Apparent)** | **69,497.8** | **67,934.4** | **69,395.8** | **71,364.6** | **72,997.9** | **73,815.8** | **76,242.4** | **77,589.9** | **77,561.4** | **79,015.7** | **80,181.0** |
| Coal | 18,408.1 | 17,498.9 | 17,817.6 | 18,339.5 | 18,791.5 | 18,601.1 | 19,567.8 | 20,230.2 | 20,104.1 | 20,188.7 | 20,728.7 |
| Natural Gas | 19,264.8 | 19,244.0 | 19,752.1 | 20,466.7 | 20,910.5 | 21,794.5 | 22,179.3 | 22,155.9 | 21,520.0 | 21,918.3 | 22,972.2 |
| Petroleum | 31,824.9 | 31,191.5 | 31,826.1 | 33,558.5 | 33,295.9 | 33,420.2 | 34,495.3 | 35,203.9 | 35,937.3 | 36,908.7 | 37,480.1 |
| **Difference** | **-2.1%** | **-3.8%** | **-3.6%** | **-2.9%** | **-2.8%** | **-2.9%** | **-2.9%** | **-2.7%** | **-2.7%** | **-2.7%** | **-2.9%** |
| Coal | 1.3% | -3.2% | -2.5% | -3.1% | -1.7% | -3.1% | -2.8% | -2.1% | -3.7% | -3.6% | -4.6% |
| Natural Gas | 1.9% | -0.1% | + | 0.1% | -0.1% | -0.1% | -0.1% | -0.7% | -0.1% | + | -0.3% |
| Petroleum | -6.1% | -6.3% | -6.2% | -4.7% | -5.0% | -4.6% | -4.8% | -4.2% | -3.8% | -3.8% | -3.5% |

* Includes U.S. territories

+ Does not exceed 0.05%

Note: Totals may not sum due to independent rounding.

## Table U-8: $CO_2$ Emissions from Fossil Fuel Combustion by Estimating Approach (Tg $CO_2$ Eq.)

| Approach | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sectoral** | **4,779.6** | **4,732.8** | **4,835.8** | **4,950.7** | **5,047.0** | **5,084.8** | **5,266.3** | **5,339.2** | **5,355.8** | **5,448.4** | **5,623.1** |
| Coal | 1,692.6 | 1,684.0 | 1,702.2 | 1,764.1 | 1,782.6 | 1,792.7 | 1,878.4 | 1,930.5 | 1,949.7 | 1,956.9 | 2,030.1 |
| Natural Gas | 988.8 | 1,006.1 | 1,035.0 | 1,070.3 | 1,093.6 | 1,141.3 | 1,162.4 | 1,166.7 | 1,125.8 | 1,145.2 | 1,204.8 |
| Petroleum | 2,098.2 | 2,042.6 | 2,098.6 | 2,116.3 | 2,170.8 | 2,150.9 | 2,25.6 | 2,242.0 | 2,280.3 | 2,346.3 | 2,388.2 |
| **Reference (Apparent)** | **4,832.3** | **4,693.2** | **4,800.5** | **4,931.7** | **5,035.8** | **5,067.2** | **5,249.7** | **5,349.3** | **5,357.7** | **5,437.1** | **5,591.8** |
| Coal | 1,746.9 | 1,657.8 | 1,686.0 | 1,735.1 | 1,778.8 | 1,761.3 | 1,852.3 | 1,914.5 | 1,905.6 | 1,915.9 | 1,964.7 |
| Natural Gas | 1,007.4 | 1,006.7 | 1,034.8 | 1,071.8 | 1,093.0 | 1,140.3 | 1,160.6 | 1,158.7 | 1,125.2 | 1,145.8 | 1,201.3 |
| Petroleum | 2,078.0 | 2,028.7 | 2,079.6 | 2,124.8 | 2,163.9 | 2,165.6 | 2,236.8 | 2,276.1 | 2,326.9 | 2,375.4 | 2,425.8 |
| **Difference** | **1.1%** | **-0.8%** | **-0.7%** | **-0.4%** | **-0.2%** | **-0.3%** | **-0.3%** | **0.2%** | **+** | **-0.2%** | **-0.6%** |
| Coal | 3.2% | -1.6% | -0.9% | -1.6% | -0.2% | -1.7% | -1.4% | -0.8% | -2.3% | -2.1% | -3.2% |
| Natural Gas | 1.9% | 0.1% | -0.0% | -0.1% | -0.1% | -0.1% | -0.2% | -0.7% | -0.1% | + | -0.3% |
| Petroleum | -1.0% | -0.7% | -0.9% | -0.4% | -0.3% | 0.7% | 0.5% | 1.5% | 2.0% | 1.2% | 1.6% |

+ Does not exceed 0.05%

Note: Totals may not sum due to independent rounding. Includes U.S. territories.

# ANNEX V

## Sources of Greenhouse Gas Emissions Excluded

Although this report is intended to be a comprehensive assessment of anthropogenic[1] sources and sinks of greenhouse gas emissions for the United States, certain sources have been identified yet excluded from the estimates presented for various reasons. Before discussing these sources, however, it is important to note that processes or activities that are not *anthropogenic in origin* or do not result in a *net source or sink* of greenhouse gas emissions are intentionally excluded from a national inventory of anthropogenic greenhouse gas emissions. In general, processes or activities that are not anthropogenic are considered natural (i.e., not directly influenced by human activity) in origin and, as an example, would include the following:

- Volcanic eruptions
- Carbon dioxide ($CO_2$) exchange (i.e., uptake or release) by oceans
- Natural forest fires[2]
- Methane ($CH_4$) emissions from wetlands not affected by human induced land-use changes

Some processes or activities may be anthropogenic in origin but do not result in net emissions of greenhouse gases, such as the respiration of $CO_2$ by people or domesticated animals.[3] Given a source category that is both anthropogenic and results in net greenhouse gas emissions, reasons for excluding a source related to an anthropogenic activity include one or more of the following:

- There is insufficient scientific understanding to develop a reliable method for estimating emissions at a national level.
- Although an estimating method has been developed, data were not adequately available to calculate emissions.
- Emissions were implicitly accounted for within another source category (e.g., $CO_2$ from Fossil Fuel Combustion).

It is also important to note that the United States believes the exclusion of the sources discussed below introduces only a minor bias in its overall estimate of U.S. greenhouse gas emissions.

### Separate Cruise and LTO Emissions from the Combustion of Jet Fuel

The combustion of jet fuel by aircraft results in emissions of $CH_4$, $N_2O$, CO, $NO_x$, and NMVOCs. The emissions per mass of fuel combusted during landing/take-off (LTO) operations differ from those during aircraft cruising. Accurate estimation of these emissions requires a detailed accounting of LTO cycles and fuel consumption during cruising by aircraft model (e.g., Boeing 747-400) as well as appropriate emission factors. Sufficient data for separately calculating near ground-level emissions during landing and take-off and cruise altitude emissions by aircraft model were not available for this report. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, pp. 1.93 - 1.96)

---

[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] In some cases forest fires that are started either intentionally or unintentionally are viewed as mimicking natural burning processes that have been suppressed by other human forest management activities. The United States does not consider forest fires within its national boundaries to be a net source of greenhouse emissions.

[3] Respiration of $CO_2$ by biological organisms is simply part of the broader global carbon cycle that also includes uptake of $CO_2$ by photosynthetic organisms.

### $CO_2$ from Burning in Coal Deposits and Waste Piles

Coal is periodically burned in deposits and waste piles. It has been estimated that the burning of coal in deposits and waste piles would represent less than 1.3 percent of total U.S. coal consumption, averaged over ten-years. Because there is currently no known source of data on the quantity of coal burned in waste piles and there is uncertainty as to the fraction of coal oxidized during such burnings, these $CO_2$ emissions are not currently estimated. Further research would be required to develop accurate emission factors and activity data for these emissions to be estimated (see *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 1.112 - 1.113).

### Fossil $CO_2$ from Petroleum and Natural Gas Wells, $CO_2$ Separated from Natural Gas, and $CO_2$ from Enhanced Oil Recovery (EOR)

Petroleum and natural gas well drilling, petroleum and natural gas production, and natural gas processing—including removal of $CO_2$—may result in emissions of $CO_2$ that was at one time stored in underground formations.

Carbon dioxide and other gases are naturally present in raw natural gas, in proportions that vary depending on the geochemical circumstances that caused the formation of the gas. After the heavier gases are removed during processing, small amounts of carbon dioxide may be allowed to remain in the natural gas. If the amount of $CO_2$ sufficiently lowers the heating value of the natural gas, it is typically extracted by amine scrubbing and, in most cases, released into the atmosphere. These emissions can be estimated by calculating the difference between the average carbon dioxide content of raw natural gas and the carbon dioxide content of pipeline gas. The Energy Information Administration (EIA) estimates that annual $CO_2$ emissions from scrubbing are about 15 Tg $CO_2$ Eq. Because of imprecision in the reporting of U.S. natural gas production and processing, emissions estimates from energy production sources may be double-counted or under-reported, and thus are uncertain.

Carbon dioxide is also injected into underground deposits to increase crude oil reservoir pressure in a field technique known as enhanced oil recovery (EOR). It is thought that much of the injected $CO_2$ may be effectively and permanently sequestered, but the fraction of injected $CO_2$ that is re-released remains uncertain. The fraction re-released varies from well to well depending upon the field geology and the gas capture/re-injection technology employed at the wellhead. Over time, carbon dioxide may also seep into the producing well and mix with the oil and natural gas present there. If the gas portion of this mixture has a sufficiently high energy content, it may be collected and sent to a natural gas plant; if not, it may be vented or flared. The EIA estimates that the amount of $CO_2$ used for EOR is on the order of 44 Tg $CO_2$ Eq., of which emissions would be some fraction yet to be defined. This figure is based on the difference between U.S. Department of Commerce sales figures for industrial $CO_2$ (62 Tg $CO_2$ Eq.) minus the 18 Tg $CO_2$ Eq. reported by the Freedonia Group that is used for purposes other than EOR. Further research into EOR is required before the resulting $CO_2$ emissions can be adequately quantified. (See Carbon Dioxide Consumption in the Industrial Processes chapter).

### Carbon Sequestration in Underground Injection Wells

Data for sequestration of carbon in underground injection wells is obtained from the EPA Toxic Release Inventory (EIA 2000). The carbon content of wastes reported in the EPA TRI as being injected into underground injection wells is estimated from the TRI data, and the carbon is assumed to be sequestered. The sequestration of underground injection carbon is one of the many elements in calculating the storage factor for petrochemical feedstock (see Annex B). The "base year" for this storage factor calculation is 1998 and only EPA TRA data for calendar year 1998 is used in the storage factor calculation. Further research is required if the entire time series for this potential sink is to be fully quantified.

### $CH_4$ from Abandoned Coal Mines

Abandoned coal mines are a source of $CH_4$ emissions. In general, many of the same factors that affect emissions from operating coal mines will affect emissions from abandoned mines such as the permeability and gassiness of the coal, the mine's depth, geologic characteristics, and whether it has been flooded. A few gas developers have recovered methane from abandoned mine workings; therefore, emissions from this source may be

significant. Further research and methodological development is needed if these emissions are to be estimated. (See Coal Mining in the Energy chapter.)

### $CO_2$ from "Unaccounted for" Natural Gas

There is a discrepancy between the amount of natural gas sold by producers and that reported as purchased by consumers. This discrepancy, known as "unaccounted for" or unmetered natural gas, was assumed to be the sum of leakage, measurement errors, data collection problems, undetected non-reporting, undetected over reporting, and undetected under reporting. Historically, the amount of gas sold by producers has always exceeded that reportedly purchased by consumers; therefore, some portion of unaccounted for natural gas was assumed to be a source of $CO_2$ emissions. In other words, it was assumed that consumers were underreporting their usage of natural gas. In DOE/EIA's energy statistics for 1996, however, reported consumption of natural gas exceeded the amount sold by producers. Therefore, the historical explanation given for this discrepancy has lost credibility and unaccounted for natural gas is no longer used to calculate $CO_2$ emissions.

### $CO_2$ from Shale Oil Production

Oil shale is shale saturated with kerogen.[4] It can be thought of as the geological predecessor to crude oil. Carbon dioxide is released as a by-product of the process of producing petroleum products from shale oil. As of now, it is not cost-effective to mine and process shale oil into usable petroleum products. The only identified large-scale oil shale processing facility in the United States was operated by Unocal during the years 1985 to 1990. There have been no known emissions from shale oil processing in the United States since 1990 when the Unocal facility closed.

### $CH_4$ from the Production of Carbides other than Silicon Carbide

Methane ($CH_4$) may be emitted from the production of carbides because the petroleum coke used in the process contains volatile organic compounds, which form $CH_4$ during thermal decomposition. Methane emissions from the production of silicon carbide were estimated and accounted for, but emissions from the production of calcium carbide and other carbides were not. Further research is needed to estimate $CH_4$ emissions from the production of calcium carbide and other carbides other than silicon carbide. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, pp. 2.20 - 2.21)

### $CO_2$ from Calcium Carbide and Silicon Carbide Production

Carbon dioxide is formed by the oxidation of petroleum coke in the production of both calcium carbide and silicon carbide. These $CO_2$ emissions are implicitly accounted for with emissions from the combustion of petroleum coke in the Energy chapter. There is currently not sufficient data on coke consumption to estimate emissions from these sources explicitly. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, pp. 2.20 - 2.21)

### $CO_2$ from Graphite Consumption in Ferroalloy and Steel Production

Emissions from "graphite" "wood" or "biomass" in calculating $CO_2$ emissions from ferroalloy production, iron and steel production or other "Industrial Processes" included in Chapter 3 of the inventory are not explicitly calculated. It is assumed that 100% of the carbon used in ferroalloy production is derived from petroleum coke and that all of the carbon used in iron and steel production is derived from coal coke or petroleum coke. It is possible that some non-coke carbon is used in the production of ferroalloys and iron and steel, but no data are available to conduct inventory calculations for sources of carbon other than petroleum coke and coal coke used in these processes.

---

[4] Kerogen is fossilized insoluble organic material found in sedimentary rocks, usually shales, which can be converted to petroleum products by distillation.

Non-fuel uses of coal coke and petroleum coke are accounted for in the Industrial Process chapter, either directly for iron and steel, aluminum, ferroalloy, and titanium dioxide production, or indirectly by applying a storage factor to "uncharacterized" non-fuel uses of petroleum coke and coal coke.

Non-fuel uses of wood and biomass are not accounted for in the Energy or Industrial Process chapters, as all uses of wood and biomass are accounted for in the Land Use and Forestry chapter. It is assumed for the purposes of the $CO_2$ emission calculation that no wood or other biogenic carbon is used in any of these industrial processes. Some biogenic carbon may be used in these industrial processes but sufficient data to estimate emissions are not available.

Consumption of either natural or synthetic graphite is not explicitly accounted for in the Industrial Process chapter. It is assumed that all of the carbon used in manufacturing carbon anodes for production of aluminum, ferroalloys, and electric arc furnace (EAF) steel are derived directly from petroleum coke and coal tar pitch (a coal coke byproduct), not from natural graphite or synthetic graphite sources. Some amount of carbon used in these industrial processes may be derived from natural or synthetic graphite sources, but sufficient data to estimate emissions are not currently available.

### $N_2O$ from Caprolactam Production

Caprolactam is a widely used chemical intermediate, primarily to produce nylon-6. All processes for producing caprolactam involve the catalytic oxidation of ammonia, with $N_2O$ being produced as a by-product. Caprolactam production could be a significant source of $N_2O$—it has been identified as such in the Netherlands. More research is required to determine this source's significance because there is currently insufficient information available on caprolactam production to estimate emissions in the United States. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, pp. 2.22 - 2.23)

### $N_2O$ from Cracking of Certain Oil Fractions

In order to improve the gasoline yield in crude oil refining, certain oil fractions are processed in a catcracker. Because crude oil contains some nitrogen, $N_2O$ emissions may result from this cracking process. There is currently insufficient data to develop a methodology for estimating these emissions. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 2.23)

### $CH_4$ from Coke Production

Coke production may result in $CH_4$ emissions. Detailed coke production statistics were not available for the purposes of estimating $CH_4$ emissions from this minor source. (See Petrochemical Production in the Industrial Processes chapter and the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 2.23)

### $CO_2$ from Metal Production

Coke is used as a reducing agent in the production of some metals from their ores, including magnesium, chromium, lead, nickel, silicon, tin, and zinc. Carbon dioxide may be emitted during the metal's production from the oxidization of this coke and, in some cases, from the carbonate ores themselves (e.g., some magnesium ores contain carbonate). The $CO_2$ emissions from the carbonate ores are not presently accounted for, but their quantities are thought to be minor. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 2.37 - 2.38)

### $N_2O$ from Acrylonitrile Production

Nitrous oxide may be emitted during acrylonitrile production. No methodology was available for estimating these emissions, and therefore further research is needed if these emissions are to be included. (See *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p. 2.22)

### $SF_6$ from Aluminum Fluxing and Degassing

Occasionally, sulfur hexafluoride ($SF_6$) is used by the aluminum industry as a fluxing and degassing agent in experimental and specialized casting operations. In these cases it is normally mixed with argon, nitrogen, and/or chlorine and blown through molten aluminum; however, this practice is not used by primary aluminum production firms in the United States and is not believed to be extensively used by secondary casting firms. Where it does occur, the concentration of $SF_6$ in the mixture is small and a portion of the $SF_6$ is decomposed in the process (Waite and Bernard 1990, Corns 1990). It has been estimated that 230 Mg of $SF_6$ were used by the aluminum industry in the United States and Canada (Maiss and Brenninkmeijer 1998); however, this estimate is highly uncertain.

### $SF_6$ from Production/Leakage/Breakage of Soundproofed Double-glazed Windows

Sulfur hexafluoride ($SF_6$) may be emitted from the production, breakage, or leakage of soundproof double-glazed windows. No methodology was available for estimating these emissions, and therefore further research is needed if these emissions are to be included.

### $SF_6$ from Production/Leakage/Dismantling of Radar, Tracer and Night Vision Equipment

Sulfur hexafluoride ($SF_6$) may be emitted from the production, leakage, and dismantling of radar, tracer, and night vision equipment. Emissions from this source are believed to be minor, and no data were available for estimating the emissions.

### $SF_6$ from Applications in Sports Shoes, Tires, and Tennis Balls

Sulfur hexafluoride ($SF_6$) may be emitted from application involving the production of sport shoes, tires, and tennis balls. These emissions are believed to be minor, and no data were available for estimating emissions.

### $SF_6$ from Applications to Trace Leakage of Pressure Vessels and Used as a Tracer Gas in Open Air

Sulfur hexafluoride ($SF_6$) may be emitted from application involving tracer gasses to detect leakage from pressure vessels and as a tracer gas in the open air. Although emissions from this source are believed to be minor, emissions estimation data and methodologies were not available.

### Miscellaneous $SF_6$ Uses

Sulfur hexafluoride may be used in foam insulation, for dry etching, in laser systems, for indoor air quality testing, for laboratory hood testing, for chromatography, in tandem accelerators, in loudspeakers, in shock absorbers, and for certain biomedical applications. Data need to be gathered and methodologies developed if these emissions are to be estimated. A preliminary global assessment of aggregate emissions from these applications can be found in Maiss, M. Brenninkmeijer, and C.A.M. Brenninkmeijer (1998).

### $CO_2$ from Solvent Incineration

Carbon dioxide may be released during the incineration of solvents. Although emissions from this source are believed to be minor, data need to be gathered and methodologies developed if these emissions are to be estimated. Solvents are hazardous wastes, and emissions from solvent incineration were taken into account to estimate the carbon the carbon storage factor for hazardous waste incineration. However, sufficient data is not available to obtain a complete time series estimate for this source category. Further research is required for these potential emissions to be fully quantified.

### $N_2O$ from Domestic House Animal Waste Deposited on Soils

A substantial amount of liquid and solid waste is produced by domestic animals that are kept as pets. A preliminary methodology was developed to estimate nitrous oxide ($N_2O$) emissions from the deposition of domestic house animal (i.e., dogs and cats) waste on lawns, fields and parks. Estimates calculated with this methodology suggest that, in 1990, approximately 330 Gg of nitrogen originating as domestic house animal waste were deposited on soils resulting in approximately 2.9 Tg $CO_2$ Eq. of $N_2O$ emissions from soils. To estimate the amount of nitrogen

deposited by domestic house animals, only those excretions that remained on land surfaces—as opposed to wastes that were collected by owners and are managed as municipal solid waste—were included.

Annual dog and cat population numbers were obtained from the Pet Food Institute.[5] Annual nitrogen excretion rates were estimated from protein intake. The recommended protein intake for an average size adult of each animal type[6] was multiplied by the average amount of nitrogen per unit of protein (0.16 kg N/kg protein, from the *Revised 1996 IPCC Guidelines*) to estimate nitrogen consumption. It was then assumed that 95 percent of this nitrogen was excreted, either in solid or liquid form (i.e., it was assumed that 5 percent was retained for fur and milk production). Of the total nitrogen excretion, 90 percent was assumed to occur through liquid waste, with the balance from solid waste[7]. Both cat and dog populations were divided into urban and rural fractions, using the metropolitan and non-metropolitan human population categories, respectively, of the U.S. Census Bureau[8]. Both liquid and solid wastes from the urban cat population, and solid waste from the urban dog population were assumed to be collected (i.e., not deposited on soils). Nitrous oxide emission estimates from domestic house animal excretion were calculated in the same manner as performed for estimating emissions from livestock excretion. Producing these estimates involved making a number of simplifying assumptions regarding average animal size and protein consumption, as well as the proportions of animal populations residing in urban and rural areas and the proportions of wastes that are deposited on land. Further methodological development and data collection is required in order to reduce the uncertainty involved in the domestic house animal excretion estimates.

### $CO_2$ from Food Scraps Disposed in Landfills

A certain amount of food scraps generated from food processing or as leftovers join the waste stream and are landfilled. Nationally, an estimated 0.4 Tg $CO_2$ Eq. per year are stored in the form of organic carbon contained in food scraps in landfills, acting as a carbon sink. A portion of the landfilled food scraps becomes a source of methane emissions, which offset the sink estimates to an extent. Further data collection on the amount and composition of food scraps generated and landfilled is required in order to reduce the uncertainty associated with this estimate.

### $CO_2$ from Industrial Waste Combustion

Waste combustion is incorporated in two sections of the energy chapter of the inventory: in the section on $CO_2$ emissions from waste combustion, and in the calculation of emissions and storage from non-energy uses of fossil fuels. The former section addresses fossil-derived materials (such as plastics) that are discarded as part of the municipal wastestream and combusted (generally for energy recovery). The latter addresses two types of combustion: hazardous waste incineration of organic materials (assumed to be fossil-derived), in which regulated wastes are burned without energy recovery, and burning of fossil-derived materials for energy recovery. There is one potentially significant category of waste combustion that is not included in our calculus: industrial non-hazardous waste, burned for disposal (rather than energy recovery). Data are not readily available for this source; further research is needed to estimate the magnitude of $CO_2$ emissions.

### $CH_4$ from Land-Use Changes Including Wetlands Creation or Destruction

Wetlands are a known source of methane ($CH_4$) emissions. When wetlands are destroyed, $CH_4$ emissions may be reduced. Conversely, when wetlands are created (e.g., during the construction of hydroelectric plants), $CH_4$ emissions may increase. Grasslands and forestlands may also be weak sinks for $CH_4$ due to the presence of methanotrophic bacteria that use $CH_4$ as an energy source (i.e., they oxidize $CH_4$ to $CO_2$). Currently, an adequate scientific basis for estimating these emissions and sinks does not exist, and therefore further research and methodological development is required.

---

[5] Pet Food Institute (1999) *Pet Incidence Trend Report.* Pet Food Institute, Washington DC.

[6] Bright, S. (1999) Personal communication between Marco Alcaraz of ICF Consulting and Susan Bright of the Dupont Animal Clinic, Washington, DC, August 1999.

[7] Swenson, M.J. and W.G. Reece, eds. (1993) *Duke's Physiology of Domestic Animals.* Cornell University Press. 11th Edition.

[8] U.S. Census Bureau (1999) <http://www.census.gov/population/estimates/metro-city/ma96-08.txt>

### $N_2O$ from Wastewater Treatment and Biological Processes

As a result of nitrification and denitrification processes, nitrous oxide ($N_2O$) may be produced and emitted from large-scale composting, small scale composting (e.g. households), post-composting of anaerobic digested wastes, and both domestic and industrial wastewater treatment plants. Nitrogen-containing compounds are found in composted wastes and wastewater due to the presence of both human excrement and other nitrogen- containing constituents (e.g. garbage, industrial wastes, animal carcasses, etc.) The portion of emitted $N_2O$ that originates from human excrement is currently estimated under the Human Sewage source category- based upon average dietary assumptions. The portion of emitted $N_2O$ that originates from other nitrogen-containing constituents is not currently estimated. Further research and methodological development is needed if these emissions are to be accurately estimated.

### $CH_4$ from Large and Small Scale Composting

Methane ($CH_4$) may be released through large and small scale (e.g. household) composting. Detailed composting data is necessary in order to estimate emissions but were not available.

### $CH_4$ from Treatment of Dredging Sludge, Remediation of Groundwater, Intermediate Storage of Slaughter Waste, Production of Process Water from Groundwater, and Post Composting of Anaerobic Digested Wastes.

Methane ($CH_4$) may be released through the treatment of dredging sludge, remediation of groundwater, intermediate storage of slaughter waste, production of process water from groundwater, and post composting of anaerobic digested wastes. No methodology was available for estimating these emissions, and therefore further research is needed if these emissions are to be included.

### $N_2O$ from Applications of Anesthetics in Healthcare, Consumer Packaging of Whipped Cream, Fireworks, Applications as Party-drug/Horns/Balloons, Laboratories, Engine Booster Fuel, and Explosives.

Nitrous oxide ($N_2O$) may be released from anesthetic in healthcare (i.e. dentists, doctors, veterinarians, and elderly care), consumer packaging of whipped cream, fireworks, applications as party-drug/horns/balloons, laboratories, engine booster fuel, and explosives. Although emissions from these sources are believed to be minor, emissions estimation data and methodologies were not available.

## References

EPA (2000b). Toxics Release Inventory, 1998. U.S. Environmental Protection Agency, Office of Environmental Information, Office of Information Analysis and Access, Washington, DC. Available online at <http://www.epa.gov/triexplorer/chemical.htm>.

# ANNEX W

## Constants, Units, and Conversions

### Metric Prefixes

Although most activity data for the United States is gathered in customary U.S. units, these units are converted into metric units per international reporting guidelines. The following table provides a guide for determining the magnitude of metric units.

**Table W-1: Guide to Metric Unit Prefixes**

| Prefix/Symbol | Factor |
|---|---|
| atto (a) | $10^{-18}$ |
| femto (f) | $10^{-15}$ |
| pico (p) | $10^{-12}$ |
| nano (n) | $10^{-9}$ |
| micro (μ ) | $10^{-6}$ |
| milli (m) | $10^{-3}$ |
| centi (c) | $10^{-2}$ |
| deci (d) | $10^{-1}$ |
| deca (da) | 10 |
| hecto (h) | $10^{2}$ |
| kilo (k) | $10^{3}$ |
| mega (M) | $10^{6}$ |
| giga (G) | $10^{9}$ |
| tera (T) | $10^{12}$ |
| peta (P) | $10^{15}$ |
| exa (E) | $10^{18}$ |

### Unit Conversions

1 kilogram = 2.205 pounds
1 pound = 0.454 kilograms
1 short ton = 2,000 pounds = 0.9072 metric tons
1 metric ton = 1,000 kilograms = 1.1023 short tons

1 cubic meter = 35.315 cubic feet
1 cubic foot = 0.02832 cubic meters
1 U.S. gallon = 3.785412 liters
1 barrel (bbl) = 0.159 cubic meters
1 barrel (bbl) = 42 U.S. gallons
1 liter = 0.1 cubic meters

1 foot = 0.3048 meters
1 meter = 3.28 feet
1 mile = 1.609 kilometers
1 kilometer = 0.622 miles

1 acre = 43,560 square feet = 0.4047 hectares = 4,047 square meters
1 square mile = 2.589988 square kilometers

To convert degrees Fahrenheit to degrees Celsius, subtract 32 and multiply by 5/9
To convert degrees Celsius to Kelvin, add 273.15 to the number of Celsius degrees

## Density Conversions[1]

| | | | |
|---|---|---|---|
| Methane | 1 cubic meter | = | 0.67606 kilograms |
| Carbon dioxide | 1 cubic meter | = | 1.85387 kilograms |

| | | | | | |
|---|---|---|---|---|---|
| Natural gas liquids | 1 metric ton | = | 11.6 barrels | = | 1,844.2 liters |
| Unfinished oils | 1 metric ton | = | 7.46 barrels | = | 1,186.04 liters |
| Alcohol | 1 metric ton | = | 7.94 barrels | = | 1,262.36 liters |
| Liquefied petroleum gas | 1 metric ton | = | 11.6 barrels | = | 1,844.2 liters |
| Aviation gasoline | 1 metric ton | = | 8.9 barrels | = | 1,415.0 liters |
| Naphtha jet fuel | 1 metric ton | = | 8.27 barrels | = | 1,314.82 liters |
| Kerosene jet fuel | 1 metric ton | = | 7.93 barrels | = | 1,260.72 liters |
| Motor gasoline | 1 metric ton | = | 8.53 barrels | = | 1,356.16 liters |
| Kerosene | 1 metric ton | = | 7.73 barrels | = | 1,228.97 liters |
| Naphtha | 1 metric ton | = | 8.22 barrels | = | 1,306.87 liters |
| Distillate | 1 metric ton | = | 7.46 barrels | = | 1,186.04 liters |
| Residual oil | 1 metric ton | = | 6.66 barrels | = | 1,058.85 liters |
| Lubricants | 1 metric ton | = | 7.06 barrels | = | 1,122.45 liters |
| Bitumen | 1 metric ton | = | 6.06 barrels | = | 963.46 liters |
| Waxes | 1 metric ton | = | 7.87 barrels | = | 1,251.23 liters |
| Petroleum coke | 1 metric ton | = | 5.51 barrels | = | 876.02 liters |
| Petrochemical feedstocks | 1 metric ton | = | 7.46 barrels | = | 1,186.04 liters |
| Special naphtha | 1 metric ton | = | 8.53 barrels | = | 1,356.16 liters |
| Miscellaneous products | 1 metric ton | = | 8.00 barrels | = | 1,271.90 liters |

## Energy Conversions

### Converting Various Energy Units to Joules

The common energy unit used in international reports of greenhouse gas emissions is the joule. A joule is the energy required to push with a force of one Newton for one meter. A terajoule (TJ) is one trillion ($10^{12}$) joules. A British thermal unit (Btu, the customary U.S. energy unit) is the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit at or near 39.2 Fahrenheit.

1 TJ =
- $2.388 \times 10^{11}$ calories
- 23.88 metric tons of crude oil equivalent
- 947.8 million Btus
- 277,800 kilowatt-hours

### Converting Various Physical Units to Energy Units

Data on the production and consumption of fuels are first gathered in physical units. These units must be converted to their energy equivalents. The values in the following table of conversion factors can be used as default factors, if local data are not available. See Appendix A of EIA's *Annual Energy Review 1997* (EIA 1998) for more detailed information on the energy content of various fuels.

[1] Reference: EIA (1998a)

**Table W-2: Conversion Factors to Energy Units (Heat Equivalents)**

| Fuel Type (Units) | Factor |
|---|---|
| **Solid Fuels (Million Btu/Short ton)** | |
| Anthracite coal | 22.573 |
| Bituminous coal | 23.89 |
| Sub-bituminous coal | 17.14 |
| Lignite | 12.866 |
| Coke | 24.8 |
| **Natural Gas (Btu/Cubic foot)** | **1,027** |
| **Liquid Fuels (Million Btu/Barrel)** | |
| Crude oil | 5.800 |
| Natural gas liquids and LRGs | 3.777 |
| Other liquids | 5.825 |
| Motor gasoline | 5.253 |
| Aviation gasoline | 5.048 |
| Kerosene | 5.670 |
| Jet fuel, kerosene-type | 5.670 |
| Distillate fuel | 5.825 |
| Residual oil | 6.287 |
| Naphtha for petrochemicals | 5.248 |
| Petroleum coke | 6.024 |
| Other oil for petrochemicals | 5.825 |
| Special naphthas | 5.248 |
| Lubricants | 6.065 |
| Waxes | 5.537 |
| Asphalt | 6.636 |
| Still gas | 6.000 |
| Misc. products | 5.796 |

Note: For petroleum and natural gas, *Annual Energy Review 1997* (EIA 1998b). For coal ranks, *State Energy Data Report 1992* (EIA 1993). All values are given in higher heating values (gross calorific values).

## References


EIA (1998a) *Emissions of Greenhouse Gases in the United States*, DOE/EIA-0573(97), Energy Information Administration, U.S. Department of Energy. Washington, DC. October.

EIA (1998b) *Annual Energy Review*, DOE/EIA-0384(97), Energy Information Administration, U.S. Department of Energy. Washington, DC. July.

EIA (1993) *State Energy Data Report 1992*, DOE/EIA-0214(93), Energy Information Administration, U.S. Department of Energy. Washington, DC. December.

# ANNEX X

## Abbreviations

| | |
|---|---|
| AAPFCO | American Association of Plant Food Control Officials |
| AFEAS | Alternative Fluorocarbon Environmental Acceptability Study |
| AGA | American Gas Association |
| APC | American Plastics Council |
| ASAE | American Society of Agricultural Engineers |
| BEA | Bureau of Economic Analysis, U.S. Department of Commerce |
| $BOD_5$ | Biochemical oxygen demand over a 5-day period |
| BTS | Bureau of Transportation Statistics, U.S. Department of Transportation |
| Btu | British thermal unit |
| CAAA | Clean Air Act Amendments of 1990 |
| CAPP | Canadian Association of Petroleum Producers |
| C&EN | Chemical and Engineering News |
| CFC | Chlorofluorocarbon |
| CFR | Code of Federal Regulations |
| CMA | Chemical Manufacturer's Association |
| CMOP | Coalbed Methane Outreach Program |
| CVD | Chemical vapor deposition |
| DESC | Defense Energy Support Center-DoD's defense logistics agency |
| DIC | Dissolved inorganic carbon |
| DOC | U.S. Department of Commerce |
| DoD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| DOI | U.S. Department of the Interior |
| DOT | U.S. Department of Transportation |
| EIA | Energy Information Administration, U.S. Department of Energy |
| EIIP | Emissions Inventory Improvement Program |
| EOR | Enhanced oil recovery |
| EPA | U.S. Environmental Protection Agency |
| FAA | Federal Aviation Administration |
| FAO | Food and Agricultural Organization |
| FCCC | Framework Convention on Climate Change |
| FEB | Fiber Economics Bureau |
| FHWA | Federal Highway Administration |
| GAA | Governmental Advisory Associates |
| GCV | Gross calorific value |
| GDP | Gross domestic product |
| GHG | Greenhouse gas |
| GRI | Gas Research Institute |
| GSAM | Gas Systems Analysis Model |
| GWP | Global warming potential |
| HBFC | Hydrobromofluorocarbon |
| HCFC | Hydrochlorofluorocarbon |
| HDGV | Heavy duty gas vehicle |
| HDDV | Heavy duty diesel vehicle |
| HDPE | High density polyethylene |
| HFC | Hydrofluorocarbon |
| HFE | Hydrofluoroethers |
| ICAO | International Civil Aviation Organization |
| IEA | International Energy Association |
| IISRP | International Institute of Synthetic Rubber Products |
| ILENR | Illinois Department of Energy and Natural Resources |
| IMO | International Maritime Organization |
| IPAA | Independent Petroleum Association of America |
| IPCC | Intergovernmental Panel on Climate Change |
| LDDT | Light duty diesel truck |
| LDDV | Light duty diesel vehicle |
| LDGV | Light duty gas vehicle |

| | |
|---|---|
| LDGT | Light duty gas truck |
| LDPE | Low density polyethylene |
| LEV | Low emission vehicles |
| LFG | Landfill gas |
| LFGTE | Landfill gas-to-energy |
| LLPDE | Linear low density polyethylene |
| LMOP | EPA's Landfill Methane Outreach Program |
| LPG | Liquefied petroleum gas(es) |
| LTO | Landing and take-off |
| LULUCF | Land use, land-use change, and forestry |
| MC | Motorcycle |
| MCF | Methane conversion factor |
| MMS | Minerals Management Service |
| MMTCE | Million metric tons carbon equivalent |
| MSHA | Mine Safety and Health Administration |
| MSW | Municipal solid waste |
| NAPAP | National Acid Precipitation and Assessment Program |
| NASS | USDA's National Agriculture Statistics Service |
| NCV | Net calorific value |
| NIAR | Norwegian Institute for Air Research |
| NMVOC | Non-methane volatile organic compound |
| $NO_x$ | Nitrogen Oxides |
| NRCS | Natural Resources Conservation Service |
| NSCR | Non-selective catalytic reduction |
| NVFEL | National Vehicle Fuel Emissions Laboratory |
| OAQPS | EPA Office of Air Quality Planning and Standards |
| ODS | Ozone depleting substances |
| OECD | Organization of Economic Co-operation and Development |
| OMS | EPA Office of Mobile Sources |
| ORNL | Oak Ridge National Laboratory |
| OSHA | Occupational Safety and Health Administration |
| OTA | Office of Technology Assessment |
| PPC | Precipitated calcium carbonate |
| PFC | Perfluorocarbon |
| PFPE | Perfluoropolyether |
| POTW | Publicly Owned Treatment Works |
| Ppmv | Parts per million($10^6$) by volume |
| Ppbv | Parts per billion ($10^9$) by volume |
| Pptv | Parts per trillion ($10^{12}$) by volume |
| PVC | Polyvinyl chloride |
| RCRA | Resource Conservation and Recovery Act |
| SAE | Society of Automotive Engineers |
| SBSTA | Subsidiary Body for Scientific and Technical Advice |
| SCR | Selective catalytic reduction |
| SNG | Synthetic natural gas |
| SWANA | Solid Waste Association of North America |
| Tbtu | Trillion Btu |
| $TgCO_2Eq$ | Teragrams carbon dioxide equivalent |
| TJ | Terajoule |
| TSDF | Hazardous waste treatment, storage, and disposal facility |
| TVA | Tennessee Valley Authority |
| UEP | United Egg Producers |
| U.S. | United States |
| USAF | United States Air Force |
| USDA | United States Department of Agriculture |
| USFS | United States Forest Service |
| USGS | United States Geological Survey |
| UNEP | United Nations Environmental Programme |
| UNFCCC | United Nations Framework Convention on Climate Change |
| VAIP | EPA's Voluntary Aluminum Industrial Partnership |
| VMT | Vehicle miles traveled |
| WMO | World Meteorological Organization |

# ANNEX Y

## Chemical Formulas

### Table Y-1: Guide to Chemical Formulas

| Symbol | Name |
|---|---|
| Al | Aluminum |
| $Al_2O_3$ | Aluminum Oxide |
| Br | Bromine |
| C | Carbon |
| $CH_4$ | Methane |
| $C_2H_6$ | Ethane |
| $C_3H_8$ | Propane |
| $CF_4$ | Perfluoromethane |
| $C_2F_6$ | Perfluoroethane, hexafluoroethane |
| c-$C_3F_6$ | Perfluorocyclopropane |
| $C_3F_8$ | Perfluoropropane |
| c-$C_4F_8$ | Perfluorocyclobutane |
| $C_4F_{10}$ | Perfluorobutane |
| $C_5F_{12}$ | Perfluoropentane |
| $C_6F_{14}$ | Perfluorohexane |
| $CF_3I$ | Trifluoroiodomethane |
| $CFCl_3$ | Trichlorofluoromethane (CFC-11) |
| $CF_2Cl_2$ | Dichlorodifluoromethane (CFC-12) |
| $CF_3Cl$ | Chlorotrifluoromethane (CFC-13) |
| $C_2F_3Cl_3$ | Trichlorotrifluoroethane (CFC-113)* |
| $CCl_3CF_3$ | CFC-113a* |
| $C_2F_4Cl_2$ | Dichlorotetrafluoroethane (CFC-114) |
| $C_2F_5Cl$ | Chloropentafluoroethane (CFC-115) |
| $CHCl_2F$ | HCFC-21 |
| $CHF_2Cl$ | Chlorodifluoromethane (HCFC-22) |
| $C_2F_3HCl_2$ | HCFC-123 |
| $C_2F_4HCl$ | HCFC-124 |
| $C_2FH_3Cl_2$ | HCFC-141b |
| $C_2H_3F_2Cl$ | HCFC-142b |
| $CF_3CF_2CHCl_2$ | HCFC-225ca |
| $CClF_2CF_2CHClF$ | HCFC-225cb |
| $CCl_4$ | Carbon tetrachloride |
| $CHClCCl_2$ | Trichloroethylene |
| $CCl_2CCl_2$ | Perchloroethylene, tetrachloroethene |
| $CH_3Cl$ | Methylchloride |
| $CH_3CCl_3$ | Methylchloroform |
| $CH_2Cl_2$ | Methylenechloride |
| $CHCl_3$ | Chloroform, trichloromethane |
| $CHF_3$ | HFC-23 |
| $CH_2F_2$ | HFC-32 |
| $CH_3F$ | HFC-41 |
| $C_2HF_5$ | HFC-125 |
| $C_2H_2F_4$ | HFC-134 |
| $CH_2FCF_3$ | HFC-134a |
| $C_2H_3F_3$ | HFC-143* |
| $C_2H_3F_3$ | HFC-143a* |
| $CH_2FCH_2F$ | HFC-152* |
| $C_2H_4F_2$ | HFC-152a* |
| $CH_3CH_2F$ | HFC-161 |
| $C_3HF_7$ | HFC-227ea |
| $CF_3CF_2CH_2F$ | HFC-236cb |

| | |
|---|---|
| $CF_3CHFCHF_2$ | HFC-236ea |
| $C_3H_2F_6$ | HFC-236fa |
| $C_3H_3F_5$ | HFC-245ca |
| $CHF_2CH_2CF_3$ | HFC-245fa |
| $CF_3CH_2CF_2CH_3$ | HFC-365mfc |
| $C_5H_2F_{10}$ | HFC-43-10mee |
| $CF_3OCHF_2$ | HFE-125 |
| $CF_2HOCF_2H$ | HFE-134 |
| $CH_3OCF_3$ | HFE-143a |
| $CF_3CHFOCF_3$ | HFE-227ea |
| $CF_3CHClOCHF_2$ | HCFE-235da2 |
| $CF_3CHFOCHF_2$ | HFE-236ea2 |
| $CF_3CH_2OCF_3$ | HFE-236fa |
| $CF_3CF_2OCH_3$ | HFE-245cb2 |
| $CHF_2CH_2OCF_3$ | HFE-245fa1 |
| $CF_3CH_2OCHF_2$ | HFE-245fa2 |
| $CHF_2CF_2OCH_3$ | HFE-254cb2 |
| $CF_3CH_2OCH_3$ | HFE-263fb2 |
| $CF_3CF_2OCF_2CHF_2$ | HFE-329mcc2 |
| $CF_3CF_2OCH_2CF_3$ | HFE-338mcf2 |
| $CF_3CF_2CF_2OCH_3$ | HFE-347mcc3 |
| $CF_3CF_2OCH_2CHF_2$ | HFE-347mcf2 |
| $CF_3CHFCF_2OCH_3$ | HFE-356mec3 |
| $CHF_2CF_2CF_2OCH_3$ | HFE-356pcc3 |
| $CHF_2CF_2OCH_2CHF_2$ | HFE-356pcf2 |
| $CHF_2CF_2CH_2OCHF_2$ | HFE-356pcf3 |
| $CF_3CF_2CH_2OCH_3$ | HFE-365mcf3 |
| $CHF_2CF_2OCH_2CH_3$ | HFE-374pcf2 |
| $C_4F_9OCH_3$ | HFE-7100 |
| $C_4F_9OC_2H_5$ | HFE-7200 |
| $CHF_2OCF_2OC_2F_4OCHF_2$ | H-Galden 1040x |
| $CHF_2OCF_2OCHF_2$ | HG-10 |
| $CHF_2OCF_2CF_2OCHF_2$ | HG-01 |
| $CH_3OCH_3$ | Dimethyl ether |
| $CH_2Br_2$ | Dibromomethane |
| $CH_2BrCl$ | Dibromochloromethane |
| $CHBr_3$ | Tribromomethane |
| $CHBrF_2$ | Bromodifluoromethane |
| $CH_3Br$ | Methylbromide |
| $CF_2BrCl$ | Bromodichloromethane (Halon 1211) |
| $CF_3Br(CBrF_3)$ | Bromotrifluoromethane (Halon 1301) |
| $CF_3I$ | FIC-13I1 |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| $CaCO_3$ | Calcium carbonate, Limestone |
| $CaMg(CO_3)_2$ | Dolomite |
| CaO | Calcium oxide, Lime |
| Cl | atomic Chlorine |
| F | Fluorine |
| Fe | Iron |
| $Fe_2O_3$ | Ferric oxide |
| FeSi | Ferrosilicon |
| H, $H_2$ | atomic Hydrogen, molecular Hydrogen |
| $H_2O$ | Water |
| $H_2O_2$ | Hydrogen peroxide |
| OH | Hydroxyl |
| N, $N_2$ | atomic Nitrogen, molecular Nitrogen |
| $NH_3$ | Ammonia |
| $NH_4^+$ | Ammonium ion |
| $HNO_3$ | Nitric Acid |
| $NF_3$ | Nitrogen trifluoride |
| $N_2O$ | Nitrous oxide |

| | |
|---|---|
| NO | Nitric oxide |
| $NO_2$ | Nitrogen dioxide |
| $NO_3$ | Nitrate radical |
| Na | Sodium |
| $Na_2CO_3$ | Sodium carbonate, soda ash |
| $Na_3AlF_6$ | Synthetic cryolite |
| O, $O_2$ | atomic Oxygen, molecular Oxygen |
| $O_3$ | Ozone |
| S | atomic Sulfur |
| $H_2SO_4$ | Sulfuric acid |
| $SF_6$ | Sulfur hexafluoride |
| $SF_5CF_3$ | Trifluoromethylsulphur pentafluoride |
| $SO_2$ | Sulfur dioxide |
| Si | Silicon |
| SiC | Silicon carbide |
| $SiO_2$ | Quartz |

* Distinct isomers.

# ANNEX Z

## Glossary

**Abiotic.** [7] Nonliving. Compare *biotic.*

**Absorption of radiation.**[1] The uptake of radiation by a solid body, liquid or gas. The absorbed energy may be transferred or re-emitted.

**Acid deposition.** [6] A complex chemical and atmospheric process whereby recombined emissions of sulfur and nitrogen compounds are redeposited on earth in wet or dry form. See *acid rain.*

**Acid rain.** [6] Rainwater that has an acidity content greater than the postulated natural pH of about 5.6. It is formed when sulfur dioxides and nitrogen oxides, as gases or fine particles in the atmosphere, combine with water vapor and precipitate as sulfuric acid or nitric acid in rain, snow, or fog. The dry forms are acidic gases or particulates. See *acid deposition.*

**Acid solution.** [7] Any water solution that has more hydrogen ions (H+) than hydroxide ions (OH-); any water solution with a pH less than 7. See *basic solution, neutral solution.*

**Acidic.** [7] See acid solution.

**Adiabatic process.** [9] A thermodynamic change of state of a system such that no heat or mass is transferred across the boundaries of the system. In an adiabatic process, expansion always results in cooling, and compression in warming.

**Aerosol.** [1&9] Particulate matter, solid or liquid, larger than a molecule but small enough to remain suspended in the atmosphere. Natural sources include salt particles from sea spray, dust and clay particles as a result of weathering of rocks, both of which are carried upward by the wind. Aerosols can also originate as a result of human activities and are often considered pollutants. Aerosols are important in the atmosphere as nuclei for the condensation of water droplets and ice crystals, as participants in various chemical cycles, and as absorbers and scatters of solar radiation, thereby influencing the radiation budget of the Earth's climate system. See *climate, particulate matter.*

**Afforestation.** [2] Planting of new forests on lands that have not been recently forested.

**Air carrier** [8] An operator (e.g., airline) in the commercial system of air transportation consisting of aircraft that hold certificates of, Public Convenience and Necessity, issued by the Department of Transportation, to conduct scheduled or non-scheduled flights within the country or abroad.

**Air pollutant.** See *air pollution.*

**Air pollution.** [7] One or more chemicals or substances in high enough concentrations in the air to harm humans, other animals, vegetation, or materials. Such chemicals or physical conditions (such as excess heat or noise) are called air pollutants.

**Albedo.** [9] The fraction of the total solar radiation incident on a body that is reflected by it.

**Alkalinity.** [6] Having the properties of a base with a pH of more than 7. A common alkaline is baking soda.

**Alternative energy.** [6] Energy derived from nontraditional sources (e.g., compressed natural gas, solar, hydroelectric, wind).

**Anaerobic.** [6] A life or process that occurs in, or is not destroyed by, the absence of oxygen.

**Anaerobic decomposition.** [2] The breakdown of molecules into simpler molecules or atoms by microorganisms that can survive in the partial or complete absence of oxygen.

**Anaerobic lagoon.** [2] A liquid-based manure management system, characterized by waste residing in water to a depth of at least six feet for a period ranging between 30 and 200 days. Bacteria produce methane in the absence of oxygen while breaking down waste.

**Anaerobic organism.** [7] Organism that does not need oxygen to stay alive. See *aerobic organism.*

**Antarctic "Ozone Hole."** [6] Refers to the seasonal depletion of stratospheric ozone in a large area over Antarctica. See *ozone layer.*

**Anthracite.** [2] A hard, black, lustrous coal containing a high percentage of fixed carbon and a low percentage of volatile matter. Often referred to as hard coal.

**Anthropogenic.** [2] Human made. In the context of greenhouse gases, emissions that are produced as the result of human activities.

**Arable land.** [7] Land that can be cultivated to grow crops.

**Aromatic.** [6] Applied to a group of hydrocarbons and their derivatives characterized by the presence of the benzene ring.

**Ash.** [6] The mineral content of a product remaining after complete combustion.

**Asphalt.** [2] A dark-brown-to-black cement-like material containing bitumen as the predominant constituent. It is obtained by petroleum processing. The definition includes crude asphalt as well as the following finished products: cements, fluxes, the asphalt content of emulsions (exclusive of water), and petroleum distillates blended with asphalt to make cutback asphalt.

**Atmosphere.** [1] The mixture of gases surrounding the Earth. The Earth's atmosphere consists of about 79.1 percent nitrogen (by volume), 20.9 percent oxygen, 0.036 percent carbon dioxide and trace amounts of other gases. The atmosphere can be divided into a number of layers according to its mixing or chemical characteristics, generally determined by its thermal properties (temperature). The layer nearest the Earth is the *troposphere*, which reaches up to an altitude of about 8 kilometers (about 5 miles) in the polar regions and up to 17 kilometers (nearly 11 miles) above the equator. The *stratosphere*, which reaches to an altitude of about 50 kilometers (31miles) lies atop the troposphere. The *mesosphere*, which extends from 80 to 90 kilometers atop the stratosphere, and finally, the *thermosphere*, or *ionosphere*, gradually diminishes and forms a fuzzy border with outer space. There is relatively little mixing of gases between layers.

**Atmospheric lifetime.** See *lifetime.*

**Atomic weight.** [6] The average weight (or mass) of all the isotopes of an element, as determined from the proportions in which they are present in a given element, compared with the mass of the 12 isotope of carbon (taken as precisely 12.000), that is the official international standard; measured in daltons.

**Atoms.** [7] Minute particles that are the basic building blocks of all chemical elements and thus all matter.

**Aviation Gasoline.** [8] All special grades of gasoline for use in aviation reciprocating engines, as given in the American Society for Testing and Materials (ASTM) specification D 910. Includes all refinery products within the gasoline range that are to be marketed straight or in blends as aviation gasoline without further processing (any refinery operation except mechanical blending). Also included are finished components in the gasoline range, which will be used for blending or compounding into aviation gasoline.

**Bacteria.** [7] One-celled organisms. Many act as decomposers that break down dead organic matter into substances that dissolve in water and are used as nutrients by plants.

**Barrel (bbl).** [6] A liquid-volume measure equal to 42 United States gallons at 60 degrees Fahrenheit; used in expressing quantities of petroleum-based products.

**Basic solution.** [7] Water solution with more hydroxide ions (OH-) than hydrogen ions (H+); water solutions with pH greater than 7. See *acid solution, alkalinity, acid.*

**Biodegradable.** [7] Material that can be broken down into simpler substances (elements and compounds) by bacteria or other decomposers. Paper and most organic wastes such as animal manure are biodegradable. See *nonbiodegradable.*

**Biofuel.** [3&7] Gas or liquid fuel made from plant material (biomass). Includes wood, wood waste, wood liquors, peat, railroad ties, wood sludge, spent sulfite liquors, agricultural waste, straw, tires, fish oils, tall oil, sludge waste, waste alcohol, municipal solid waste, landfill gases, other waste, and ethanol blended into motor gasoline.

**Biogeochemical cycle.** [7] Natural processes that recycle nutrients in various chemical forms from the environment, to organisms, and then back to the environment. Examples are the carbon, oxygen, nitrogen, phosphorus, and hydrologic cycles.

**Biological oxygen demand (BOD).** [7] Amount of dissolved oxygen needed by aerobic decomposers to break down the organic materials in a given volume of water at a certain temperature over a specified time period. See *BOD5*.

**Biomass.** [7] Total dry weight of all living organisms that can be supported at each tropic level in a food chain. Also, materials that are biological in origin, including organic material (both living and dead) from above and below ground, for example, trees, crops, grasses, tree litter, roots, and animals and animal waste.

**Biomass energy.** [1] Energy produced by combusting biomass materials such as wood. The carbon dioxide emitted from burning biomass will not increase total atmospheric carbon dioxide if this consumption is done on a sustainable basis (i.e., if in a given period of time, regrowth of biomass takes up as much carbon dioxide as is released from biomass combustion). Biomass energy is often suggested as a replacement for fossil fuel combustion.

**Biosphere.** [2&7] The living and dead organisms found near the earth's surface in parts of the lithosphere, atmosphere, and hydrosphere. The part of the global carbon cycle that includes living organisms and biogenic organic matter.

**Biotic.** [7] Living. Living organisms make up the biotic parts of ecosystems. See *abiotic.*

**Bitumen.** [7] Gooey, black, high-sulfur, heavy oil extracted from tar sand and then upgraded to synthetic fuel oil. See *tar sand.*

**Bituminous coal.** [2] A dense, black, soft coal, often with well-defined bands of bright and dull material. The most common coal, with moisture content usually less than 20 percent. Used for generating electricity, making coke, and space heating.

**BOD5.** [2] The biochemical oxygen demand of wastewater during decomposition occurring over a 5-day period. A measure of the organic content of wastewater. See *biological oxygen demand.*

**British thermal unit (Btu).** [3] The quantity of heat required to raise the temperature of one pound of water one degree of Fahrenheit at or near 39.2 degrees Fahrenheit.

**Bunker fuel.** [2] Fuel supplied to ships and aircraft for international transportation, irrespective of the flag of the carrier, consisting primarily of residual and distillate fuel oil for ships and jet fuel for aircraft.

**Bus.** [6&8] A rubber-tired, self-propelled, manually steered vehicle that is generally designed to transport 30 individuals or more. Bus types include intercity, school and transit.

**Capacity Factor.**[3] 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.

**Carbon black.** [2] An amorphous form of carbon, produced commercially by thermal or oxidative decomposition of hydrocarbons and used principally in rubber goods, pigments, and printer's ink.

**Carbon cycle.** [2] All carbon reservoirs and exchanges of carbon from reservoir to reservoir by various chemical, physical, geological, and biological processes. Usually thought of as a series of the four main reservoirs of carbon interconnected by pathways of exchange. The four reservoirs, regions of the Earth in which carbon behaves in a systematic manner, are the atmosphere, terrestrial biosphere (usually includes freshwater systems), oceans, and sediments (includes fossil fuels). Each of these global reservoirs may be subdivided into smaller pools, ranging in size from individual communities or ecosystems to the total of all living organisms (biota).

**Carbon dioxide.** [2] A colorless, odorless, non-poisonous gas that is a normal part of the ambient air. Carbon dioxide is a product of fossil fuel combustion. Although carbon dioxide does not directly impair human health, it is a greenhouse gas that traps terrestrial (i.e., infrared) radiation and contributes to the potential for global warming. See *global warming.*

**Carbon equivalent (CE).** [1] A metric measure used to compare the emissions of the different greenhouse gases based upon their global warming potential (GWP). Greenhouse gas emissions in the United States are most

commonly expressed as "million metric tons of carbon equivalents" (MMTCE). Global warming potentials are used to convert greenhouse gases to carbon dioxide equivalents. See *global warming potential, greenhouse gas.*

**Carbon flux.** [9] The rate of exchange of carbon between pools (i.e., reservoirs).

**Carbon intensity.** The relative amount of carbon emitted per unit of energy or fuels consumed.

**Carbon pool.** [9] The reservoir containing carbon as a principal element in the geochemical cycle.

**Carbon sequestration.** [1] The uptake and storage of carbon. Trees and plants, for example, absorb carbon dioxide, release the oxygen and store the carbon. Fossil fuels were at one time biomass and continue to store the carbon until burned. See *carbon sinks.*

**Carbon sinks.** [1] Carbon reservoirs and conditions that take-in and store more carbon (i.e., carbon sequestration) than they release. Carbon sinks can serve to partially offset greenhouse gas emissions. Forests and oceans are large carbon sinks. See *carbon sequestration.*

**Carbon tetrachloride ($CCl_4$).** [11] A compound consisting of one carbon atom and four chlorine atoms. It is an ozone depleting substance. Carbon tetrachloride was widely used as a raw material in many industrial applications, including the production of chlorofluorocarbons, and as a solvent. Solvent use was ended in the United States when it was discovered to be carcinogenic. See *ozone depleting substance.*

**Chemical reaction.** [7] Interaction between chemicals in which there is a change in the chemical composition of the elements or compounds involved.

**Chlorofluorocarbons (CFCs).** [7] Organic compounds made up of atoms of carbon, chlorine, and fluorine. An example is CFC-12 ($CCl_2F_2$), used as a refrigerant in refrigerators and air conditioners and as a foam blowing agent. Gaseous CFCs can deplete the ozone layer when they slowly rise into the stratosphere, are broken down by strong ultraviolet radiation, release chlorine atoms, and then react with ozone molecules. See *Ozone Depleting Substance.*

**Climate.** [1&9] The average weather, usually taken over a 30 year time period, for a particular region and time period. Climate is not the same as weather, but rather, it is the average pattern of weather for a particular region. Weather describes the short-term state of the atmosphere. Climatic elements include precipitation, temperature, humidity, sunshine, wind velocity, phenomena such as fog, frost, and hail-storms, and other measures of the weather. See *weather.*

**Climate change.** [1] The term "climate change" is sometimes used to refer to all forms of climatic inconsistency, but because the Earth's climate is never static, the term is more properly used to imply a significant change from one climatic condition to another. In some cases, "climate change" has been used synonymously with the term, "global warming"; scientists however, tend to use the term in the wider sense to also include natural changes in climate. See *global warming, greenhouse effect, enhanced greenhouse effect, radiative forcing.*

**Climate feedback.** [1] An atmospheric, oceanic, terrestrial, or other process that is activated by direct climate change induced by changes in radiative forcing. Climate feedbacks may increase (positive feedback) or diminish (negative feedback) the magnitude of the direct climate change.

**Climate lag.** [1] The delay that occurs in climate change as a result of some factor that changes very slowly. For example, the effects of releasing more carbon dioxide into the atmosphere may not be known for some time because a large fraction is dissolved in the ocean and only released to the atmosphere many years later.

**Climate sensitivity.** [1] The equilibrium response of the climate to a change in radiative forcing; for example, a doubling of the carbon dioxide concentration. See *radiative forcing.*

**Climate system (or Earth system).** [1] The atmosphere, the oceans, the biosphere, the cryosphere, and the geosphere, together make up the climate system.

**Coal.** [2] A black or brownish black solid, combustible substance formed by the partial decomposition of vegetable matter without access to air. The rank of coal, which includes anthracite, bituminous coal, subbituminous coal, and lignite, is based on fixed carbon, volatile matter, and heating value. Coal rank indicates the progressive alteration, or coalification, from lignite to anthracite. See *anthracite, bituminous coal, subbituminous coal, lignite.*

**Coal coke.** [2] A hard, porous product made from baking bituminous coal in ovens at temperatures as high as 2,000 degrees Fahrenheit. It is used both as a fuel and as a reducing agent in smelting iron ore in a blast furnace.

**Coal gasification.** [7] Conversion of solid coal to synthetic natural gas (SNG) or a gaseous mixture that can be burned as a fuel.

**Coal liquefaction.** [7] Conversion of solid coal to a liquid fuel such as synthetic crude oil or methanol.

**Coalbed methane.** [2] Methane that is produced from coalbeds in the same manner as natural gas produced from other strata. Methane is the principal component of natural gas.

**Co-control benefit.** [10] It is the additional benefit derived from an environmental policy that is designed to control one type of pollution, while reducing the emissions of other pollutants as well. For example, a policy to reduce carbon dioxide emissions might reduce the combustion of coal, but when coal combustion is reduced, so too are the emissions of particulates and sulfur dioxide. The benefits associated with reductions in emissions of particulates and sulfur dioxide are the co-control benefits of reductions in carbon dioxide.

**Cogeneration.** [7] Production of two useful forms of energy such as high-temperature heat and electricity from the same process.

**Combustion.** [2] Chemical oxidation accompanied by the generation of light and heat.

**Commercial End-Use Sector**: Defined economically, consists of business establishments that are not engaged in transportation or in manufacturing or other types of industrial activities (e.g., agriculture, mining, or construction). Commercial establishments include hotels, motels, restaurants, wholesale businesses, retail stores, laundries, and other service enterprises; religious and nonprofit organizations; health, social, and educational institutions; and Federal, State, and local governments. Street lights, pumps, bridges, and public services are also included if the establishment operating them is considered commercial.

**Compost.** [7] Partially decomposed organic plant and animal matter that can be used as a soil conditioner or fertilizer.

**Composting.** [7] Partial breakdown of organic plant and animal matter by aerobic bacteria to produce a material that can be used as a soil conditioner or fertilizer. See *compost.*

**Compound.** [7] Combination of two or more different chemical elements held together by chemical bonds. See *element.* See *inorganic compound, organic compound.*

**Concentration.** [7] Amount of a chemical in a particular volume or weight of air, water, soil, or other medium. See *parts per billion, parts per million.*

**Conference Of Parties (COP).** [10] The supreme body of the United Nations Framework Convention on Climate Change (UNFCCC). It comprises more than 170 nations that have ratified the Convention. Its first session was held in Berlin, Germany, in 1995 and is expected to continue meeting on a yearly basis. The COP's role is to promote and review the implementation of the Convention. It will periodically review existing commitments in light of the Convention's objective, new scientific findings, and the effectiveness of national climate change programs. See *United Nations Framework Convention on Climate Change.*

**Conifer.** [7] See *coniferous trees.*

**Coniferous trees.** [7] Cone-bearing trees, mostly evergreens, that have needle-shaped or scale-like leaves. They produce wood known commercially as softwood. See *deciduous trees.*

**Cooling Degree Days**: The number of degrees per day that the average daily temperature is above 65° Fahrenheit. The daily average temperature is the mean of the maximum and minimum temperatures for a 24 hour period. (See Degree Days)

**Criteria pollutant.** [2] A pollutant determined to be hazardous to human health and regulated under EPA's National Ambient Air Quality Standards. The 1970 amendments to the Clean Air Act require EPA to describe the health and welfare impacts of a pollutant as the "criteria" for inclusion in the regulatory regime. In this report, emissions of the criteria pollutants CO, $NO_x$, NMVOCs, and $SO_2$ are reported because they are thought to be precursors to greenhouse gas formation.

**Crop residue.** [2] Organic residue remaining after the harvesting and processing of a crop.

**Crop rotation.** [7] Planting the same field or areas of fields with different crops from year to year to reduce depletion of soil nutrients. A plant such as corn, tobacco, or cotton, which remove large amounts of nitrogen from the soil, is planted one year. The next year a legume such as soybeans, which add nitrogen to the soil, is planted.

**Crude oil.** [2] A mixture of hydrocarbons that exist in liquid phase in underground reservoirs and remain liquid at atmospheric pressure after passing through surface separating facilities. See *petroleum.*

**Deciduous trees.** [7] Trees such as oaks and maples that lose their leaves during part of the year. See *coniferous trees.*

**Decomposition.** [9] The breakdown of matter by bacteria and fungi. It changes the chemical composition and physical appearance of the materials.

**Deforestation.** [1] Those practices or processes that result in the conversion of forested lands for non-forest uses. This is often cited as one of the major causes of the enhanced greenhouse effect for two reasons: 1) the burning or decomposition of the wood releases carbon dioxide; and 2) trees that once removed carbon dioxide from the atmosphere in the process of photosynthesis are no longer present.

**Degradable.** [7] See *biodegradable.*

**Degree Days (Population Weighted):** Heating or cooling degree days weighted by the population of the area in which the degree days are recorded. To compute State population-weighted degree days, each State is divided into from one to nine climatically homogeneous divisions, which are assigned weights based on the ratio of the population of the division to the total population of the State. Degree day readings for each division are multiplied by the corresponding population weight for each division and those products are then summed to arrive at the State population-weighted degree day value. To compute national population-weighted degree days, the Nation is divided into nine Census regions, each comprising from three to eight States, which are assigned weights based on the ratio of the population of the Nation. Degree day readings for each region are multiplied by the corresponding population weight for each region and those products are then summed to arrive at the national population-weighted degree day value. (See Heating Degree Days, Cooling Degree Days, and Degree Day Normals)

**Degree Day Normals:** Simple arithmetic averages of monthly or annual degree days over a long period of time (usually the 30 year period of 1961 through 1990). The averages may be dimple degree day normals or population-weighted degree day normals.

**Desertification.** [1] The progressive destruction or degradation of existing vegetative cover to form a desert. This can occur due to overgrazing, deforestation, drought, and the burning of extensive areas. Once formed, deserts can only support a sparse range of vegetation. Climatic effects associated with this phenomenon include increased reflectivity of solar radiation, reduced atmospheric humidity, and greater atmospheric dust (aerosol) loading.

**Distillate fuel oil.** [2] A general classification for the petroleum fractions produced in conventional distillation operations. Included are products known as No. 1, No. 2, and No. 4 fuel oils and No. 1, No. 2, and No. 4 diesel fuels. Used primarily for space heating, on and off-highway diesel engine fuel (including railroad engine fuel and fuel for agricultural machinery), and electric power generation.

**Economy.** [7] System of production, distribution, and consumption of economic goods.

**Ecosystem.** [10] The complex system of plant, animal, fungal, and microorganism communities and their associated non-living environment interacting as an ecological unit. Ecosystems have no fixed boundaries; instead their parameters are set to the scientific, management, or policy question being examined. Depending upon the purpose of analysis, a single lake, a watershed, or an entire region could be considered an ecosystem.

**Electric Utility Sector:** Privately and publicly owned establishments that generate, transmit, distribute, or sell electricity primarily for use by the public and meet the definition of an electric utility. Electric utilities include investor-owned, publicly owned, cooperative, and Federal utilities. Historically, they have generally been vertically integrated companies that provide for generation, transmission, distribution, and/or energy services for all customers in a designated service territory. Nonutility power producers are not included in the electric utility sector.

**Electrons.** [7] Tiny particle moving around outside the nucleus of an atom. Each electron has one unit of negative charge (-) and almost no mass.

**Element.** [7] Chemicals such as hydrogen (H), iron (Fe), sodium (Na), carbon (C), nitrogen (N), or oxygen (O), whose distinctly different atoms serve as the basic building blocks of all matter. There are 92 naturally occurring elements. Another 15 have been made in laboratories. Two or more elements combine to form compounds that make up most of the world's matter. See *compound.*

**Emission inventory.** A list of air pollutants emitted into a community's, state's, nation's, or the Earth's atmosphere in amounts per some unit time (e.g. day or year) by type of source. An emission inventory has both political and scientific applications.

**Emissions coefficient/factor.** [2] A unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity (e.g., grams of carbon dioxide emitted per barrel of fossil fuel consumed).

**Emissions.** [2] Releases of gases to the atmosphere (e.g., the release of carbon dioxide during fuel combustion). Emissions can be either intended or unintended releases. See *fugitive emissions.*

**Energy conservation.** [7] Reduction or elimination of unnecessary energy use and waste. See *energy-efficiency.*

**Energy intensity.** [5] Ratio between the consumption of energy to a given quantity of output; usually refers to the amount of primary or final energy consumed per unit of gross domestic product.

**Energy quality.** [7] Ability of a form of energy to do useful work. High-temperature heat and the chemical energy in fossil fuels and nuclear fuels are concentrated high quality energy. Low-quality energy such as low-temperature heat is dispersed or diluted and cannot do much useful work.

**Energy.** [3] The capacity for doing work as measured by the capability of doing work (potential energy) or the conversion of this capability to motion (kinetic energy). Energy has several forms, some of which are easily convertible and can be changed to another form useful for work. Most of the world's convertible energy comes from fossil fuels that are burned to produce heat that is then used as a transfer medium to mechanical or other means in order to accomplish tasks. In the United States, electrical energy is often measured in kilowatt-hours (kWh), while heat energy is often measured in British thermal units (Btu).

**Energy-efficiency.** [6&8] The ratio of the useful output of services from an article of industrial equipment to the energy use by such an article; for example, vehicle miles traveled per gallon of fuel (mpg).

**Enhanced greenhouse effect.** [1] The concept that the natural greenhouse effect has been enhanced by anthropogenic emissions of greenhouse gases. Increased concentrations of carbon dioxide, methane, and nitrous oxide, CFCs, HFCs, PFCs, $SF_6$, $NF_3$, and other photochemically important gases caused by human activities such as fossil fuel consumption, trap more infra-red radiation, thereby exerting a warming influence on the climate. See *greenhouse gas, anthropogenic, greenhouse effect, climate.*

**Enhanced oil recovery.** [7] Removal of some of the heavy oil left in an oil well after primary and secondary recovery. See *primary oil recovery, secondary oil recovery.*

**Enteric fermentation.** [2] A digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal.

**Environment.** [7] All external conditions that affect an organism or other specified system during its lifetime.

**Ethanol ($C_2H_5OH$).** [8] Otherwise known as ethyl alcohol, alcohol, or grain spirit. A clear, colorless, flammable oxygenated hydrocarbon with a boiling point of 78.5 degrees Celsius in the anhydrous state. In transportation, ethanol is used as a vehicle fuel by itself (E100), blended with gasoline (E85), or as a gasoline octane enhancer and oxygenate (10 percent concentration).

**Evapotranspiration.** [10] The loss of water from the soil by evaporation and by transpiration from the plants growing in the soil, which rises with air temperature.

**Exponential growth.** [7] Growth in which some quantity, such as population size, increases by a constant percentage of the whole during each year or other time period; when the increase in quantity over time is plotted, this type of growth yields a curve shaped like the letter J.

**Feedlot.** [7] Confined outdoor or indoor space used to raise hundreds to thousands of domesticated livestock. See *rangeland.*

**Fertilization, carbon dioxide.** [1] An expression (sometimes reduced to 'fertilization') used to denote increased plant growth due to a higher carbon dioxide concentration.

**Fertilizer.** [7] Substance that adds inorganic or organic plant nutrients to soil and improves its ability to grow crops, trees, or other vegetation. See *organic fertilizer.*

**Flaring.** [9] The burning of waste gases through a flare stack or other device before releasing them to the air.

**Fluidized bed combustion (FBC).** [7] Process for burning coal more efficiently, cleanly, and cheaply. A stream of hot air is used to suspend a mixture of powdered coal and limestone during combustion. About 90 to 98 percent of the sulfur dioxide produced during combustion is removed by reaction with limestone to produce solid calcium sulfate.

**Fluorocarbons.** [1] Carbon-fluorine compounds that often contain other elements such as hydrogen, chlorine, or bromine. Common fluorocarbons include chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). See *chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, perfluorocarbons.*

**Forcing mechanism.** [1] A process that alters the energy balance of the climate system (i.e., changes the relative balance between incoming solar radiation and outgoing infrared radiation from Earth). Such mechanisms include changes in solar irradiance, volcanic eruptions, and enhancement of the natural greenhouse effect by emission of carbon dioxide.

**Forest.** [7] Terrestrial ecosystem (biome) with enough average annual precipitation (at least 76 centimeters or 30 inches) to support growth of various species of trees and smaller forms of vegetation.

**Fossil fuel.** A general term for buried combustible geologic deposits of organic materials, formed from decayed plants and animals that have been converted to crude oil, coal, natural gas, or heavy oils by exposure to heat and pressure in the earth's crust over hundreds of millions of years. See *coal, petroleum, crude oil, natural gas.*

**Fossil fuel combustion.** [1] Burning of coal, oil (including gasoline), or natural gas. The burning needed to generate energy release carbon dioxide by-products that can include unburned hydrocarbons, methane, and carbon monoxide. Carbon monoxide, methane, and many of the unburned hydrocarbons slowly oxidize into carbon dioxide in the atmosphere. Common sources of fossil fuel combustion include cars and electric utilities.

**Freon.** See chlorofluorocarbon.

**Fugitive emissions.** [2] Unintended gas leaks from the processing, transmission, and/or transportation of fossil fuels, CFCs from refrigeration leaks, $SF_6$ from electrical power distributor, etc.

**Gasohol.** [7] Vehicle fuel consisting of a mixture of gasoline and ethyl or methyl alcohol; typically 10 to 23 percent ethanol by volume.

**General Aviation.** [8] That portion of civil aviation, which encompasses all facets of aviation except air carriers. It includes any air taxis, commuter air carriers, and air travel clubs, which do not hold Certificates of Public Convenience and Necessity. See *air carriers.*

**General circulation model (GCM).** [1] A global, three-dimensional computer model of the climate system which can be used to simulate human-induced climate change. GCMs are highly complex and they represent the effects of such factors as reflective and absorptive properties of atmospheric water vapor, greenhouse gas concentrations, clouds, annual and daily solar heating, ocean temperatures and ice boundaries. The most recent GCMs include global representations of the atmosphere, oceans, and land surface.

**Geosphere.** [1] The soils, sediments, and rock layers of the Earth's crust, both continental and beneath the ocean floors.

**Geothermal energy.** [7] Heat transferred from the earth's molten core to under-ground deposits of dry steam (steam with no water droplets), wet steam (a mixture of steam and water droplets), hot water, or rocks lying fairly close to the earth's surface.

**Global Warming Potential (GWP).** [1] The index used to translate the level of emissions of various gases into a common measure in order to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWPs are calculated as the ratio of the radiative forcing that would result from the emissions of one kilogram of a greenhouse gas to that from the emission of one

kilogram of carbon dioxide over a period of time (usually 100 years). Gases involved in complex atmospheric chemical processes have not been assigned GWPs. See *lifetime.*

**Global warming.** [10] The progressive gradual rise of the earth's surface temperature thought to be caused by the greenhouse effect and responsible for changes in global climate patterns. See *enhanced greenhouse effect, greenhouse effect, climate change.*

**Grassland.** [7] Terrestrial ecosystem (biome) found in regions where moderate annual average precipitation (25 to 76 centimeters or 10 to 30 inches) is enough to support the growth of grass and small plants but not enough to support large stands of trees.

**Greenhouse effect.** [7] Trapping and build-up of heat in the atmosphere (troposphere) near the earth's surface. Some of the heat flowing back toward space from the earth's surface is absorbed by water vapor, carbon dioxide, ozone, and several other gases in the atmosphere and then reradiated back toward the earth's surface. If the atmospheric concentrations of these greenhouse gases rise, the average temperature of the lower atmosphere will gradually increase. See *enhanced greenhouse effect, climate change, global warming.*

**Greenhouse gas (GHG).** [1] Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include, but are not limited to, water vapor, carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), hydrochlorofluorocarbons (HCFCs), ozone ($O_3$), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride ($SF_6$). See *carbon dioxide, methane, nitrous oxide, hydrochlorofluorocarbon, ozone, hydrofluorocarbon, perfluorocarbon, sulfur hexafluoride.*

**Halocarbons.** [1] Chemicals consisting of carbon, sometimes hydrogen, and either chlorine, fluorine, bromine or iodine.

**Halons.** [1] Compounds, also known as bromofluorocarbons, that contain bromine, fluorine, and carbon. They are generally used as fire extinguishing agents and cause ozone depletion. Bromine is many times more effective at destroying stratospheric ozone than chlorine. See *ozone depleting substance.*

**Heat.** [7] Form of kinetic energy that flows from one body to another when there is a temperature difference between the two bodies. Heat always flows spontaneously from a hot sample of matter to a colder sample of matter. This is one way to state the second law of thermodynamics. See *temperature.*

**Heat content.** [5] The amount of heat per unit mass released upon complete combustion.

**Heating Degree Days**: The number of degrees per day that the average daily temperature is below 65° Fahrenheit. The daily average temperature is the mean of the maximum and minimum temperatures for a 24 hour period. (See Degree Days)

**Higher heating value.** [5] Quantity of heat liberated by the complete combustion of a unit volume or weight of a fuel assuming that the produced water vapor is completely condensed and the heat is recovered; also known as gross calorific value. See *lower heating value.*

**Histosol.** [9] Wet organic soils, such as peats and mucks.

**Hydrocarbons.** [1] Substances containing only hydrogen and carbon. Fossil fuels are made up of hydrocarbons. Some hydrocarbon compounds are major air pollutants.

**Hydrochlorofluorocarbons (HCFCs).** [1] Compounds containing hydrogen, fluorine, chlorine, and carbon atoms. Although ozone depleting substances, they are less potent at destroying stratospheric ozone than chlorofluorocarbons (CFCs). They have been introduced as temporary replacements for CFCs and are also greenhouse gases. See *ozone depleting substance.*

**Hydroelectric power plant.** [7] Structure in which the energy of fading or flowing water spins a turbine generator to produce electricity.

**Hydrofluorocarbons (HFCs).** [1] Compounds containing only hydrogen, fluorine, and carbon atoms. They were introduced as alternatives to ozone depleting substances in serving many industrial, commercial, and personal needs. HFCs are emitted as by-products of industrial processes and are also used in manufacturing. They do not significantly deplete the stratospheric ozone layer, but they are powerful greenhouse gases with global warming potentials ranging from 140 (HFC-152a) to 11,700 (HFC-23).

**Hydrologic cycle.** The process of evaporation, vertical and horizontal transport of vapor, condensation, precipitation, and the flow of water from continents to oceans. It is a major factor in determining climate through its influence on surface vegetation, the clouds, snow and ice, and soil moisture. The hydrologic cycle is responsible for 25 to 30 percent of the mid-latitudes' heat transport from the equatorial to polar regions.

**Hydropower.** [7] Electrical energy produced by falling or flowing water. See *hydroelectric power plant.*

**Hydrosphere.** [7] All the earth's liquid water (oceans, smaller bodies of fresh water, and underground aquifers), frozen water (polar ice caps, floating ice, and frozen upper layer of soil known as permafrost), and small amounts of water vapor in the atmosphere.

**Industrial End-Use Sector:** Comprises manufacturing industries, which make up the largest part of the sector, along with mining, construction, agriculture, fisheries, and forestry. Establishments in this sector range from steel mills to small farms to companies assembling electronic components. Nonutility power producers are also included in the industrial end-use sector.

**Infrared radiation.** [1] The heat energy that is emitted from all solids, liquids, and gases. In the context of the greenhouse issue, the term refers to the heat energy emitted by the Earth's surface and its atmosphere. Greenhouse gases strongly absorb this radiation in the Earth's atmosphere, and re-radiate some of it back towards the surface, creating the greenhouse effect.

**Inorganic compound.** [7] Combination of two or more elements other than those used to form organic compounds. See *organic compound.*

**Inorganic fertilizer.** [7] See *synthetic fertilizer.*

**Intergovernmental Panel on Climate Change (IPCC).** [1] The IPCC was established jointly by the United Nations Environment Programme and the World Meteorological Organization in 1988. The purpose of the IPCC is to assess information in the scientific and technical literature related to all significant components of the issue of climate change. The IPCC draws upon hundreds of the world's expert scientists as authors and thousands as expert reviewers. Leading experts on climate change and environmental, social, and economic sciences from some 60 nations have helped the IPCC to prepare periodic assessments of the scientific underpinnings for understanding global climate change and its consequences. With its capacity for reporting on climate change, its consequences, and the viability of adaptation and mitigation measures, the IPCC is also looked to as the official advisory body to the world's governments on the state of the science of the climate change issue. For example, the IPCC organized the development of internationally accepted methods for conducting national greenhouse gas emission inventories.

**Irreversibilities.** [10] Changes that, once set in motion, cannot be reversed, at least on human time scales.

**Jet fuel** [8] Includes both naphtha-type and kerosene-type fuels meeting standards for use in aircraft turbine engines. Although most jet fuel is used in aircraft, some is used for other purposes such as generating electricity.

**Joule.** [1] The energy required to push with a force of one Newton for one meter.

**Kerogen.** [7] Solid, waxy mixture of hydrocarbons found in oil shale, with a fine grained sedimentary rock. When the rock is heated to high temperatures, the kerogen is vaporized. The vapor is condensed and then sent to a refinery to produce gasoline, heating oil, and other products. See *oil shale, shale oil.*

**Kerosene.** [2] A petroleum distillate that has a maximum distillation temperature of 401 degrees Fahrenheit at the 10 percent recovery point, a final boiling point of 572 degrees Fahrenheit, and a minimum flash point of 100 degrees Fahrenheit. Used in space heaters, cookstoves, and water heaters, and suitable for use as an illuminant when burned in wick lamps.

**Kyoto Protocol.** [10] This is an international agreement struck by 159 nations attending the Third Conference of Parties (COP) to the United Nations Framework Convention on Climate Change (held in December of 1997 in Kyoto Japan) to reduce worldwide emissions of greenhouse gases. If ratified and put into force, individual countries have committed to reduce their greenhouse gas emissions by a specified amount. See *Framework Convention on Climate Change, Conference of Parties.*

**Landfill.** [7] Land waste disposal site in which waste is generally spread in thin layers, compacted, and covered with a fresh layer of soil each day.

**Lifetime (atmospheric).** [1] The lifetime of a greenhouse gas refers to the approximate amount of time it would take for the anthropogenic increment to an atmospheric pollutant concentration to return to its natural level (assuming emissions cease) as a result of either being converted to another chemical compound or being taken out of the atmosphere via a sink. This time depends on the pollutant's sources and sinks as well as its reactivity. The lifetime of a pollutant is often considered in conjunction with the mixing of pollutants in the atmosphere; a long lifetime will allow the pollutant to mix throughout the atmosphere. Average lifetimes can vary from about a week (e.g., sulfate aerosols) to more than a century (e.g., CFCs, carbon dioxide). See *residence time.*

**Light-duty vehicles.** [8] Automobiles and light trucks combined.

**Lignite.** [2] A brownish-black coal of low rank with high inherent moisture and volatile matter content, used almost exclusively for electric power generation. Also referred to as brown coal.

**Liquefied natural gas (LNG).** [7] Natural gas converted to liquid form by cooling to a very low temperature.

**Liquefied petroleum gas (LPG).** [2] Ethane, ethylene, propane, propylene, normal butane, butylene, and isobutane produced at refineries or natural gas processing plants, including plants that fractionate new natural gas plant liquids.

**Litter.** [9] Undecomposed plant residues on the soil surface. See *decomposition.*

**Longwave radiation.** [9] The radiation emitted in the spectral wavelength greater than 4 micrometers corresponding to the radiation emitted from the Earth and atmosphere. It is sometimes referred to as terrestrial radiation or infrared radiation, although somewhat imprecisely. See *infrared radiation.*

**Low Emission Vehicle (LEV).** [8] A vehicle meeting the low-emission vehicle standards.

**Lower heating value.** [5] Quantity of heat liberated by the complete combustion of a unit volume or weight of a fuel assuming that the produced water remains as a vapor and the heat of the vapor is not recovered; also known as net calorific value. See *higher heating value.*

**Lubricant.** [2] A substance used to reduce friction between bearing surfaces or as a process material, either incorporated into other materials used as aids in manufacturing processes or as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Other substances may be added to impart or improve useful properties. Does not include by-products of lubricating oil from solvent extraction or tars derived from de-asphalting. Lubricants include all grades of lubricating oils from spindle oil to cylinder oil and those used in greases. Lubricant categories are paraffinic and naphthenic.

**Manure.** [7] Dung and urine of animals that can be used as a form of organic fertilizer.

**Mass balance.** [9] The application of the principle of the conservation of matter.

**Mauna Loa.** [9] An intermittently active volcano 13,680 feet (4,170 meters) high in Hawaii.

**Methane ($CH_4$).** [1] A hydrocarbon that is a greenhouse gas with a global warming potential most recently estimated at 21. Methane is produced through anaerobic (without oxygen) decomposition of waste in landfills, animal digestion, decomposition of animal wastes, production and distribution of natural gas and petroleum, coal production, and incomplete fossil fuel combustion. The atmospheric concentration of methane as been shown to be increasing at a rate of about 0.6 percent per year and the concentration of about 1.7 per million by volume (ppmv) is more than twice its pre-industrial value. However, the rate of increase of methane in the atmosphere may be stabilizing.

**Methanol ($CH_3OH$).** [8] A colorless poisonous liquid with essentially no odor and little taste. It is the simplest alcohol with a boiling point of 64.7 degrees Celsius. In transportation, methanol is used as a vehicle fuel by itself (M100), or blended with gasoline (M85).

**Methanotrophic.** [7] Having the biological capacity to oxidize methane to $CO_2$ and water by metabolism under aerobic conditions. See *aerobic.*

**Methyl bromide ($CH_3Br$).** [11] An effective pesticide; used to fumigate soil and many agricultural products. Because it contains bromine, it depletes stratospheric ozone when released to the atmosphere. See *ozone depleting substance.*

**Metric ton.** [1] Common international measurement for the quantity of greenhouse gas emissions. A metric ton is equal to 1000 kilograms, 2204.6 pounds, or 1.1023 short tons.

**Mineral.** [7] Any naturally occurring inorganic substance found in the earth's crust as a crystalline solid.

**Model year.** [8] Refers to the "sales" model year; for example, vehicles sold during the period from October 1 to the next September 31 is considered one model year.

**Molecule.** [7] Chemical combination of two or more atoms of the same chemical element (such as $O_2$) or different chemical elements (such as $H_2O$).

**Montreal Protocol on Substances that Deplete the Ozone Layer.** [11] The Montreal Protocol and its amendments control the phaseout of ozone depleting substances production and use. Under the Protocol, several international organizations report on the science of ozone depletion, implement projects to help move away from ozone depleting substances, and provide a forum for policy discussions. In the United States, the Protocol is implemented under the rubric of the Clean Air Act Amendments of 1990. See *ozone depleting substance, ozone layer.*

**Motor gasoline.** [2] A complex mixture of relatively volatile hydrocarbons, with or without small quantities of additives, obtained by blending appropriate refinery streams to form a fuel suitable for use in spark-ignition engines. Motor gasoline includes both leaded and unleaded grades of finished gasoline, blending components, and gasohol.

**Municipal solid waste (MSW).** [2] Residential solid waste and some non-hazardous commercial, institutional, and industrial wastes. This material is generally sent to municipal landfills for disposal. See *landfill.*

**Naphtha.** [2] A generic term applied to a petroleum fraction with an approximate boiling range between 122 and 400 degrees Fahrenheit.

**Natural gas.** [7] Underground deposits of gases consisting of 50 to 90 percent methane ($CH_4$) and small amounts of heavier gaseous hydrocarbon compounds such as propane ($C_3H_4$) and butane ($C_4H_{10}$).

**Natural gas liquids (NGLs).** [2] Those hydrocarbons in natural gas that are separated as liquids from the gas. Includes natural gas plant liquids and lease condensate.

**Nitrogen cycle.** [7] Cyclic movement of nitrogen in different chemical forms from the environment, to organisms, and then back to the environment.

**Nitrogen fixation.** [7] Conversion of atmospheric nitrogen gas into forms useful to plants and other organisms by lightning, bacteria, and blue-green algae; it is part of the nitrogen cycle.

**Nitrogen oxides ($NO_x$).** [1] Gases consisting of one molecule of nitrogen and varying numbers of oxygen molecules. Nitrogen oxides are produced, for example, by the combustion of fossil fuels in vehicles and electric power plants. In the atmosphere, nitrogen oxides can contribute to formation of photochemical ozone (smog), impair visibility, and have health consequences; they are considered pollutants.

**Nitrous oxide ($N_2O$).** [1] A powerful greenhouse gas with a global warming potential most recently evaluated at 310. Major sources of nitrous oxide include soil cultivation practices, especially the use of commercial and organic fertilizers, fossil fuel combustion, nitric acid production, and biomass burning.

**Nonbiodegradable.** [7] Substance that cannot be broken down in the environment by natural processes. See *biodegradable.*

**Nonlinearities.** [10] Occur when changes in one variable cause a more than proportionate impact on another variable.

**Non-methane volatile organic compounds (NMVOCs).** [2] Organic compounds, other than methane, that participate in atmospheric photochemical reactions.

**Non-point source.** [7] Large land area such as crop fields and urban areas that discharge pollutant into surface and underground water over a large area. See *point source.*

**Nonutility Power Producer:** A corporation, person, agency, authority, or other legal entity of instrumentality that owns electric generating capacity and is not an electric utility. Nonutility producers include qualifying cogenerators, qualifying small power producers, and other nonutility generators (including independent power

producers) without a designated, franchised, service area that do not file forms listed in the Code of Federal Regulations, Title 18, Part 141.

**Nuclear electric power.** [3] Electricity generated by an electric power plant whose turbines are driven by steam generated in a reactor by heat from the fissioning of nuclear fuel.

**Nuclear energy.** [7] Energy released when atomic nuclei undergo a nuclear reaction such as the spontaneous emission of radioactivity, nuclear fission, or nuclear fusion.

**Oil shale.** [7] Underground formation of a fine-grained sedimentary rock containing varying amounts of kerogen, a solid, waxy mixture of hydrocarbon compounds. Heating the rock to high temperatures converts the kerogen to a vapor, which can be condensed to form a slow flowing heavy oil called shale oil. See *kerogen, shale oil.*

**Oil.** See crude oil, petroleum.

**Ore.** [7] Mineral deposit containing a high enough concentration of at least one metallic element to permit the metal to be extracted and sold at a profit.

**Organic compound.** [7] Molecule that contains atoms of the element carbon, usually combined with itself and with atoms of one or more other element such as hydrogen, oxygen, nitrogen, sulfur, phosphorus, chlorine, or fluorine. See *inorganic compound.*

**Organic fertilizer.** [7] Organic material such as manure or compost, applied to cropland as a source of plant nutrients.

**Oxidize.** [2] To chemically transform a substance by combining it with oxygen.

**Oxygen cycle.** [7] Cyclic movement of oxygen in different chemical forms from the environment, to organisms, and then back to the environment.

**Ozone.** [6] A colorless gas with a pungent odor, having the molecular form of $O_3$, found in two layers of the atmosphere, the stratosphere and the troposphere. Ozone is a form of oxygen found naturally in the stratosphere that provides a protective layer shielding the Earth from ultraviolet radiation's harmful health effects on humans and the environment. In the troposphere, ozone is a chemical oxidant and major component of photochemical smog. Ozone can seriously affect the human respiratory system.

**Ozone Depleting Substance (ODS).** [11] A family of man-made compounds that includes, but are not limited to, chlorofluorocarbons (CFCs), bromofluorocarbons (halons), methyl chloroform, carbon tetrachloride, methyl bromide, and hydrochlorofluorocarbons (HCFCs). These compounds have been shown to deplete stratospheric ozone, and therefore are typically referred to as ODSs.

**Ozone layer.** [7] Layer of gaseous ozone ($O_3$) in the stratosphere that protects life on earth by filtering out harmful ultraviolet radiation from the sun. See *stratosphere, ultraviolet radiation.*

**Ozone precursors.** [2] Chemical compounds, such as carbon monoxide, methane, non-methane hydrocarbons, and nitrogen oxides, which in the presence of solar radiation react with other chemical compounds to form ozone, mainly in the troposphere. See *troposphere*

**Particulate matter (PM).** [7] Solid particles or liquid droplets suspended or carried in the air.

**Particulates.** See *particulate matter.*

**Parts per billion (ppb).** [7] Number of parts of a chemical found in one billion parts of a particular gas, liquid, or solid mixture. See *concentration.*

**Parts per million (ppm).** [7] Number of parts of a chemical found in one million parts of a particular gas, liquid, or solid. See *concentration.*

**Pentanes plus.** [2] A mixture of hydrocarbons, mostly pentanes and heavier fractions, extracted from natural gas.

**Perfluorocarbons (PFCs).** [1] A group of human-made chemicals composed of carbon and fluorine only. These chemicals (predominantly $CF_4$ and $C_2F_6$) were introduced as alternatives, along with hydrofluorocarbons, to the ozone depleting substances. In addition, PFCs are emitted as by-products of industrial processes and are also used in manufacturing. PFCs do not harm the stratospheric ozone layer, but they are powerful greenhouse gases: $CF_4$ has a global warming potential (GWP) of 6,500 and $C_2F_6$ has a GWP of 9,200.

**Petrochemical feedstock.** [2] Feedstock derived from petroleum, used principally for the manufacture of chemicals, synthetic rubber, and a variety of plastics. The categories reported are naphtha (endpoint less than 401 degrees Fahrenheit) and other oils (endpoint equal to or greater than 401 degrees Fahrenheit).

**Petrochemicals.** [7] Chemicals obtained by refining (i.e., distilling) crude oil. They are used as raw materials in the manufacture of most industrial chemicals, fertilizers, pesticides, plastics, synthetic fibers, paints, medicines, and many other products. See *crude oil.*

**Petroleum coke.** [2] A residue that is the final product of the condensation process in cracking.

**Petroleum.** [2] A generic term applied to oil and oil products in all forms, such as crude oil, lease condensate, unfinished oils, petroleum products, natural gas plant liquids, and non-hydrocarbon compounds blended into finished petroleum products. See *crude oil.*

**Photosynthesis.** [7] Complex process that takes place in living green plant cells. Radiant energy from the sun is used to combine carbon dioxide ($CO_2$) and water ($H_2O$) to produce oxygen ($O_2$) and simple nutrient molecules, such as glucose ($C_6H_{12}O_6$).

**Photovoltaic and solar thermal energy.** [2] Energy radiated by the sun as electromagnetic waves (electromagnetic radiation) that is converted into electricity by means of solar (i.e., photovoltaic) cells or useable heat by concentrating (i.e., focusing) collectors.

**Point source.** [7] A single identifiable source that discharges pollutants into the environment. Examples are smokestack, sewer, ditch, or pipe. See *non-point source.*

**Pollution.** [7] A change in the physical, chemical, or biological characteristics of the air, water, or soil that can affect the health, survival, or activities of humans in an unwanted way. Some expand the term to include harmful effects on all forms of life.

**Polyvinyl chloride (PVC).** [2] A polymer of vinyl chloride. It is tasteless, odorless and insoluble in most organic solvents. A member of the family vinyl resin, used in soft flexible films for food packaging and in molded rigid products, such as pipes, fibers, upholstery, and bristles.

**Population.** [7] Group of individual organisms of the same species living within a particular area.

**Prescribed burning.** [7] Deliberate setting and careful control of surface fires in forests to help prevent more destructive fires and to kill off unwanted plants that compete with commercial species for plant nutrients; may also be used on grasslands.

**Primary oil recovery.** [7] Pumping out the crude oil that flows by gravity into the bottom of an oil well. See *enhanced oil recovery, secondary oil recovery.*

**Quad.** [8] Quad stands for quadrillion, which is, $10^{15}$.

**Radiation.** [1] Energy emitted in the form of electromagnetic waves. Radiation has differing characteristics depending upon the wavelength. Because the radiation from the Sun is relatively energetic, it has a short wavelength (e.g., ultraviolet, visible, and near infrared) while energy re-radiated from the Earth's surface and the atmosphere has a longer wavelength (e.g., infrared radiation) because the Earth is cooler than the Sun. See *ultraviolet radiation, infrared radiation, solar radiation, longwave radiation, terrestrial radiation.*

**Radiative forcing.** [1] A change in the balance between incoming solar radiation and outgoing infrared (i.e., thermal) radiation. Without any radiative forcing, solar radiation coming to the Earth would continue to be approximately equal to the infrared radiation emitted from the Earth. The addition of greenhouse gases to the atmosphere traps an increased fraction of the infrared radiation, reradiating it back toward the surface of the Earth and thereby creates a warming influence.

**Rail.** [8] Includes "heavy" and "light" transit rail. Heavy transit rail is characterized by exclusive rights-of-way, multi-car trains, high speed rapid acceleration, sophisticated signaling, and high platform loading. Also known as subway, elevated railway, or metropolitan railway (metro). Light transit rail may be on exclusive or shared rights of way, high or low platform, multi-car trains or single cars, automated or manually operated. In generic usage, light rail includes streetcars, trolley cars, and tramways.

**Rangeland.** [7] Land, mostly grasslands, whose plants can provide food (i.e., forage) for grazing or browsing animals. See *feedlot.*

**Recycling.** [7] Collecting and reprocessing a resource so it can be used again. An example is collecting aluminum cans, melting them down, and using the aluminum to make new cans or other aluminum products.

**Reforestation.** [2] Replanting of forests on lands that have recently been harvested.

**Renewable energy.** [2] Energy obtained from sources that are essentially inexhaustible, unlike, for example, the fossil fuels, of which there is a finite supply. Renewable sources of energy include wood, waste, geothermal, wind, photovoltaic, and solar thermal energy. See *hydropower, photovoltaic.*

**Residence time.** [1] Average time spent in a reservoir by an individual atom or molecule. Also, this term is used to define the age of a molecule when it leaves the reservoir. With respect to greenhouse gases, residence time usually refers to how long a particular molecule remains in the atmosphere. See *lifetime.*

**Residential End-Use Sector:** Consists of all private residences, whether occupied or vacant, owned or rented, including single family homes, multifamily housing units, and mobile homes. Secondary home, such as summer homes, are also included. Institutional housing, such as school dormitories, hospitals, and military barracks, generally are not included in the residential end-use sector, but are instead included in the commercial end-use sector.

**Residual fuel oil.** [2] The heavier oils that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations and that conform to ASTM Specifications D396 and D975. Included are No. 5, a residual fuel oil of medium viscosity; Navy Special, for use in steam-powered vessels in government service and in shore power plants; and No. 6, which includes Bunker C fuel oil and is used for commercial and industrial heating, electricity generation, and to power ships. Imports of residual fuel oil include imported crude oil burned as fuel.

**Secondary oil recovery.** [7] Injection of water into an oil well after primary oil recovery to force out some of the remaining thicker crude oil. See *enhanced oil recovery, primary oil recovery.*

**Sector.** Division, most commonly used to denote type of energy consumer (e.g., residential) or according to the Intergovernmental Panel on Climate Change, the type of greenhouse gas emitter (e.g. industrial process). See *Intergovernmental Panel on Climate Change.*

**Septic tank.** [7] Underground tank for treatment of wastewater from a home in rural and suburban areas. Bacteria in the tank decompose organic wastes and the sludge settles to the bottom of the tank. The effluent flows out of the tank into the ground through a field of drainpipes.

**Sewage treatment (primary).** [7] Mechanical treatment of sewage in which large solids are filtered out by screens and suspended solids settle out as sludge in a sedimentation tank.

**Shale oil.** [7] Slow-flowing, dark brown, heavy oil obtained when kerogen in oil shale is vaporized at high temperatures and then condensed. Shale oil can be refined to yield gasoline, heating oil, and other petroleum products. See *kerogen, oil shale.*

**Short ton.** [1] Common measurement for a ton in the United States. A short ton is equal to 2,000 lbs. or 0.907 metric tons.

**Sink.** [1] A reservoir that uptakes a pollutant from another part of its cycle. Soil and trees tend to act as natural sinks for carbon.

**Sludge.** [7] Gooey solid mixture of bacteria and virus laden organic matter, toxic metals, synthetic organic chemicals, and solid chemicals removed from wastewater at a sewage treatment plant.

**Soil.** [7] Complex mixture of inorganic minerals (i.e., mostly clay, silt, and sand), decaying organic matter, water, air, and living organisms.

**Soil carbon.** [9] A major component of the terrestrial biosphere pool in the carbon cycle. The amount of carbon in the soil is a function of the historical vegetative cover and productivity, which in turn is dependent in part upon climatic variables.

**Solar energy.** [7] Direct radiant energy from the sun. It also includes indirect forms of energy such as wind, falling or flowing water (hydropower), ocean thermal gradients, and biomass, which are produced when direct solar energy interact with the earth. See *solar radiation.*

**Solar radiation.** [1] Energy from the Sun. Also referred to as short-wave radiation. Of importance to the climate system, solar radiation includes ultra-violet radiation, visible radiation, and infrared radiation.

**Source.** [4] Any process or activity that releases a greenhouse gas, an aerosol, or a precursor of a greenhouse gas into the atmosphere.

**Special naphtha.** [2] All finished products within the naphtha boiling range that are used as paint thinners, cleaners, or solvents. Those products are refined to a specified flash point.

**Still gas.** [2] Any form or mixture of gases produced in refineries by distillation, cracking, reforming, and other processes. Principal constituents are methane, ethane, ethylene, normal butane, butylene, propane, propylene, etc. Used as a refinery fuel and as a petrochemical feedstock.

**Stratosphere.** [7] Second layer of the atmosphere, extending from about 19 to 48 kilometers (12 to 30 miles) above the earth's surface. It contains small amounts of gaseous ozone ($O_3$), which filters out about 99 percent of the incoming harmful ultraviolet (UV) radiation. Most commercial airline flights operate at a cruising altitude in the lower stratosphere. See *ozone layer, ultraviolet radiation.*

**Stratospheric ozone.** See *ozone layer.*

**Strip mining.** [7] Cutting deep trenches to remove minerals such as coal and phosphate found near the earth's surface in flat or rolling terrain. See *surface mining.*

**Subbituminous coal.** [2] A dull, black coal of rank intermediate between lignite and bituminous coal.

**Sulfur cycle.** [7] Cyclic movement of sulfur in different chemical forms from the environment, to organisms, and then back to the environment.

**Sulfur dioxide ($SO_2$).** [1] A compound composed of one sulfur and two oxygen molecules. Sulfur dioxide emitted into the atmosphere through natural and anthropogenic processes is changed in a complex series of chemical reactions in the atmosphere to sulfate aerosols. These aerosols are believed to result in negative radiative forcing (i.e., tending to cool the Earth's surface) and do result in acid deposition (e.g., acid rain). See *aerosols, radiative forcing, acid deposition, acid rain.*

**Sulfur hexafluoride ($SF_6$).** [1] A colorless gas soluble in alcohol and ether, slightly soluble in water. A very powerful greenhouse gas used primarily in electrical transmission and distribution systems and as a dielectric in electronics. The global warming potential of $SF_6$ is 23,900. See *Global Warming Potential.*

**Surface mining.** [7] Removal of soil, sub-soil, and other strata and then extracting a mineral deposit found fairly close to the earth's surface. See *strip mining.*

**Synthetic fertilizer.** [7] Commercially prepared mixtures of plant nutrients such as nitrates, phosphates, and potassium applied to the soil to restore fertility and increase crop yields. See *organic fertilizer.*

**Synthetic natural gas (SNG).** [3] A manufactured product chemically similar in most respects to natural gas, resulting from the conversion or reforming of petroleum hydrocarbons. It may easily be substituted for, or interchanged with, pipeline quality natural gas.

**Tailings.** [7] Rock and other waste materials removed as impurities when minerals are mined and mineral deposits are processed. These materials are usually dumped on the ground or into ponds.

**Tar sand.** [7] Swamp-like deposit of a mixture of fine clay, sand, water, and variable amounts of tar-like heavy oil known as bitumen. Bitumen can be extracted from tar sand by heating. It can then be purified and upgraded to synthetic crude oil. See *bitumen.*

**Temperature.** [7] Measure of the average speed of motion of the atoms or molecules in a substance or combination of substances at a given moment. See *heat.*

**Terrestrial.** [7] Pertaining to land.

**Terrestrial radiation.** [9] The total infrared radiation emitted by the Earth and its atmosphere in the temperature range of approximately 200 to 300 Kelvin. Terrestrial radiation provides a major part of the potential energy changes necessary to drive the atmospheric wind system and is responsible for maintaining the surface air temperature within limits of livability.

**Trace gas.** [1] Any one of the less common gases found in the Earth's atmosphere. Nitrogen, oxygen, and argon make up more than 99 percent of the Earth's atmosphere. Other gases, such as carbon dioxide, water vapor, methane, oxides of nitrogen, ozone, and ammonia, are considered trace gases. Although relatively unimportant in terms of their absolute volume, they have significant effects on the Earth's weather and climate.

**Transportation End-Use Sector**: Consists of private and public vehicles that move people and commodities. Included are automobiles, trucks, buses, motorcycles, railroads and railways (including streetcars and subways), aircraft, ships, barges, and natural gas pipelines.

**Troposphere.** [1&7] The lowest layer of the atmosphere and contains about 95 percent of the mass of air in the Earth's atmosphere. The troposphere extends from the Earth's surface up to about 10 to 15 kilometers. All weather processes take place in the troposphere. Ozone that is formed in the troposphere plays a significant role in both the greenhouse gas effect and urban smog. See *ozone precursor, stratosphere, atmosphere.*

**Tropospheric ozone precursor.** See *ozone precursor.*

**Tropospheric ozone.** [1] See *ozone.*

**Ultraviolet radiation (UV).** [11] A portion of the electromagnetic spectrum with wavelengths shorted than visible light. The sun produces UV, which is commonly split into three bands of decreasing wavelength. Shorter wavelength radiation has a greater potential to cause biological damage on living organisms. The longer wavelength ultraviolet band, UVA, is not absorbed by ozone in the atmosphere. UVB is mostly absorbed by ozone, although some reaches the Earth. The shortest wavelength band, UVC, is completely absorbed by ozone and normal oxygen in the atmosphere.

**Unfinished oils.** [3] All oils requiring further refinery processing, except those requiring only mechanical blending. Includes naphtha and lighter oils, kerosene and light gas oils, heavy gas oils, and residuum.

**United Nations Framework Convention on Climate Change (UNFCCC).** [1] The international treaty unveiled at the United Nations Conference on Environment and Development (UNCED) in June 1992. The UNFCCC commits signatory countries to stabilize anthropogenic (i.e. human-induced) greenhouse gas emissions to "levels that would prevent dangerous anthropogenic interference with the climate system". The UNFCCC also requires that all signatory parties develop and update national inventories of anthropogenic emissions of all greenhouse gases not otherwise controlled by the Montreal Protocol. Out of 155 countries that have ratified this accord, the United States was the first industrialized nation to do so.

**Vehicle miles traveled (VMT).** [8] One vehicle traveling the distance of one mile. Thus, total vehicle miles is the total mileage traveled by all vehicles.

**Volatile organic compounds (VOCs).** [6] Organic compounds that evaporate readily into the atmosphere at normal temperatures. VOCs contribute significantly to photochemical smog production and certain health problems. See *non-methane volatile organic compounds.*

**Wastewater.** [2] Water that has been used and contains dissolved or suspended waste materials. See *sewage treatment.*

**Water vapor.** [1] The most abundant greenhouse gas; it is the water present in the atmosphere in gaseous form. Water vapor is an important part of the natural greenhouse effect. While humans are not significantly increasing its concentration, it contributes to the enhanced greenhouse effect because the warming influence of greenhouse gases leads to a positive water vapor feedback. In addition to its role as a natural greenhouse gas, water vapor plays an important role in regulating the temperature of the planet because clouds form when excess water vapor in the atmosphere condenses to form ice and water droplets and precipitation.

**Waxes.** [2] Solid or semisolid materials derived from petroleum distillates or residues. Light-colored, more or less translucent crystalline masses, slightly greasy to the touch, consisting of a mixture of solid hydrocarbons in which the paraffin series predominates. Included are all marketable waxes, whether crude scale or fully refined. Used primarily as industrial coating for surface protection.

**Weather.** [1] Weather is the specific condition of the atmosphere at a particular place and time. It is measured in terms of such things as wind, temperature, humidity, atmospheric pressure, cloudiness, and precipitation. In most places, weather can change from hour-to-hour, day-to-day, and season-to-season. Climate is the average

of weather over time and space. A simple way of remembering the difference is that climate is what you expect (e.g. cold winters) and 'weather' is what you get (e.g. a blizzard). See *climate.*

**Wetland.**[7] Land that stays flooded all or part of the year with fresh or salt water.

**Wetlands.**[2] Areas regularly saturated by surface or groundwater and subsequently characterized by a prevalence of vegetation adapted for life in saturated-soil conditions.

**Wood energy.**[2] Wood and wood products used as fuel, including roundwood (i.e., cordwood), limbwood, wood chips, bark, sawdust, forest residues, and charcoal.

## References


[1] U.S. Environmental Protection Agency, Global Warming website, <http://www.epa.gov/globalwarming>. February 26, 1999.

[2] Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97), U.S. Department of Energy, Washington, DC. October 1998. [See< http://www.eia.doe.gov>]

[3] Energy Information Administration, *Annual Energy Review 1997*, DOE/EIA-0387(97), U.S. Department of Energy, Washington, DC., July 1998.

[4] United Nations Framework Convention on Climate Change. [See <http://www.unfccc.de>]

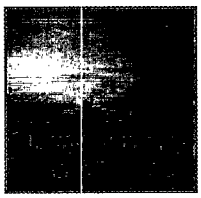
[5] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change*, Cambridge University Press: New York, 1996

[6] *Cooper's Comprehensive Environmental Desk Reference*, Arthur R. Cooper, Sr., Van Nostrand Reinhold: New York, 1996.

[7] Miller, G. Tyler, Jr., *Living in the Environment, An Introduction to Environment Science*, sixth edition, 1990.

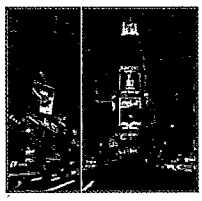
[8] Davis, Stacy, *Transportation Energy Data Book*, Oak Ridge National Laboratory, U.S. Department of Energy, Edition 17, 1997.

**Industrial:** The industrial economic sector is the only economic sector to exhibit a decrease in emissions between 1990 and 2000. The majority of emissions are comprised of $CO_2$ from fossil fuel combustion, although more than 25 specific industrial processes contribute to greenhouse gas emissions from this sector.



**Transportation:** This economic sector has been steadily increasing from 1990 through 2000 due to several factors, including population growth, urban sprawl, low fuel prices, decreased average fuel efficiency, increased air travel and freight transportation. While transportation emissions are mostly from vehicles on the roads, they also come from airplanes, boats, trains, and other equipment.

**Electricity Generation at Power Plants:** Electricity generation in the United States is composed of traditional electric utilities, cogenerators, and nonutility power producers. This economic sector includes the generation, transmission, and distribution of electricity. Emissions result primarily in the form of $CO_2$ from fossil fuel combustion. Electricity generation accounts for over one-third of all U.S. greenhouse gas emissions, and is the largest of the economic sectors.



**Commercial:** Like most of the other economic sectors, commercial emissions are derived mainly from $CO_2$ emissions from the combustion of fossil fuels used to supply businesses with heat and electricity. Other types of emissions that result from this economic sector come from the use of landfills, combustion of waste, leaks from the use of refrigerants, and stationary combustion.

EPA

United States
Enviromental Protection
Agency

EPA 430-R-02-003 April 2002
Office of Atmospheric Programs (6204N)
Washington, DC 20460

Official Business
Penalty for Private Use
$300