Annexes

The following seven annexes provide additional information related to the material presented in the main body of this report as directed in the *UNFCCC Guidelines on Reporting and Review* (GE.03-60887). Annex 1 contains an analysis of the key categories of emissions discussed in this report and a review of the methodology used to identify those key categories. Annex 2 describes the methodologies used to estimate CO_2 emissions from fossil fuel combustion, the carbon content of fossil fuels, and the amount of carbon stored in products from non-energy uses of fossil fuels. Annex 3 discusses the methodologies used for a number of individual source categories in greater detail than was presented in the main body of the report and includes explicit activity data and emission factor tables. Annex 4 presents the IPCC reference approach for estimating CO_2 emissions from fossil fuel combustion. Annex 5 addresses the criteria for the inclusion of an emission source category and discusses some of the sources that are excluded from U.S. estimates. Annex 6 provides a range of additional information that is relevant to the contents of this report. Finally, Annex 7 provides data on the uncertainty of the emission estimates included in this report.

ANNEX 1 Key Category Analysis

The United States has identified national key categories based on the estimates presented in this report. The IPCC's *Good Practice Guidance* (IPCC 2000) describes a key category as a "[category] that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both."[1] By definition, key categories are sources or sinks that have the greatest contribution to the absolute overall level of national emissions in any of the years covered by the time series. In addition, when an entire time series of emission estimates is prepared, a determination of key categories must also account for the influence of the trends of individual categories. Therefore, a trend assessment is conducted to identify source and sink categories for which significant uncertainty in the estimate would have considerable effects on overall emission trends. Finally, a qualitative evaluation of key categories should be performed, in order to capture any key categories that were not identified in either of the quantitative analyses, but can be considered key because of the unique country-specific estimation methods.

The methodology for conducting a key category analysis, as defined by IPCC's *Good Practice Guidance* (IPCC 2000), IPCC's *Good Practice Guidance for Land Use, Land-Use Change, and Forestry (IPCC 2003)*, and IPCC's *2006 Guidelines for National Greenhouse Gas Inventories* IPCC (2006); 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.

This Annex presents an analysis of key categories, both for sources only and also for sources and sinks (i.e., including LULUCF); discusses Tier 1, Tier 2, and qualitative approaches to identifying key categories; provides level and trend assessment equations; and provides a brief statistical evaluation of IPCC's quantitative methodologies for defining key categories. Table A- 1 presents the key categories for the United States (including and excluding LULUCF categories) using emissions and uncertainty data in this report, and ranked according to their sector and global warming potential-weighted emissions in 2009. The table also indicates the criteria used in identifying these categories (i.e., level, trend, Tier 1, Tier 2, and/or qualitative assessments).

Table A-1: Key Source Categories for the United States (1990-2009)

IPCC Source Categories	Gas	Tier 1				Tier 2				Qual[a]	2009 Emissions (Tg CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF		
Energy											
CO_2 Emissions from Stationary Combustion - Coal	CO_2	•		•	•	•		•	•		1,841.0
CO_2 Emissions from Mobile Combustion: Road	CO_2	•	•	•	•	•	•	•	•		1,475.6
CO_2 Emissions from Stationary Combustion - Gas	CO_2	•	•	•	•	•	•	•	•		1,164.6
CO_2 Emissions from Stationary Combustion - Oil	CO_2	•	•	•	•	•	•	•	•		483.3
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	•	•	•	•	•	•	•	•		140.7
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	•		•	•	•		•			123.4
CO_2 Emissions from Mobile Combustion: Other	CO_2	•	•	•	•						73.5
CO_2 Emissions from Natural Gas Systems	CO_2	•	•	•	•	•	•	•	•		32.2
CO_2 Emissions from Mobile Combustion: Marine	CO_2	•	•	•	•						30.0
Fugitive Emissions from Natural Gas Systems	CH_4	•	•	•	•	•	•	•	•		221.2
Fugitive Emissions from Coal Mining	CH_4	•	•	•	•	•	•	•	•		71.0
Fugitive Emissions from Petroleum Systems	CH_4	•	•	•	•	•	•	•	•		30.9
Non-CO_2 Emissions from Stationary Combustion	CH_4					•		•			6.2
N_2O Emissions from Mobile Combustion: Road	N_2O	•	•	•	•		•		•		20.3
Non-CO_2 Emissions from Stationary Combustion	N_2O					•		•			12.8
International Bunker Fuels[b]	Several									•	124.4
Industrial Processes											
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	•	•	•	•	•	•	•	•		41.9
CO_2 Emissions from Cement Production	CO_2		•	•	•						29.0
CO_2 Emissions from Ammonia Production and Urea Consumption	CO_2		•		•						11.8
CO_2 Emissions from Aluminum Production	CO_2										3.0
N_2O Emissions from Nitric Acid Production	N_2O				•		•				14.6
N_2O Emissions from Adipic Acid Production	N_2O		•		•		•		•		1.9
Emissions from Substitutes for Ozone Depleting Substances	HiGWP	•	•	•	•		•	•	•		120.0
SF_6 Emissions from Electrical Transmission and Distribution	HiGWP		•		•		•		•		12.8
HFC-23 Emissions from HCFC-22 Production	HiGWP	•	•	•	•		•		•		5.4
PFC Emissions from Aluminum Production	HiGWP		•		•		•				1.6
SF_6 Emissions from Magnesium Production and Processing	HiGWP		•		•						1.1
Agriculture											
CH_4 Emissions from Enteric Fermentation	CH_4	•		•		•		•			139.8
CH_4 Emissions from Manure Management	CH_4	•	•	•	•		•		•		49.5
CH_4 Emissions from Rice Cultivation	CH_4					•		•			7.3
Direct N_2O Emissions from Agricultural Soil Management	N_2O	•	•	•	•	•	•	•	•		160.2
Indirect N_2O Emissions from Applied Nitrogen	N_2O	•		•		•	•	•	•		44.4
Waste											

IPCC Source Categories	Gas	Tier 1				Tier 2				Qual[a]	2009 Emissions (Tg CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF		
CH_4 Emissions from Landfills	CH_4	•	•	•	•	•	•	•	•		117.5
CH_4 Emissions from Wastewater Treatment	CH_4					•		•			24.5
Land Use, Land Use Change, and Forestry											
CO_2 Emissions from Changes in Forest Carbon Stocks	CO_2			•	•			•	•		(863.1)
CO_2 Emissions from Urban Trees	CO_2		•		•			•	•		(95.9)
CO_2 Emissions from Cropland Remaining Cropland	CO_2				•			•	•		(17.4)
CO_2 Emissions from Landfilled Yard Trimmings and Food Scraps	CO_2				•			•	•		(12.6)
CO_2 Emissions from Grassland Remaining Grassland	CO_2			•	•			•	•		(8.3)
CH_4 Emissions from Forest Fires	CH_4							•	•		7.8
N_2O Emissions from Forest Fires	N_2O								•		6.4
Subtotal Without LULUCF											**6,512.7**
Total Emissions Without LULUCF											**6,608.2**
Percent of Total Without LULUCF											**99%**
Subtotal With LULUCF											**5,529.5**
Total Emissions With LULUCF											**5,618.2**
Percent of Total With LULUCF											**98%**

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

Note: Parentheses indicate negative values (or sequestration). Table A-2 provides a complete listing of source categories by IPCC sector, along with notations on the criteria used in identifying key categories, without LULUCF sources and sinks. Similarly, Table A-3 provides a complete listing of source and sink categories by IPCC sector, along with notations on the criteria used in identifying key categories, including LULUCF sources and sinks. The notations refer specifically to the year(s) in the inventory time series (i.e., 1990 to 2009) in which each source category reached the threshold for being a key category based on either a Tier 1 or Tier 2 level assessment.

In addition to conducting Tier 1 and 2 level and trend assessments, a qualitative assessment of the source categories, as described in the IPCC's *Good Practice Guidance* (IPCC 2000), was conducted to capture any key categories that were not identified by any quantitative method. One additional key category, international bunker fuels, was identified using this qualitative assessment. International bunker fuels are fuels consumed for aviation or marine international transport activities, and emissions from these fuels are reported separately from totals in accordance with IPCC guidelines. If these emissions were included in the totals, bunker fuels would qualify as a key category according to the Tier 1 approach. The amount of uncertainty associated with estimation of emissions from international bunker fuels also supports the qualification of this source category as key, which would qualify it as a key category according to the Tier 2 approach.

Table A-2: U.S Greenhouse Gas Inventory Source Categories without LULUCF

IPCC Source Categories	Direct GHG	2009 Emissions (Tg CO_2 Eq.)	Key Category?	ID Criteria[a]	Level in which year(s)?[b]
Energy					
CO_2 Emissions from Stationary Combustion - Coal	CO_2	1,841.0	•	$L_1 L_2$	1990, 2009
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,475.6	•	$L_1 T_1 L_2 T_2$	1990, 2009
CO_2 Emissions from Stationary Combustion - Gas	CO_2	1,164.6	•	$L_1 T_1 L_2 T_2$	1990, 2009
CO_2 Emissions from Stationary Combustion - Oil	CO_2	483.3	•	$L_1 T_1 L_2 T_2$	1990, 2009
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	140.7	•	$L_1 T_1 L_2 T_2$	1990, 2009
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	123.4	•	$L_1 L_2$	1990, 2009
CO_2 Emissions from Mobile Combustion: Other	CO_2	73.5	•	$L_1 T_1$	1990, 2009
CO_2 Emissions from Natural Gas Systems	CO_2	32.2	•	$L_1 T_1 L_2 T_2$	1990, 2009[1]
CO_2 Emissions from Mobile Combustion: Marine	CO_2	30.0	•	$L_1 T_1$	1990
CO_2 Emissions from Incineration of Waste	CO_2	12.3			
CO_2 Emissions from Petroleum Systems	CO_2	0.5			
CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4			
Fugitive Emissions from Natural Gas Systems	CH_4	221.2	•	$L_1 T_1 L_2 T_2$	1990, 2009
Fugitive Emissions from Coal Mining	CH_4	71.0	•	$L_1 T_1 L_2 T_2$	1990, 2009
Fugitive Emissions from Petroleum Systems	CH_4	30.9	•	$L_1 T_1 L_2 T_2$	1990[1], 2009
Non-CO_2 Emissions from Stationary Combustion	CH_4	6.2	•	T_2	
Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	5.5			
CH_4 Emissions from Mobile Combustion: Road	CH_4	1.4			
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.4			
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.1			
CH_4 Emissions from Mobile Combustion: Marine	CH_4	+			
CH_4 Emissions from Incineration of Waste	CH_4	+			
N_2O Emissions from Mobile Combustion: Road	N_2O	20.3	•	$L_1 T_1 T_2$	1990
Non-CO_2 Emissions from Stationary Combustion	N_2O	12.8	•	L_2	1990, 2009
N_2O Emissions from Mobile Combustion: Other	N_2O	1.8			
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.3			
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.4			
N_2O Emissions from Incineration of Waste	N_2O	0.4			
International Bunker Fuels[c]	Several	124.4	•	Q	
Industrial Processes					
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	41.9	•	$L_1 T_1 L_2 T_2$	1990[2], 2009
CO_2 Emissions from Cement Production	CO_2	29.0	•	T_1	
CO_2 Emissions from Ammonia Production and Urea Consumption	CO_2	11.8	•	T_1	
CO_2 Emissions from Lime Production	CO_2	11.2			
CO_2 Emissions from Limestone and Dolomite Use	CO_2	7.6			
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	4.3			
CO_2 Emissions from Aluminum Production	CO_2	3.0			
CO_2 Emissions from Petrochemical Production	CO_2	2.7			
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.8			
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.5			
CO_2 Emissions from Ferroalloy Production	CO_2	1.5			
CO_2 Emissions from Phosphoric Acid Production	CO_2	1.0			

IPCC Source Categories	Direct GHG	2009 Emissions (Tg CO_2 Eq.)	Key Category?	ID Criteria[a]	Level in which year(s)?[b]
CO_2 Emissions from Zinc Production	CO_2	1.0			
CO_2 Emissions from Lead Production	CO_2	0.5			
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.1			
CH_4 Emissions from Petrochemical Production	CH_4	0.8			
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	0.4			
CH_4 Emissions from Ferroalloy Production	CH_4	+			
CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+			
N_2O Emissions from Nitric Acid Production	N_2O	14.6	•	T_2	
N_2O Emissions from Product Uses	N_2O	4.4			
N_2O Emissions from Adipic Acid Production	N_2O	1.9	•	$T_1\,T_2$	
Emissions from Substitutes for Ozone Depleting Substances	HiGWP	120.0	•	$L_1\,T_1\,T_2$	2009
SF_6 Emissions from Electrical Transmission and Distribution	HiGWP	12.8	•	$T_1\,T_2$	
HFC-23 Emissions from HCFC-22 Production	HiGWP	5.4	•	$L_1\,T_1\,T_2$	1990
PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture	HiGWP	5.3			
PFC Emissions from Aluminum Production	HiGWP	1.6	•	$T_1\,T_2$	
SF_6 Emissions from Magnesium Production and Processing	HiGWP	1.1	•	T_1	
Agriculture					
CH_4 Emissions from Enteric Fermentation	CH_4	139.8	•	$L_1\,L_2$	1990, 2009
CH_4 Emissions from Manure Management	CH_4	49.5	•	$L_1\,T_1\,T_2$	2009
CH_4 Emissions from Rice Cultivation	CH_4	7.3	•	L_2	2009
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.2			
Direct N_2O Emissions from Agricultural Soil Management	N_2O	160.2	•	$L_1\,T_1\,L_2\,T_2$	1990, 2009
Indirect N_2O Emissions from Applied Nitrogen	N_2O	44.4	•	$L_1\,L_2\,T_2$	1990, 2009
N_2O Emissions from Manure Management	N_2O	17.9			
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1			
Waste					
CH_4 Emissions from Landfills	CH_4	117.5	•	$L_1\,T_1\,L_2\,T_2$	1990, 2009
CH_4 Emissions from Wastewater Treatment	CH_4	24.5	•	L_2	1990, 2009
CH_4 Emissions from Composting	CH_4	1.7			
N_2O Emissions from Wastewater Treatment	N_2O	5.0			
N_2O Emissions from Composting	N_2O	1.8			

[a] For the ID criteria, L refers to a key category identified through a level assessment; T refers to a key category identified through a trend assessment and the subscripted number refers to either a Tier 1 or Tier 2 assessment (e.g., L_2 designates a source is a key category for a Tier 2 level assessment).

[b] If the source is a key category for both L_1 and L_2 (as designated in the ID criteria column), it is a key category for both assessments in the years provided unless noted by a subscript, in which case it is a key category for that assessment in that year only (.e.g., 1990_2 designates a source is a key category for the Tier 2 assessment only in 1990).

[c] Emissions from these sources not included in totals.

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: LULUCF sources and sinks are not included in this analysis.

Table A-3: U.S Greenhouse Gas Inventory Source Categories with LULUCF

IPCC Source Categories	Gas	2009 Emissions (Tg CO_2 Eq.)	Key Category?	ID Criteria[a]	Level in which year(s)?[b]
Energy					
CO_2 Emissions from Stationary Combustion - Coal	CO_2	1,841.0	•	$L_1\,T_1\,L_2\,T_2$	1990, 2009
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,475.6	•	$L_1\,T_1\,L_2\,T_2$	1990, 2009
CO_2 Emissions from Stationary Combustion - Gas	CO_2	1,164.6	•	$L_1\,T_1\,L_2\,T_2$	1990, 2009
CO_2 Emissions from Stationary Combustion - Oil	CO_2	483.3	•	$L_1\,T_1\,L_2\,T_2$	1990, 2009
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	140.7	•	$L_1\,T_1\,L_2\,T_2$	1990, 2009
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	123.4	•	$L_1\,T_1\,L_2$	1990, 2009
CO_2 Emissions from Mobile Combustion: Other	CO_2	73.5	•	$L_1\,T_1$	1990, 2009

IPCC Source Categories	Gas	2009 Emissions (Tg CO_2 Eq.)	Key Category?	ID Criteria[a]	Level in which year(s)?[b]
CO_2 Emissions from Natural Gas Systems	CO_2	32.2	•	$L_1 T_1 L_2 T_2$	1990$_2$, 2009
CO_2 Emissions from Mobile Combustion: Marine	CO_2	30.0	•	$L_1 T_1$	1990
CO_2 Emissions from Incineration of Waste	CO_2	12.3			
CO_2 Emissions from Petroleum Systems	CO_2	0.5			
CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4			
Fugitive Emissions from Natural Gas Systems	CH_4	221.2	•	$L_1 T_1 L_2 T_2$	1990, 2009
Fugitive Emissions from Coal Mining	CH_4	71.0	•	$L_1 T_1 L_2 T_2$	1990, 2009
Fugitive Emissions from Petroleum Systems	CH_4	30.9	•	$L_1 T_1 L_2 T_2$	1990, 2009
Non-CO_2 Emissions from Stationary Combustion	CH_4	6.2	•	T_2	
Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	5.5			
CH_4 Emissions from Mobile Combustion: Road	CH_4	1.4			
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.4			
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.1			
CH_4 Emissions from Mobile Combustion: Marine	CH_4	+			
CH_4 Emissions from Incineration of Waste	CH_4	+			
N_2O Emissions from Mobile Combustion: Road	N_2O	20.3	•	$L_1 T_1 T_2$	1990
Non-CO_2 Emissions from Stationary Combustion	N_2O	12.8	•	L_2	1990, 2009
N_2O Emissions from Mobile Combustion: Other	N_2O	1.8			
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.3			
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.4			
N_2O Emissions from Incineration of Waste	N_2O	0.4			
International Bunker Fuels[c]	Several	124.4	•	Q	
Industrial Processes					
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	41.9	•	$L_1 T_1 L_2 T_2$	1990$_2$, 2009
CO_2 Emissions from Cement Production	CO_2	29.0	•	$L_1 T_1$	1990
CO_2 Emissions from Ammonia Production and Urea Consumption	CO_2	11.8	•	T_1	
CO_2 Emissions from Lime Production	CO_2	11.2			
CO_2 Emissions from Limestone and Dolomite Use	CO_2	7.6			
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	4.3			
CO_2 Emissions from Aluminum Production	CO_2	3.0			
CO_2 Emissions from Petrochemical Production	CO_2	2.7			
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.8			
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.5			
CO_2 Emissions from Ferroalloy Production	CO_2	1.5			
CO_2 Emissions from Phosphoric Acid Production	CO_2	1.0			
CO_2 Emissions from Zinc Production	CO_2	1.0			
CO_2 Emissions from Lead Production	CO_2	0.5			
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.1			
CH_4 Emissions from Petrochemical Production	CH_4	0.8			
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	0.4			
CH_4 Emissions from Ferroalloy Production	CH_4	+			
CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+			
N_2O Emissions from Nitric Acid Production	N_2O	14.6	•	T_1	
N_2O Emissions from Product Uses	N_2O	4.4			
N_2O Emissions from Adipic Acid Production	N_2O	1.9	•	$T_1 T_2$	
Emissions from Substitutes for Ozone Depleting Substances	HiGWP	120.0	•	$L_1 T_1 L_2 T_2$	2009
SF_6 Emissions from Electrical Transmission and Distribution	HiGWP	12.8	•	$T_1 T_2$	
HFC-23 Emissions from HCFC-22 Production	HiGWP	5.4	•	$L_1 T_1 T_2$	1990

IPCC Source Categories	Gas	2009 Emissions (Tg CO_2 Eq.)	Key Category?	ID Criteria[a]	Level in which year(s)?[b]
PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture	HiGWP	5.3			
PFC Emissions from Aluminum Production	HiGWP	1.6	•	T_1	
SF_6 Emissions from Magnesium Production and Processing	HiGWP	1.1	•	T_1	
Agriculture					
CH_4 Emissions from Enteric Fermentation	CH_4	139.8	•	$L_1 L_2$	1990, 2009
CH_4 Emissions from Manure Management	CH_4	49.5	•	$L_1 T_1 T_2$	1990, 2009
CH_4 Emissions from Rice Cultivation	CH_4	7.3	•	L_2	2009
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.2			
Direct N_2O Emissions from Agricultural Soil Management	N_2O	160.2	•	$L_1 T_1 L_2 T_2$	1990, 2009
Indirect N_2O Emissions from Applied Nitrogen	N_2O	44.4	•	$L_1 L_2 T_2$	1990, 2009
N_2O Emissions from Manure Management	N_2O	17.9			
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1			
Waste					
CH_4 Emissions from Landfills	CH_4	117.5	•	$L_1 T_1 L_2 T_2$	1990, 2009
CH_4 Emissions from Wastewater Treatment	CH_4	24.5	•	L_2	1990, 2009
CH_4 Emissions from Composting	CH_4	1.7			
N_2O Emissions from Wastewater Treatment	N_2O	5.0			
N_2O Emissions from Composting	N_2O	1.8			
Land Use, Land Use Change, and Forestry					
CO_2 Emissions from Changes in Forest Carbon Stocks	CO_2	(863.1)	•	$L_1 T_1 L_2 T_2$	
CO_2 Emissions from Urban Trees	CO_2	(95.9)	•	$L_1 T_1 L_2 T_2$	
CO_2 Emissions from Land Converted to Grassland	CO_2	(23.6)			
CO_2 Emissions from Cropland Remaining Cropland	CO_2	(17.4)	•	$L_2 T_1 T_2$	1990, 2009
CO_2 Emissions from Landfilled Yard Trimmings and Food Scraps	CO_2	(12.6)	•	$L_2 T_1 T_2$	1990
CO_2 Emissions from Grassland Remaining Grassland	CO_2	(8.3)	•	$L_1 T_1 L_2 T_2$	1990
CO_2 Emissions from Land Converted to Cropland	CO_2	5.9			
CO_2 Emissions from Liming of Agricultural Soils	CO_2	4.2			
CO_2 Emissions from Urea Fertilization	CO_2	3.6			
CO_2 Emissions from Wetlands Remaining Wetlands	CO_2	1.1			
CH_4 Emissions from Forest Fires	CH_4	7.8	•	$L_2 T_2$	2009
N_2O Emissions from Forest Fires	N_2O	6.4	•	T_2	
N_2O Emissions from Settlement Soils	N_2O	1.5			
N_2O Emissions from Forest Soils	N_2O	0.4			
N_2O Emissions from Wetlands Remaining Wetlands	N_2O	+			

[a] For the ID criteria, L refers to a key category identified through a level assessment; T refers to a key category identified through a trend assessment and the subscripted number refers to either a Tier 1 or Tier 2 assessment (e.g., L_2 designates a source is a key category for a Tier 2 level assessment).

[b] If the source is a key category for both L_1 and L_2 (as designated in the ID criteria column), it is a key category for both assessments in the years provided unless noted by a subscript, in which case it is a key category only for that assessment in only that year (.e.g., 1990_2 designates a source is a key category for the Tier 2 assessment only in 1990).

[c] Emissions from these sources not included in totals.

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Parentheses indicate negative values (or sequestration).

Evaluation of Key Categories

Level Assessment

When using a Tier 1 approach for the level assessment, a predetermined cumulative emissions threshold is used to identify key categories. When source and sink categories are sorted in order of decreasing absolute emissions, those that fall at the top of the list and cumulatively account for 95 percent of emissions are considered key categories. The 95 percent threshold in the IPCC *Good Practice Guidance* (IPCC 2000) was designed to establish a general level where the key category analysis covers approximately 75 to 92 percent of inventory uncertainty.

Including the Tier 2 approach provides additional insight into why certain source categories are considered key, and how to prioritize inventory improvements. In the Tier 2 approach, the level assessment for each category from the Tier 1 approach is multiplied by its percent relative uncertainty. If the uncertainty reported is asymmetrical, the absolute value

of the larger uncertainty is used. Uncertainty is not estimated for the following sources: CO_2 emissions from stationary combustion – geothermal energy; CO_2 emissions from mobile combustion by mode of transportation; CH_4 and N_2O emissions from mobile combustion by mode of off-road transportation; and CH_4 from the incineration of waste. While CO_2 emissions from geothermal energy are included in the overall emissions estimate, they are not an official IPCC source category. As a result, there are no guidelines to associate uncertainty with the emissions estimate; therefore, an uncertainty analysis was not conducted. The uncertainty associated with CO_2 from mobile combustion is applied to each mode's emissions estimate, and the uncertainty associated with off-road vehicle CH_4 and N_2O emissions are applied to both CH_4 and N_2O emissions from aviation, marine, and other sources. No uncertainty was associated with CH_4 emissions from waste incineration because emissions are less than 0.05 Gg CH_4 and an uncertainty analysis was not conducted. When source and sink categories are sorted in decreasing order of this calculation, those that fall at the top of the list and cumulatively account for 90 percent of emissions are considered key categories. The key categories identified by the Tier 2 level assessment may differ from those identified by the Tier 1 assessment. The final set of key categories includes all source and sink categories identified as key by either the Tier 1 or the Tier 2 assessment, keeping in mind that the two assessments are not mutually exclusive.

It is important to note that a key category analysis can be sensitive to the definitions of the source and sink 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. The United States has attempted to define source and sink categories by the conventions which would allow comparison with other international key categories, while still maintaining the category definitions that constitute how the emissions estimates were calculated for this report. As such, some of the category names used in the key category analysis may differ from the names used in the main body of the report. Additionally, the United States accounts for some source categories, including fossil fuel feedstocks, international bunkers, and emissions from U.S. territories, that are derived from unique data sources using country-specific methodologies.

Table A- 4 through Table A- 7 contain the 1990 and 2009 level assessments for both with and without LULUCF sources and sinks, and contain further detail on where each source falls within the analysis. Tier 1 key categories are shaded dark gray. Additional key categories identified by the Tier 2 assessment are shaded light gray.

Trend Assessment

The Tier 1 approach for trend assessment is defined as the product of the source or sink category level assessment and the absolute difference between the source or sink category trend and the total trend. In turn, the source or sink category trend is defined as the change in emissions from the base year to the current year, as a percentage of current year emissions from that source or sink category. The total trend is the percentage change in total inventory emissions from the base year to the current year.

Thus, the source or sink category trend assessment will be large if the source or sink category represents a large percentage of emissions and/or has a trend that is quite different from the overall inventory trend. To determine key categories, the trend assessments are sorted in decreasing order, so that the source or sink categories with the highest trend assessments appear first. The trend assessments are summed until the threshold of 95 percent is reached; all categories that fall within that cumulative 95 percent are considered key categories.

For the Tier 2 approach, the trend assessment for each category from the Tier 1 approach is multiplied by its percent relative uncertainty. If the uncertainty reported is asymmetrical, the larger uncertainty is used. When source and sink categories are sorted in decreasing order of this calculation, those that fall at the top of the list and cumulatively account for 90 percent of emissions are considered key categories. The key categories identified by the Tier 2 trend assessment may differ from those identified by the Tier 1 assessment. The final set of key categories includes all source and sink categories identified as key by either the Tier 1 or the Tier 2 assessment, keeping in mind that the two assessments are not mutually exclusive.

Table A- 8 and Table A- 9 contain the 1990 through 2009 trend assessment for both with and without LULUCF sources and sinks, and contain further detail on where each source falls within the analysis. Tier 1 key categories are shaded dark gray. Additional key categories identified by the Tier 2 assessment are shaded light gray

Table A- 4: 1990 Key Source Category Tier 1 and Tier 2 Analysis—Level Assessment, without LULUCF

IPCC Source Categories	Direct GHG	1990 Estimate (Tg CO_2 Eq.)	Tier 1 Level Assessment	Cumulative Total	Uncertainty[a]	Tier 2 Level Assessment
CO_2 Emissions from Stationary Combustion - Coal	CO_2	1,718.4	0.28	0.28	9%	0.026
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,188.9	0.19	0.47	8%	0.016
CO_2 Emissions from Stationary Combustion - Gas	CO_2	964.5	0.16	0.63	6%	0.010
CO_2 Emissions from Stationary Combustion - Oil	CO_2	569.1	0.09	0.72	7%	0.007
Fugitive Emissions from Natural Gas Systems	CH_4	189.8	0.03	0.75	30%	0.009
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	179.3	0.03	0.78	8%	0.002
Direct N_2O Emissions from Agricultural Soil Management	N_2O	153.8	0.02	0.80	56%	0.014
CH_4 Emissions from Landfills	CH_4	147.4	0.02	0.83	48%	0.012
CH_4 Emissions from Enteric Fermentation	CH_4	132.1	0.02	0.85	18%	0.004
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	118.6	0.02	0.87	21%	0.004
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	99.5	0.02	0.89	16%	0.003
Fugitive Emissions from Coal Mining	CH_4	84.1	0.01	0.90	16%	0.002
CO_2 Emissions from Mobile Combustion: Other	CO_2	73.3	0.01	0.91	8%	0.001
CO_2 Emissions from Mobile Combustion: Marine	CO_2	44.5	0.01	0.92	8%	0.001
Indirect N_2O Emissions from Applied Nitrogen	N_2O	44.0	0.01	0.93	151%	0.011
N_2O Emissions from Mobile Combustion: Road	N_2O	40.3	0.01	0.93	17%	0.001
CO_2 Emissions from Natural Gas Systems	CO_2	37.6	0.01	0.94	30%	0.002
HFC-23 Emissions from HCFC-22 Production	HFCs	36.4	0.01	0.94	10%	0.001
Fugitive Emissions from Petroleum Systems	CH_4	35.4	0.01	0.95	149%	0.009
CO_2 Emissions from Cement Production	CO_2	33.3	0.01	0.96	14%	0.001
CH_4 Emissions from Manure Management	CH_4	31.7	0.01	0.96	20%	0.001
SF_6 Emissions from Electrical Transmission and Distribution	SF_6	28.4	<0.01	0.96	22%	0.001
CH_4 Emissions from Wastewater Treatment	CH_4	23.5	<0.01	0.97	47%	0.002
PFC Emissions from Aluminum Production	PFCs	18.5	<0.01	0.97	11%	<0.001
N_2O Emissions from Nitric Acid Production	N_2O	17.7	<0.01	0.97	42%	0.001
CO_2 Emissions from Ammonia Production and Urea Consumption	CO_2	16.8	<0.01	0.98	8%	<0.001
N_2O Emissions from Adipic Acid Production	N_2O	15.8	<0.01	0.98	42%	0.001
N_2O Emissions from Manure Management	N_2O	14.5	<0.01	0.98	24%	0.001
Non-CO_2 Emissions from Stationary Combustion	N_2O	12.8	<0.01	0.98	187%	0.004
CO_2 Emissions from Lime Production	CO_2	11.5	<0.01	0.99	10%	<0.001
CO_2 Emissions from Incineration of Waste	CO_2	8.0	<0.01	0.99	24%	<0.001
Non-CO_2 Emissions from Stationary Combustion	CH_4	7.4	<0.01	0.99	127%	0.002
CH_4 Emissions from Rice Cultivation	CH_4	7.1	<0.01	0.99	146%	0.002
CO_2 Emissions from Aluminum Production	CO_2	6.8	<0.01	0.99	4%	<0.001
Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	6.0	<0.01	0.99	32%	<0.001
SF_6 Emissions from Magnesium Production and Processing	SF_6	5.4	<0.01	0.99	4%	<0.001
CO_2 Emissions from Limestone and Dolomite Use	CO_2	5.1	<0.01	0.99	19%	<0.001
N_2O Emissions from Product Uses	N_2O	4.4	<0.01	0.99	8%	<0.001
CH_4 Emissions from Mobile Combustion: Road	CH_4	4.2	<0.01	1.00	15%	<0.001
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	4.1	<0.01	1.00	7%	<0.001
N_2O Emissions from Wastewater Treatment	N_2O	3.7	<0.01	1.00	93%	0.001
CO_2 Emissions from Petrochemical Production	CO_2	3.3	<0.01	1.00	31%	<0.001
PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture	Several	2.9	<0.01	1.00	11%	<0.001
CO_2 Emissions from Ferroalloy Production	CO_2	2.2	<0.01	1.00	13%	<0.001
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.7	<0.01	1.00	68%	<0.001
CO_2 Emissions from Phosphoric Acid Production	CO_2	1.5	<0.01	1.00	19%	<0.001
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.4	<0.01	1.00	30%	<0.001
N_2O Emissions from Mobile Combustion: Other	N_2O	1.3	<0.01	1.00	47%	<0.001
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.2	<0.01	1.00	13%	<0.001
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	1.0	<0.01	1.00	23%	<0.001
CH_4 Emissions from Petrochemical Production	CH_4	0.9	<0.01	1.00	27%	<0.001
CO_2 Emissions from Zinc Production	CO_2	0.7	<0.01	1.00	18%	<0.001
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6	<0.01	1.00	57%	<0.001
CO_2 Emissions from Petroleum Systems	CO_2	0.6	<0.01	1.00	149%	<0.001
CO_2 Emissions from Lead Production	CO_2	0.5	<0.01	1.00	15%	<0.001
N_2O Emissions from Incineration of Waste	N_2O	0.5	<0.01	1.00	320%	<0.001
CO_2 Emissions from Stationary Combustion - Geothermal	CO_2	0.4	<0.01	1.00	NE	<0.001

IPCC Source Categories	Direct GHG	1990 Estimate (Tg CO_2 Eq.)	Tier 1 Level Assessment	Cumulative Total	Uncertainty[a]	Tier 2 Level Assessment
Energy						
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.4	<0.01	1.00	9%	<0.001
N_2O Emissions from Composting	N_2O	0.4	<0.01	1.00	50%	<0.001
Emissions from Substitutes for Ozone Depleting Substances	Several	0.3	<0.01	1.00	8%	<0.001
CH_4 Emissions from Composting	CH_4	0.3	<0.01	1.00	50%	<0.001
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.3	<0.01	1.00	47%	<0.001
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.3	<0.01	1.00	42%	<0.001
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.2	<0.01	1.00	61%	<0.001
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1	<0.01	1.00	31%	<0.001
CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+	<0.01	1.00	9%	<0.001
CH_4 Emissions from Mobile Combustion: Marine	CH_4	+	<0.01	1.00	73%	<0.001
CH_4 Emissions from Ferroalloy Production	CH_4	+	<0.01	1.00	12%	<0.001
CH_4 Emissions from Incineration of Waste	CH_4	+	<0.01	1.00	NE	<0.001

Note: LULUCF sources and sinks are not included in this analysis.
[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.
NE Uncertainty not estimated.
+ Does not exceed 0.05 Tg CO_2 Eq.

Table A- 5: 1990 Key Source Category Tier 1 and Tier 2 Analysis—Level Assessment, with LULUCF

IPCC Source Categories	Direct GHG	1990 Estimate (Tg CO_2 Eq.)	Tier 1 Level Assessment	Cumulative Total	Uncertainty[a]	Tier 2 Level Assessment
CO_2 Emissions from Stationary Combustion - Coal	CO_2	1,718.4	0.24	0.24	9%	0.023
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,188.9	0.17	0.41	8%	0.014
CO_2 Emissions from Stationary Combustion - Gas	CO_2	964.5	0.14	0.55	6%	0.009
CO_2 Emissions from Changes in Forest Carbon Stocks	CO_2	681.1	0.10	0.65	18%	0.017
CO_2 Emissions from Stationary Combustion - Oil	CO_2	569.1	0.08	0.73	7%	0.006
Fugitive Emissions from Natural Gas Systems	CH_4	189.8	0.03	0.75	30%	0.008
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	179.3	0.03	0.78	8%	0.002
Direct N_2O Emissions from Agricultural Soil Management	N_2O	153.8	0.02	0.80	56%	0.012
CH_4 Emissions from Landfills	CH_4	147.4	0.02	0.82	48%	0.010
CH_4 Emissions from Enteric Fermentation	CH_4	132.1	0.02	0.84	18%	0.003
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	118.6	0.02	0.86	21%	0.004
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	99.5	0.01	0.87	16%	0.002
Fugitive Emissions from Coal Mining	CH_4	84.1	0.01	0.88	16%	0.002
CO_2 Emissions from Mobile Combustion: Other	CO_2	73.3	0.01	0.89	8%	0.001
CO_2 Emissions from Urban Trees	CO_2	57.1	0.01	0.90	22%	0.002
CO_2 Emissions from Grassland Remaining Grassland	CO_2	52.2	0.01	0.91	32%	0.002
CO_2 Emissions from Mobile Combustion: Marine	CO_2	44.5	0.01	0.92	8%	0.001
Indirect N_2O Emissions from Applied Nitrogen	N_2O	44.0	0.01	0.92	151%	0.009
N_2O Emissions from Mobile Combustion: Road	N_2O	40.3	0.01	0.93	17%	0.001
CO_2 Emissions from Natural Gas Systems	CO_2	37.6	0.01	0.93	30%	0.002
HFC-23 Emissions from HCFC-22 Production	HFCs	36.4	0.01	0.94	10%	0.001
Fugitive Emissions from Petroleum Systems	CH_4	35.4	0.01	0.94	149%	0.007
CO_2 Emissions from Cement Production	CO_2	33.3	<0.01	0.95	14%	0.001
CH_4 Emissions from Manure Management	CH_4	31.7	<0.01	0.95	20%	0.001
CO_2 Emissions from Cropland Remaining Cropland	CO_2	29.4	<0.01	0.96	172%	0.007
SF_6 Emissions from Electrical Transmission and Distribution	SF_6	28.4	<0.01	0.96	22%	0.001
CO_2 Emissions from Landfilled Yard Trimmings and Food Scraps	CO_2	24.2	<0.01	0.96	68%	0.002
CH_4 Emissions from Wastewater Treatment	CH_4	23.5	<0.01	0.97	47%	0.002
CO_2 Emissions from Land Converted to Grassland	CO_2	19.8	<0.01	0.97	15%	<0.001
PFC Emissions from Aluminum Production	PFCs	18.5	<0.01	0.97	11%	<0.001
N_2O Emissions from Nitric Acid Production	N_2O	17.7	<0.01	0.98	42%	0.001
CO_2 Emissions from Ammonia Production and Urea Consumption	CO_2	16.8	<0.01	0.98	8%	<0.001

IPCC Source Categories	Direct GHG	1990 Estimate (Tg CO_2 Eq.)	Tier 1 Level Assessment	Cumulative Total	Uncertainty[a]	Tier 2 Level Assessment
N_2O Emissions from Adipic Acid Production	N_2O	15.8	<0.01	0.98	42%	0.001
N_2O Emissions from Manure Management	N_2O	14.5	<0.01	0.98	24%	<0.001
Non-CO_2 Emissions from Stationary Combustion	N_2O	12.8	<0.01	0.98	187%	0.003
CO_2 Emissions from Lime Production	CO_2	11.5	<0.01	0.99	10%	<0.001
CO_2 Emissions from Incineration of Waste	CO_2	8.0	<0.01	0.99	24%	<0.001
Non-CO_2 Emissions from Stationary Combustion	CH_4	7.4	<0.01	0.99	127%	0.001
CH_4 Emissions from Rice Cultivation	CH_4	7.1	<0.01	0.99	146%	0.001
CO_2 Emissions from Aluminum Production	CO_2	6.8	<0.01	0.99	4%	<0.001
Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	6.0	<0.01	0.99	32%	<0.001
SF_6 Emissions from Magnesium Production and Processing	SF_6	5.4	<0.01	0.99	4%	<0.001
CO_2 Emissions from Limestone and Dolomite Use	CO_2	5.1	<0.01	0.99	19%	<0.001
CO_2 Emissions from Liming of Agricultural Soils	CO_2	4.7	<0.01	0.99	99%	0.001
N_2O Emissions from Product Uses	N_2O	4.4	<0.01	0.99	8%	<0.001
CH_4 Emissions from Mobile Combustion: Road	CH_4	4.2	<0.01	0.99	15%	<0.001
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	4.1	<0.01	0.99	7%	<0.001
N_2O Emissions from Wastewater Treatment	N_2O	3.7	<0.01	0.99	93%	<0.001
CO_2 Emissions from Petrochemical Production	CO_2	3.3	<0.01	1.00	31%	<0.001
CH_4 Emissions from Forest Fires	CH_4	3.2	<0.01	1.00	145%	0.001
PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture	Several	2.9	<0.01	1.00	11%	<0.001
N_2O Emissions from Forest Fires	N_2O	2.6	<0.01	1.00	145%	0.001
CO_2 Emissions from Urea Fertilization	CO_2	2.4	<0.01	1.00	43%	<0.001
CO_2 Emissions from Ferroalloy Production	CO_2	2.2	<0.01	1.00	13%	<0.001
CO_2 Emissions from Land Converted to Cropland	CO_2	2.2	<0.01	1.00	40%	<0.001
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.7	<0.01	1.00	68%	<0.001
CO_2 Emissions from Phosphoric Acid Production	CO_2	1.5	<0.01	1.00	19%	<0.001
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.4	<0.01	1.00	30%	<0.001
N_2O Emissions from Mobile Combustion: Other	N_2O	1.3	<0.01	1.00	47%	<0.001
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.2	<0.01	1.00	13%	<0.001
CO_2 Emissions from Wetlands Remaining Wetlands	CO_2	1.0	<0.01	1.00	34%	<0.001
N_2O Emissions from Settlement Soils	N_2O	1.0	<0.01	1.00	163%	<0.001
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	1.0	<0.01	1.00	23%	<0.001
CH_4 Emissions from Petrochemical Production	CH_4	0.9	<0.01	1.00	27%	<0.001
CO_2 Emissions from Zinc Production	CO_2	0.7	<0.01	1.00	18%	<0.001
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6	<0.01	1.00	57%	<0.001
CO_2 Emissions from Petroleum Systems	CO_2	0.6	<0.01	1.00	149%	<0.001
CO_2 Emissions from Lead Production	CO_2	0.5	<0.01	1.00	15%	<0.001
N_2O Emissions from Incineration of Waste	N_2O	0.5	<0.01	1.00	320%	<0.001
CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4	<0.01	1.00	NE	<0.001
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.4	<0.01	1.00	9%	<0.001
N2O Emissions from Composting	N_2O	0.4	<0.01	1.00	50%	<0.001
Emissions from Substitutes for Ozone Depleting Substances	Several	0.3	<0.01	1.00	8%	<0.001
CH_4 Emissions from Composting	CH_4	0.3	<0.01	1.00	50%	<0.001
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.3	<0.01	1.00	47%	<0.001
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.3	<0.01	1.00	42%	<0.001
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.2	<0.01	1.00	61%	<0.001
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1	<0.01	1.00	31%	<0.001
N_2O Emissions from Forest Soils	N_2O	0.1	<0.01	1.00	211%	<0.001
CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+	<0.01	1.00	9%	<0.001
CH_4 Emissions from Mobile Combustion: Marine	CH_4	+	<0.01	1.00	73%	<0.001
CH_4 Emissions from Ferroalloy Production	CH_4	+	<0.01	1.00	12%	<0.001
N_2O Emissions from Wetlands Remaining Wetlands	N_2O	+	<0.01	1.00	74%	<0.001
CH_4 Emissions from Incineration of Waste	CH_4	+	<0.01	1.00	NE	<0.001

[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.
NE Uncertainty not estimated.
+ Does not exceed 0.05 Tg CO_2 Eq.

Table A- 6: 2009 Key Source Category Tier 1 and Tier 2 Analysis—Level Assessment, without LULUCF

IPCC Source Categories	Direct GHG	2009 Estimate (Tg CO_2 Eq.)	Tier 1 Level Assessment	Cumulative Total	Uncertainty[a]	Tier 2 Level Assessment
CO_2 Emissions from Stationary Combustion - Coal	CO_2	1,841.0	0.28	0.28	9%	0.026
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,475.6	0.22	0.50	8%	0.019
CO_2 Emissions from Stationary Combustion - Gas	CO_2	1,164.6	0.18	0.68	6%	0.011
CO_2 Emissions from Stationary Combustion - Oil	CO_2	483.3	0.07	0.75	7%	0.005
Fugitive Emissions from Natural Gas Systems	CH_4	221.2	0.03	0.78	30%	0.010
Direct N_2O Emissions from Agricultural Soil Management	N_2O	160.2	0.02	0.81	56%	0.014
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	140.7	0.02	0.83	8%	0.002
CH_4 Emissions from Enteric Fermentation	CH_4	139.8	0.02	0.85	18%	0.004
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	123.4	0.02	0.87	21%	0.004
Emissions from Substitutes for Ozone Depleting Substances	Several	120.0	0.02	0.89	8%	0.002
CH_4 Emissions from Landfills	CH_4	117.5	0.02	0.91	48%	0.009
CO_2 Emissions from Mobile Combustion: Other	CO_2	73.5	0.01	0.92	8%	0.001
Fugitive Emissions from Coal Mining	CH_4	71.0	0.01	0.93	16%	0.002
CH_4 Emissions from Manure Management	CH_4	49.5	0.01	0.94	20%	0.001
Indirect N_2O Emissions from Applied Nitrogen	N_2O	44.4	0.01	0.94	151%	0.010
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	41.9	0.01	0.95	16%	0.001
CO_2 Emissions from Natural Gas Systems	CO_2	32.2	<0.01	0.95	30%	0.001
Fugitive Emissions from Petroleum Systems	CH_4	30.9	<0.01	0.96	149%	0.007
CO_2 Emissions from Mobile Combustion: Marine	CO_2	30.0	<0.01	0.96	8%	<0.001
CO_2 Emissions from Cement Production	CO_2	29.0	<0.01	0.97	14%	0.001
CH_4 Emissions from Wastewater Treatment	CH_4	24.5	<0.01	0.97	47%	0.002
N_2O Emissions from Mobile Combustion: Road	N_2O	20.3	<0.01	0.97	17%	0.001
N_2O Emissions from Manure Management	N_2O	17.9	<0.01	0.98	24%	0.001
N_2O Emissions from Nitric Acid Production	N_2O	14.6	<0.01	0.98	42%	0.001
SF_6 Emissions from Electrical Transmission and Distribution	SF_6	12.8	<0.01	0.98	22%	<0.001
Non-CO_2 Emissions from Stationary Combustion	N_2O	12.8	<0.01	0.98	187%	0.004
CO_2 Emissions from Incineration of Waste	CO_2	12.3	<0.01	0.98	24%	<0.001
CO_2 Emissions from Ammonia Production and Urea Consumption	CO_2	11.8	<0.01	0.99	8%	<0.001
CO_2 Emissions from Lime Production	CO_2	11.2	<0.01	0.99	10%	<0.001
CO_2 Emissions from Limestone and Dolomite Use	CO_2	7.6	<0.01	0.99	19%	<0.001
CH_4 Emissions from Rice Cultivation	CH_4	7.3	<0.01	0.99	146%	0.002
Non-CO_2 Emissions from Stationary Combustion	CH_4	6.2	<0.01	0.99	127%	0.001
Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	5.5	<0.01	0.99	32%	<0.001
HFC-23 Emissions from HCFC-22 Production	HFCs	5.4	<0.01	0.99	10%	<0.001
PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture	Several	5.3	<0.01	0.99	11%	<0.001
N_2O Emissions from Wastewater Treatment	N_2O	5.0	<0.01	0.99	93%	0.001
N_2O Emissions from Product Uses	N_2O	4.4	<0.01	0.99	8%	<0.001
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	4.3	<0.01	1.00	7%	<0.001
CO_2 Emissions from Aluminum Production	CO_2	3.0	<0.01	1.00	4%	<0.001
CO_2 Emissions from Petrochemical Production	CO_2	2.7	<0.01	1.00	31%	<0.001
N_2O Emissions from Adipic Acid Production	N_2O	1.9	<0.01	1.00	42%	<0.001
N2O Emissions from Composting	N_2O	1.8	<0.01	1.00	50%	<0.001
N_2O Emissions from Mobile Combustion: Other	N_2O	1.8	<0.01	1.00	47%	<0.001
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.8	<0.01	1.00	30%	<0.001
CH_4 Emissions from Composting	CH_4	1.7	<0.01	1.00	50%	<0.001
PFC Emissions from Aluminum Production	PFCs	1.6	<0.01	1.00	11%	<0.001
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.5	<0.01	1.00	13%	<0.001
CO_2 Emissions from Ferroalloy Production	CO_2	1.5	<0.01	1.00	13%	<0.001
CH_4 Emissions from Mobile Combustion: Road	CH_4	1.4	<0.01	1.00	15%	<0.001
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.3	<0.01	1.00	68%	<0.001
SF_6 Emissions from Magnesium Production and Processing	SF_6	1.1	<0.01	1.00	4%	<0.001
CO_2 Emissions from Phosphoric Acid Production	CO_2	1.0	<0.01	1.00	19%	<0.001
CO_2 Emissions from Zinc Production	CO_2	1.0	<0.01	1.00	18%	<0.001
CH_4 Emissions from Petrochemical Production	CH_4	0.8	<0.01	1.00	27%	<0.001
CO_2 Emissions from Lead Production	CO_2	0.5	<0.01	1.00	15%	<0.001

IPCC Source Categories	Direct GHG	2009 Estimate (Tg CO_2 Eq.)	Tier 1 Level Assessment	Cumulative Total	Uncertainty[a]	Tier 2 Level Assessment
CO_2 Emissions from Petroleum Systems	CO_2	0.5	<0.01	1.00	149%	<0.001
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.4	<0.01	1.00	57%	<0.001
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.4	<0.01	1.00	47%	<0.001
CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4	<0.01	1.00	NE	<0.001
N_2O Emissions from Incineration of Waste	N_2O	0.4	<0.01	1.00	320%	<0.001
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	0.4	<0.01	1.00	23%	<0.001
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.2	<0.01	1.00	42%	<0.001
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.1	<0.01	1.00	9%	<0.001
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.1	<0.01	1.00	61%	<0.001
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1	<0.01	1.00	31%	<0.001
CH_4 Emissions from Mobile Combustion: Marine	CH_4	+	<0.01	1.00	73%	<0.001
CH_4 Emissions from Ferroalloy Production	CH_4	+	<0.01	1.00	12%	<0.001
CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+	<0.01	1.00	9%	<0.001
CH_4 Emissions from Incineration of Waste	CH_4	+	<0.01	1.00	NE	<0.001

Note: LULUCF sources and sinks are not included in this analysis.

[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.

NE Uncertainty not estimated.

+ Does not exceed 0.05 Tg CO_2 Eq.

Table A- 7: 2009 Key Source Category Tier 1 and Tier 2 Analysis—Level Assessment with LULUCF

IPCC Source Categories	Direct GHG	2009 Estimate (Tg CO_2 Eq.)	Tier 1 Level Assessment	Cumulative Total	Uncertainty[a]	Tier 2 Level Assessment
CO_2 Emissions from Stationary Combustion - Coal	CO_2	1,841.0	0.24	0.24	9%	0.023
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,475.6	0.19	0.43	8%	0.016
CO_2 Emissions from Stationary Combustion - Gas	CO_2	1,164.6	0.15	0.58	6%	0.010
CO_2 Emissions from Changes in Forest Carbon Stocks	CO_2	863.1	0.11	0.70	18%	0.020
CO_2 Emissions from Stationary Combustion - Oil	CO_2	483.3	0.06	0.76	7%	0.005
Fugitive Emissions from Natural Gas Systems	CH_4	221.2	0.03	0.79	30%	0.009
Direct N_2O Emissions from Agricultural Soil Management	N_2O	160.2	0.02	0.81	56%	0.012
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	140.7	0.02	0.83	8%	0.002
CH_4 Emissions from Enteric Fermentation	CH_4	139.8	0.02	0.85	18%	0.003
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	123.4	0.02	0.86	21%	0.003
Emissions from Substitutes for Ozone Depleting Substances	Several	120.0	0.02	0.88	8%	0.001
CH_4 Emissions from Landfills	CH_4	117.5	0.02	0.89	48%	0.007
CO_2 Emissions from Urban Trees	CO_2	95.9	0.01	0.91	22%	0.003
CO_2 Emissions from Mobile Combustion: Other	CO_2	73.5	0.01	0.92	8%	0.001
Fugitive Emissions from Coal Mining	CH_4	71.0	0.01	0.93	16%	0.001
CH_4 Emissions from Manure Management	CH_4	49.5	0.01	0.93	20%	0.001
Indirect N_2O Emissions from Applied Nitrogen	N_2O	44.4	0.01	0.94	151%	0.009
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	41.9	0.01	0.94	16%	0.001
CO_2 Emissions from Natural Gas Systems	CO_2	32.2	<0.01	0.95	30%	0.001
Fugitive Emissions from Petroleum Systems	CH_4	30.9	<0.01	0.95	149%	0.006
CO_2 Emissions from Mobile Combustion: Marine	CO_2	30.0	<0.01	0.96	8%	<0.001
CO_2 Emissions from Cement Production	CO_2	29.0	<0.01	0.96	14%	0.001
CH_4 Emissions from Wastewater Treatment	CH_4	24.5	<0.01	0.96	47%	0.001
CO_2 Emissions from Land Converted to Grassland	CO_2	23.6	<0.01	0.97	15%	<0.001
N_2O Emissions from Mobile Combustion: Road	N_2O	20.3	<0.01	0.97	17%	<0.001
N_2O Emissions from Manure Management	N_2O	17.9	<0.01	0.97	24%	0.001
CO_2 Emissions from Cropland Remaining Cropland	CO_2	17.4	<0.01	0.97	172%	0.004
N_2O Emissions from Nitric Acid Production	N_2O	14.6	<0.01	0.97	42%	0.001
SF_6 Emissions from Electrical Transmission and Distribution	SF_6	12.8	<0.01	0.98	22%	<0.001
Non-CO_2 Emissions from Stationary Combustion	N_2O	12.8	<0.01	0.98	187%	0.003
CO_2 Emissions from Landfilled Yard Trimmings and Food Scraps	CO_2	12.6	<0.01	0.98	68%	0.001
CO_2 Emissions from Incineration of Waste	CO_2	12.3	<0.01	0.98	24%	<0.001

CO_2 Emissions from Ammonia Production and Urea Consumption	CO_2	11.8	<0.01	0.98	8%	<0.001
CO_2 Emissions from Lime Production	CO_2	11.2	<0.01	0.98	10%	<0.001
CO_2 Emissions from Grassland Remaining Grassland	CO_2	8.3	<0.01	0.99	32%	<0.001
CH_4 Emissions from Forest Fires	CH_4	7.8	<0.01	0.99	145%	0.001
CO_2 Emissions from Limestone and Dolomite Use	CO_2	7.6	<0.01	0.99	19%	<0.001
CH_4 Emissions from Rice Cultivation	CH_4	7.3	<0.01	0.99	146%	0.001
N_2O Emissions from Forest Fires	N_2O	6.4	<0.01	0.99	145%	0.001
Non-CO_2 Emissions from Stationary Combustion	CH_4	6.2	<0.01	0.99	127%	0.001
CO_2 Emissions from Land Converted to Cropland	CO_2	5.9	<0.01	0.99	40%	<0.001
Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	5.5	<0.01	0.99	32%	<0.001
HFC-23 Emissions from HCFC-22 Production	HFCs	5.4	<0.01	0.99	10%	<0.001
PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture	Several	5.3	<0.01	0.99	11%	<0.001
N_2O Emissions from Wastewater Treatment	N_2O	5.0	<0.01	0.99	93%	0.001
N_2O Emissions from Product Uses	N_2O	4.4	<0.01	0.99	8%	<0.001
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	4.3	<0.01	0.99	7%	<0.001
CO_2 Emissions from Liming of Agricultural Soils	CO_2	4.2	<0.01	1.00	99%	0.001
CO_2 Emissions from Urea Fertilization	CO_2	3.6	<0.01	1.00	43%	<0.001
CO_2 Emissions from Aluminum Production	CO_2	3.0	<0.01	1.00	4%	<0.001
CO_2 Emissions from Petrochemical Production	CO_2	2.7	<0.01	1.00	31%	<0.001
N_2O Emissions from Adipic Acid Production	N_2O	1.9	<0.01	1.00	42%	<0.001
N2O Emissions from Composting	N_2O	1.8	<0.01	1.00	50%	<0.001
N_2O Emissions from Mobile Combustion: Other	N_2O	1.8	<0.01	1.00	47%	<0.001
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.8	<0.01	1.00	30%	<0.001
CH_4 Emissions from Composting	CH_4	1.7	<0.01	1.00	50%	<0.001
PFC Emissions from Aluminum Production	PFCs	1.6	<0.01	1.00	11%	<0.001
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.5	<0.01	1.00	13%	<0.001
N_2O Emissions from Settlement Soils	N_2O	1.5	<0.01	1.00	163%	<0.001
CO_2 Emissions from Ferroalloy Production	CO_2	1.5	<0.01	1.00	13%	<0.001
CH_4 Emissions from Mobile Combustion: Road	CH_4	1.4	<0.01	1.00	15%	<0.001
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.3	<0.01	1.00	68%	<0.001
CO_2 Emissions from Wetlands Remaining Wetlands	CO_2	1.1	<0.01	1.00	34%	<0.001
SF_6 Emissions from Magnesium Production and Processing	SF_6	1.1	<0.01	1.00	4%	<0.001
CO_2 Emissions from Phosphoric Acid Production	CO_2	1.0	<0.01	1.00	19%	<0.001
CO_2 Emissions from Zinc Production	CO_2	1.0	<0.01	1.00	18%	<0.001
CH_4 Emissions from Petrochemical Production	CH_4	0.8	<0.01	1.00	27%	<0.001
CO_2 Emissions from Lead Production	CO_2	0.5	<0.01	1.00	15%	<0.001
CO_2 Emissions from Petroleum Systems	CO_2	0.5	<0.01	1.00	149%	<0.001
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.4	<0.01	1.00	57%	<0.001
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.4	<0.01	1.00	47%	<0.001
CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4	<0.01	1.00	NE	<0.001
N_2O Emissions from Incineration of Waste	N_2O	0.4	<0.01	1.00	320%	<0.001
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	0.4	<0.01	1.00	23%	<0.001
N_2O Emissions from Forest Soils	N_2O	0.4	<0.01	1.00	211%	<0.001
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.2	<0.01	1.00	42%	<0.001
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.1	<0.01	1.00	9%	<0.001
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.1	<0.01	1.00	61%	<0.001
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1	<0.01	1.00	31%	<0.001
CH_4 Emissions from Mobile Combustion: Marine	CH_4	+	<0.01	1.00	73%	<0.001
CH_4 Emissions from Ferroalloy Production	CH_4	+	<0.01	1.00	12%	<0.001
CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+	<0.01	1.00	9%	<0.001
N_2O Emissions from Wetlands Remaining Wetlands	N_2O	+	<0.01	1.00	74%	<0.001
CH_4 Emissions from Incineration of Waste	CH_4	+	<0.01	1.00	NE	<0.001

[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.

NE Uncertainty not estimated.

+ Does not exceed 0.05 Tg CO_2 Eq.

Table A- 8: 1990-2009 Key Source Category Tier 1 and 2 Analysis—Trend Assessment, without LULUCF

IPCC Source Categories	Direct GHG	1990 Estimate (Tg CO$_2$ Eq.)	2009 Estimate (Tg CO$_2$ Eq.)	Tier 1 Trend Assessment	Tier 2 Trend Assessment	Percent Contribution to Trend (%)	Cumulative Contribution to Trend (%)
CO$_2$ Emissions from Mobile Combustion: Road	CO$_2$	1,188.9	1,475.6	0.03	0.002	20.1	20
CO$_2$ Emissions from Stationary Combustion - Gas	CO$_2$	964.5	1,164.6	0.02	0.001	13.1	33
CO$_2$ Emissions from Stationary Combustion - Oil	CO$_2$	569.1	483.3	0.02	0.001	12.6	46
Emissions from Substitutes for Ozone Depleting Substances	Several	0.3	120.0	0.02	0.001	11.9	58
CO$_2$ Emissions from Iron and Steel Production & Metallurgical Coke Production	CO$_2$	99.5	41.9	0.01	0.001	6.5	64
CO$_2$ Emissions from Mobile Combustion: Aviation	CO$_2$	179.3	140.7	0.01	0.001	5.1	69
CH$_4$ Emissions from Landfills	CH$_4$	147.4	117.5	0.01	0.003	4.0	73
HFC-23 Emissions from HCFC-22 Production	HFCs	36.4	5.4	<0.01	<0.001	3.4	77
N$_2$O Emissions from Mobile Combustion: Road	N$_2$O	40.3	20.3	<0.01	0.001	2.3	79
Fugitive Emissions from Coal Mining	CH$_4$	84.1	71.0	<0.01	<0.001	1.9	81
PFC Emissions from Aluminum Production	PFCs	18.5	1.6	<0.01	<0.001	1.8	83
Fugitive Emissions from Natural Gas Systems	CH$_4$	189.8	221.2	<0.01	0.001	1.8	85
CO$_2$ Emissions from Mobile Combustion: Marine	CO$_2$	44.5	30.0	<0.01	<0.001	1.8	86
SF$_6$ Emissions from Electrical Transmission and Distribution	SF$_6$	28.4	12.8	<0.01	0.001	1.8	88
CH$_4$ Emissions from Manure Management	CH$_4$	31.7	49.5	<0.01	<0.001	1.5	90
N$_2$O Emissions from Adipic Acid Production	N$_2$O	15.8	1.9	<0.01	0.001	1.5	91
CO$_2$ Emissions from Natural Gas Systems	CO$_2$	37.6	32.2	<0.01	<0.001	0.8	92
Fugitive Emissions from Petroleum Systems	CH$_4$	35.4	30.9	<0.01	0.001	0.7	93
CO$_2$ Emissions from Cement Production	CO$_2$	33.3	29.0	<0.01	<0.001	0.7	93
CO$_2$ Emissions from Ammonia Production and Urea Consumption	CO$_2$	16.8	11.8	<0.01	<0.001	0.6	94
CO$_2$ Emissions from Mobile Combustion: Other	CO$_2$	73.3	73.5	<0.01	<0.001	0.5	94
SF$_6$ Emissions from Magnesium Production and Processing	SF$_6$	5.4	1.1	<0.01	<0.001	0.5	95
Direct N$_2$O Emissions from Agricultural Soil Management	N$_2$O	153.8	160.2	<0.01	<0.001	0.5	95
N$_2$O Emissions from Nitric Acid Production	N$_2$O	17.7	14.6	<0.01	<0.001	0.4	96
CO$_2$ Emissions from Aluminum Production	CO$_2$	6.8	3.0	<0.01	<0.001	0.4	96
CO$_2$ Emissions from Non-Energy Use of Fuels	CO$_2$	118.6	123.4	<0.01	<0.001	0.4	97
CO$_2$ Emissions from Incineration of Waste	CO$_2$	8.0	12.3	<0.01	<0.001	0.4	97
CH$_4$ Emissions from Mobile Combustion: Road	CH$_4$	4.2	1.4	<0.01	<0.001	0.3	97
Indirect N$_2$O Emissions from Applied Nitrogen	N$_2$O	44.0	44.4	<0.01	0.001	0.3	98
N$_2$O Emissions from Manure Management	N$_2$O	14.5	17.9	<0.01	<0.001	0.2	98
PFC, HFC, and SF$_6$ Emissions from Semiconductor Manufacture	Several	2.9	5.3	<0.01	<0.001	0.2	98
CO$_2$ Emissions from Limestone and Dolomite Use	CO$_2$	5.1	7.6	<0.01	<0.001	0.2	98
Non-CO$_2$ Emissions from Stationary Combustion	CH$_4$	7.4	6.2	<0.01	<0.001	0.2	98
CH$_4$ Emissions from Enteric Fermentation	CH$_4$	132.1	139.8	<0.01	<0.001	0.2	99
N2O Emissions from Composting	N$_2$O	0.4	1.8	<0.01	<0.001	0.1	99
CH$_4$ Emissions from Composting	CH$_4$	0.3	1.7	<0.01	<0.001	0.1	99
CO$_2$ Emissions from Lime Production	CO$_2$	11.5	11.2	<0.01	<0.001	0.1	99
N$_2$O Emissions from Wastewater Treatment	N$_2$O	3.7	5.0	<0.01	<0.001	0.1	99
Fugitive Emissions from Abandoned Underground Coal Mines	CH$_4$	6.0	5.5	<0.01	<0.001	0.1	99
Non-CO$_2$ Emissions from Stationary Combustion	N$_2$O	12.8	12.8	<0.01	<0.001	0.1	99
CO$_2$ Emissions from Ferroalloy Production	CO$_2$	2.2	1.5	<0.01	<0.001	0.1	99
CO$_2$ Emissions from Petrochemical Production	CO$_2$	3.3	2.7	<0.01	<0.001	0.1	99
CH$_4$ Emissions from Iron and Steel Production & Metallurgical Coke Production	CH$_4$	1.0	0.4	<0.01	<0.001	0.1	99
CH$_4$ Emissions from Wastewater Treatment	CH$_4$	23.5	24.5	<0.01	<0.001	0.1	100
CO$_2$ Emissions from Phosphoric Acid Production	CO$_2$	1.5	1.0	<0.01	<0.001	0.1	100
N$_2$O Emissions from Mobile Combustion: Aviation	N$_2$O	1.7	1.3	<0.01	<0.001	0.1	100
N$_2$O Emissions from Mobile Combustion: Other	N$_2$O	1.3	1.8	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Stationary Combustion - Coal	CO$_2$	1,718.4	1,841.0	<0.01	<0.001	<0.1	100
N$_2$O Emissions from Product Uses	N$_2$O	4.4	4.4	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Rice Cultivation	CH$_4$	7.1	7.3	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Titanium Dioxide Production	CO$_2$	1.2	1.5	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Silicon Carbide Production and Consumption	CO$_2$	0.4	0.1	<0.01	<0.001	<0.1	100

IPCC Source Categories	Direct GHG	1990 Estimate (Tg CO$_2$ Eq.)	2009 Estimate (Tg CO$_2$ Eq.)	Tier 1 Trend Assessment	Tier 2 Trend Assessment	Percent Contribution to Trend (%)	Cumulative Contribution to Trend (%)
CO$_2$ Emissions from Zinc Production	CO$_2$	0.7	1.0	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Carbon Dioxide Consumption	CO$_2$	1.4	1.8	<0.01	<0.001	<0.1	100
N$_2$O Emissions from Mobile Combustion: Marine	N$_2$O	0.6	0.4	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Soda Ash Production and Consumption	CO$_2$	4.1	4.3	<0.01	<0.001	<0.1	100
N$_2$O Emissions from Incineration of Waste	N$_2$O	0.5	0.4	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Petroleum Systems	CO$_2$	0.6	0.5	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Mobile Combustion: Other	CH$_4$	0.3	0.4	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Petrochemical Production	CH$_4$	0.9	0.8	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Mobile Combustion: Aviation	CH$_4$	0.2	0.1	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Field Burning of Agricultural Residues	CH$_4$	0.3	0.2	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Stationary Combustion - Geothermal Energy	CO$_2$	0.4	0.4	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Lead Production	CO$_2$	0.5	0.5	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Silicon Carbide Production and Consumption	CH$_4$	+	+	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Ferroalloy Production	CH$_4$	+	+	<0.01	<0.001	<0.1	100
N$_2$O Emissions from Field Burning of Agricultural Residues	N$_2$O	0.1	0.1	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Mobile Combustion: Marine	CH$_4$	+	+	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Incineration of Waste	CH$_4$	+	+	<0.01	<0.001	<0.1	100

Note: LULUCF sources and sinks are not included in this analysis.
+ Does not exceed 0.05 Tg CO$_2$ Eq.

Table A- 9: 1990-2009 Key Source Category Tier 1 and 2 Analysis—Trend Assessment, with LULUCF

IPCC Source Categories	Direct GHG	1990 Estimate (Tg CO$_2$ Eq.)	2009 Estimate (Tg CO$_2$ Eq.)	Tier 1 Trend Assessment	Tier 2 Trend Assessment	Percent Contribution to Trend (%)	Cumulative Contribution to Trend (%)
CO$_2$ Emissions from Mobile Combustion: Road	CO$_2$	1,188.9	1,475.6	0.02	0.002	14.4	14
CO$_2$ Emissions from Stationary Combustion - Oil	CO$_2$	569.1	483.3	0.02	0.001	10.6	25
CO$_2$ Emissions from Changes in Forest Carbon Stocks	CO$_2$	681.1	863.1	0.01	0.003	9.7	35
Emissions from Substitutes for Ozone Depleting Substances	Several	0.3	120.0	0.01	0.001	9.4	44
CO$_2$ Emissions from Stationary Combustion - Gas	CO$_2$	964.5	1,164.6	0.01	0.001	9.1	53
CO$_2$ Emissions from Iron and Steel Production & Metallurgical Coke Production	CO$_2$	99.5	41.9	0.01	0.001	5.2	58
CO$_2$ Emissions from Mobile Combustion: Aviation	CO$_2$	179.3	140.7	0.01	0.001	4.3	63
CO$_2$ Emissions from Grassland Remaining Grassland	CO$_2$	52.2	8.3	0.01	0.002	3.8	67
CH$_4$ Emissions from Landfills	CH$_4$	147.4	117.5	0.01	0.002	3.4	70
HFC-23 Emissions from HCFC-22 Production	HFCs	36.4	5.4	<0.01	<0.001	2.7	73
CO$_2$ Emissions from Urban Trees	CO$_2$	57.1	95.9	<0.01	0.001	2.7	75
CO$_2$ Emissions from Stationary Combustion - Coal	CO$_2$	1,718.4	1,841.0	<0.01	<0.001	2.1	77
N$_2$O Emissions from Mobile Combustion: Road	N$_2$O	40.3	20.3	<0.01	<0.001	1.8	79
Fugitive Emissions from Coal Mining	CH$_4$	84.1	71.0	<0.01	<0.001	1.6	81
PFC Emissions from Aluminum Production	PFCs	18.5	1.6	<0.01	<0.001	1.5	82
CO$_2$ Emissions from Mobile Combustion: Marine	CO$_2$	44.5	30.0	<0.01	<0.001	1.4	84
SF$_6$ Emissions from Electrical Transmission and Distribution	SF$_6$	28.4	12.8	<0.01	<0.001	1.4	85
N$_2$O Emissions from Adipic Acid Production	N$_2$O	15.8	1.9	<0.01	0.001	1.2	86
CH$_4$ Emissions from Manure Management	CH$_4$	31.7	49.5	<0.01	<0.001	1.2	87
Fugitive Emissions from Natural Gas Systems	CH$_4$	189.8	221.2	<0.01	0.001	1.2	89
CO$_2$ Emissions from Cropland Remaining Cropland	CO$_2$	29.4	17.4	<0.01	0.003	1.1	90
CO$_2$ Emissions from Landfilled Yard Trimmings and Food Scraps	CO$_2$	24.2	12.6	<0.01	0.001	1.1	91
CO$_2$ Emissions from Natural Gas Systems	CO$_2$	37.6	32.2	<0.01	<0.001	0.7	92
Fugitive Emissions from Petroleum Systems	CH$_4$	35.4	30.9	<0.01	0.001	0.6	92
CO$_2$ Emissions from Cement Production	CO$_2$	33.3	29.0	<0.01	<0.001	0.6	93
Direct N$_2$O Emissions from Agricultural Soil Management	N$_2$O	153.8	160.2	<0.01	<0.001	0.6	93
CO$_2$ Emissions from Ammonia Production and Urea Consumption	CO$_2$	16.8	11.8	<0.01	<0.001	0.5	94

IPCC Source Categories	Direct GHG	1990 Estimate (Tg CO$_2$ Eq.)	2009 Estimate (Tg CO$_2$ Eq.)	Tier 1 Trend Assessment	Tier 2 Trend Assessment	Percent Contribution to Trend (%)	Cumulative Contribution to Trend (%)
CO$_2$ Emissions from Mobile Combustion: Other	CO$_2$	73.3	73.5	<0.01	<0.001	0.5	94
CO$_2$ Emissions from Non-Energy Use of Fuels	CO$_2$	118.6	123.4	<0.01	<0.001	0.4	95
SF$_6$ Emissions from Magnesium Production and Processing	SF$_6$	5.4	1.1	<0.01	<0.001	0.4	95
N$_2$O Emissions from Nitric Acid Production	N$_2$O	17.7	14.6	<0.01	<0.001	0.4	95
CO$_2$ Emissions from Aluminum Production	CO$_2$	6.8	3.0	<0.01	<0.001	0.3	96
CH$_4$ Emissions from Forest Fires	CH$_4$	3.2	7.8	<0.01	0.001	0.3	96
CH$_4$ Emissions from Enteric Fermentation	CH$_4$	132.1	139.8	<0.01	<0.001	0.3	96
CO$_2$ Emissions from Incineration of Waste	CO$_2$	8.0	12.3	<0.01	<0.001	0.3	97
CO$_2$ Emissions from Land Converted to Cropland	CO$_2$	2.2	5.9	<0.01	<0.001	0.3	97
N$_2$O Emissions from Forest Fires	N$_2$O	2.6	6.4	<0.01	0.001	0.3	97
Indirect N$_2$O Emissions from Applied Nitrogen	N$_2$O	44.0	44.4	<0.01	0.001	0.3	98
CH$_4$ Emissions from Mobile Combustion: Road	CH$_4$	4.2	1.4	<0.01	<0.001	0.2	98
PFC, HFC, and SF$_6$ Emissions from Semiconductor Manufacture	Several	2.9	5.3	<0.01	<0.001	0.2	98
N$_2$O Emissions from Manure Management	N$_2$O	14.5	17.9	<0.01	<0.001	0.2	98
CO$_2$ Emissions from Limestone and Dolomite Use	CO$_2$	5.1	7.6	<0.01	<0.001	0.2	98
CO$_2$ Emissions from Land Converted to Grassland	CO$_2$	19.8	23.6	<0.01	<0.001	0.2	98
Non-CO$_2$ Emissions from Stationary Combustion	CH$_4$	7.4	6.2	<0.01	<0.001	0.2	99
N2O Emissions from Composting	N$_2$O	0.4	1.8	<0.01	<0.001	0.1	99
CH$_4$ Emissions from Composting	CH$_4$	0.3	1.7	<0.01	<0.001	0.1	99
CO$_2$ Emissions from Lime Production	CO$_2$	11.5	11.2	<0.01	<0.001	0.1	99
Non-CO$_2$ Emissions from Stationary Combustion	N$_2$O	12.8	12.8	<0.01	<0.001	0.1	99
Fugitive Emissions from Abandoned Underground Coal Mines	CH$_4$	6.0	5.5	<0.01	<0.001	0.1	99
N$_2$O Emissions from Wastewater Treatment	N$_2$O	3.7	5.0	<0.01	<0.001	0.1	99
CH$_4$ Emissions from Wastewater Treatment	CH$_4$	23.5	24.5	<0.01	<0.001	0.1	99
CO$_2$ Emissions from Urea Fertilization	CO$_2$	2.4	3.6	<0.01	<0.001	0.1	99
CO$_2$ Emissions from Ferroalloy Production	CO$_2$	2.2	1.5	<0.01	<0.001	0.1	99
CO$_2$ Emissions from Petrochemical Production	CO$_2$	3.3	2.7	<0.01	<0.001	0.1	99
CO$_2$ Emissions from Liming of Agricultural Soils	CO$_2$	4.7	4.2	<0.01	<0.001	0.1	100
CH$_4$ Emissions from Iron and Steel Production & Metallurgical Coke Production	CH$_4$	1.0	0.4	<0.01	<0.001	0.1	100
CO$_2$ Emissions from Phosphoric Acid Production	CO$_2$	1.5	1.0	<0.01	<0.001	<0.1	100
N$_2$O Emissions from Mobile Combustion: Aviation	N$_2$O	1.7	1.3	<0.01	<0.001	<0.1	100
N$_2$O Emissions from Settlement Soils	N$_2$O	1.0	1.5	<0.01	<0.001	<0.1	100
N$_2$O Emissions from Mobile Combustion: Other	N$_2$O	1.3	1.8	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Rice Cultivation	CH$_4$	7.1	7.3	<0.01	<0.001	<0.1	100
N$_2$O Emissions from Product Uses	N$_2$O	4.4	4.4	<0.01	<0.001	<0.1	100
N$_2$O Emissions from Forest Soils	N$_2$O	0.1	0.4	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Silicon Carbide Production and Consumption	CO$_2$	0.4	0.1	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Titanium Dioxide Production	CO$_2$	1.2	1.5	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Zinc Production	CO$_2$	0.7	1.0	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Soda Ash Production and Consumption	CO$_2$	4.1	4.3	<0.01	<0.001	<0.1	100
N$_2$O Emissions from Mobile Combustion: Marine	N$_2$O	0.6	0.4	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Carbon Dioxide Consumption	CO$_2$	1.4	1.8	<0.01	<0.001	<0.1	100
N$_2$O Emissions from Incineration of Waste	N$_2$O	0.5	0.4	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Petroleum Systems	CO$_2$	0.6	0.5	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Petrochemical Production	CH$_4$	0.9	0.8	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Mobile Combustion: Other	CH$_4$	0.3	0.4	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Mobile Combustion: Aviation	CH$_4$	0.2	0.1	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Field Burning of Agricultural Residues	CH$_4$	0.3	0.2	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Stationary Combustion - Geothermal Energy	CO$_2$	0.4	0.4	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Lead Production	CO$_2$	0.5	0.5	<0.01	<0.001	<0.1	100
CO$_2$ Emissions from Wetlands Remaining Wetlands	CO$_2$	1.0	1.1	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Silicon Carbide Production and Consumption	CH$_4$	+	+	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Ferroalloy Production	CH$_4$	+	+	<0.01	<0.001	<0.1	100
N$_2$O Emissions from Field Burning of Agricultural Residues	N$_2$O	0.1	0.1	<0.01	<0.001	<0.1	100

IPCC Source Categories	Direct GHG	1990 Estimate (Tg CO$_2$ Eq.)	2009 Estimate (Tg CO$_2$ Eq.)	Tier 1 Trend Assessment	Tier 2 Trend Assessment	Percent Contribution to Trend (%)	Cumulative Contribution to Trend (%)
CH$_4$ Emissions from Mobile Combustion: Marine	CH$_4$	+	+	<0.01	<0.001	<0.1	100
N$_2$O Emissions from Wetlands Remaining Wetlands	N$_2$O	+	+	<0.01	<0.001	<0.1	100
CH$_4$ Emissions from Incineration of Waste	CH$_4$	+	+	<0.01	<0.001	<0.1	100

+ Does not exceed 0.05 Tg CO$_2$ Eq.

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ANNEX 2 Methodology and Data for Estimating CO_2 Emissions from Fossil Fuel Combustion

2.1. Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion

Carbon dioxide (CO_2) emissions from fossil fuel combustion were estimated using a "bottom-up" methodology characterized by seven steps. These steps are described below.

Step 1: Determine Total Fuel 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). Total consumption data and adjustments to consumption are presented in Columns 2 through 13 of Table A- 10.

Adjusted consumption data are presented in Columns 2 through 8 of Table A- 11 through Table A- 30 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 the Constants, Units, and Conversions Annex). 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 2009 total adjusted energy consumption across all sectors, including territories, and energy types was 71,949.8 trillion British thermal units (TBtu), as indicated in the last entry of Column 8 in Table A- 11. This total excludes fuel used for non-energy purposes and fuel consumed as international bunkers, both of which were deducted in earlier steps.

Electricity consumption information was allocated to each sector based on EIA's distribution of electricity retail sales to ultimate customers (i.e., residential, commercial, industrial, and other). Because the "other" fuel use includes sales to both the commercial and transportation sectors, EIA's limited transportation electricity use data were subtracted from "other" electricity use and also reported separately. This total was consequently combined with the commercial electricity data. Further information on these electricity end uses is described in EIA's *Annual Energy Review* (EIA 2010b).

There are also three basic differences between the consumption data presented in Table A- 11 through Table A-30 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.

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[1] Also referred to as Gross Calorific Values (GCV).
[2] Also referred to as Net Calorific Values (NCV).

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 UNFCCC are to include energy consumption within territories. Therefore, consumption estimates for U.S. territories[3] were added to domestic consumption of fossil fuels. Energy consumption data from U.S. territories are presented in Column 7 of Table A- 11 through Table A- 30. It is reported separately from domestic sectoral consumption, because it is collected separately by EIA with no sectoral disaggregation.

Third, 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 select amounts of coking coal, petroleum coke, natural gas, residual fuel oil, and other oil (>401 F) for processes accounted for in the Industrial Processes chapter, (2) corrections for synthetic natural gas production, (3) subtraction of other fuels used for non-energy purposes, and (4) subtraction of international bunker fuels. These adjustments are described in the following steps.

Step 2: Subtract uses accounted for in the Industrial Processes chapter.

Portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil (>401 F)—were reallocated to the Industrial Processes chapter, as these portions were consumed as raw materials during non-energy related industrial processes. Emissions from these fuels used as raw materials are presented in the Industrial Processes chapter, and are removed from the energy and non-energy consumption estimates within the Energy chapter.

- 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, lead, and zinc 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 C anodes and cathodes), (3) titanium dioxide production (in the chloride process), (4) ammonia production, and (5) silicon carbide.

- Natural gas consumption is used for the production of ammonia, and blast furnace and coke oven gas used in iron and steel production.

- Residual fuel oil and other oil (>401F) are both used in the production of C black.

- Natural gas, distillate fuel, coal, and metallurgical coke are used to produce pig iron through the reduction of iron ore in the production of iron and steel.

Step 3: Adjust for Conversion of Fossil Fuels and Exports

First, a portion of industrial "other" coal that is accounted for in EIA coal combustion statistics is actually used to make "synthetic natural gas" via coal gasification at the Dakota Gasification Plant, a synthetic natural gas plant. The plant produces synthetic natural gas and byproduct CO_2. The synthetic natural gas enters the natural gas distribution system. Since October 2000, a portion of the CO_2 produced by the coal gasification plant has been exported to Canada by pipeline. The remainder of the CO_2 byproduct from the plant is released to the atmosphere. The energy in this synthetic natural gas enters the natural gas distribution stream, and is accounted for in EIA natural gas combustion statistics. Because this energy of the synthetic natural gas is already accounted for as natural gas combustion, this amount of energy is deducted from the industrial coal consumption statistics to avoid double counting. The exported CO_2 is not emitted to the atmosphere in the United States, and therefore the energy used to produce this amount of CO_2 is subtracted from industrial other coal.

Step 4: Subtract Consumption for Non-Energy Use

U.S. aggregate energy statistics include consumption of fossil fuels for non-energy purposes. Depending on the end-use, non-energy uses of fossil fuels can result in long term storage of some or all of the C contained in the fuel. For example, asphalt made from petroleum can sequester up to 100 percent of the C contained in the petroleum feedstock for extended periods of time. Other non-energy fossil fuel products, such as lubricants or plastics also store C, but can lose or emit

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[3] 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

some of this C when they are used and/or burned as waste.[4] As the emission pathways of C used for non-energy purposes are vastly different than fuel combustion, these emissions are estimated separately in the Carbon Emitted in Products from Non-Energy Uses of Fossil Fuels section in this chapter. Therefore, the amount of fuels used for non-energy purposes, shown in Table A-31, was subtracted from total fuel consumption.

Step 5: Subtract Consumption of 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. Therefore, the amount of consumption for international bunker fuels was estimated and subtracted from total fuel consumption (see Table A-32). Emissions from international bunker fuels have been estimated separately and not included in national totals.[5]

Step 6: Determine the C Content of All Fuels

The C content of combusted fossil fuels was estimated by multiplying adjusted energy consumption (Columns 2 through 8 of Table A- 11 through Table A- 30) by fuel-specific C content coefficients (see Table A- 33 and Table A- 34) that reflect the amount of C per unit of energy in each fuel. The C content coefficients used in the U.S. inventory were derived by EIA from detailed fuel information and are similar to the C 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 7: Estimate CO_2 Emissions

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). Emission estimates are expressed in teragrams of carbon dioxide equivalents (Tg CO_2 Eq.). To convert from C content to CO_2 emissions, the fraction of C that is oxidized was applied. This fraction was 100 percent based on guidance in IPCC (2006).

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-35). This pro-rated approach to allocating emissions from electricity generation may overestimate or underestimate emissions for particular sectors due to differences in the average C content of fuel mixes burned to generate electricity.

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[4] See the Waste Incineration section of the Energy chapter and the Waste Incineration Annex for a discussion of emissions from the combustion of plastics in the municipal solid waste stream.

[5] 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.

Table A- 10: 2009 Energy Consumption Data by Fuel Type (TBtu) and Adjusted Energy Consumption Data

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*

Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Bunker Fuel	Ind.	Trans.	Terr.	Total Adjusted Consumption
			Total Consumption (TBtu)[a]						Adjustments (TBtu)[b] — Unadjusted NEU Consumption			
Total Coal	**6.8**	**61.5**	**899.3**	**NE**	**18,296.2**	**38.2**	**19,302.0**		**18.5**			**19,283.4**
Residential Coal	6.8						6.8					6.8
Commercial Coal		61.5					61.5					61.5
Industrial Coking Coal			6.1				6.1		6.1			
Industrial Other Coal			893.2				893.2		12.4			880.8
Transportation Coal				NE			NE					
Electric Power Coal					18,296.2		18,296.2					18,296.2
U.S. Territory Coal (bit)						38.2	38.2					38.2
Natural Gas	**4,852.1**	**3,168.3**	**7,275.6**	**684.2**	**7,038.5**	**27.4**	**23,046.2**		**388.4**			**22,657.8**
Total Petroleum	**1,196.5**	**708.5**	**7,865.3**	**25,177.1**	**389.8**	**560.3**	**35,897.5**	**1,678.1**	**4,079.4**	**127.1**	**56.3**	**29,956.7**
Asphalt & Road Oil			873.1				873.1		873.1			
Aviation Gasoline				26.6			26.6					26.6
Distillate Fuel Oil	591.7	406.3	1,085.5	5,555.0	70.6	74.3	7,783.4	112.3	17.5			7,653.6
Jet Fuel				2,883.3		41.7	2,925.0	961.0				1,964.0
Kerosene	26.2	5.3	4.9			7.6	43.9					43.9
LPG	578.7	165.4	1,878.4	41.2		14.9	2,678.6		1,520.5			1,158.1
Lubricants			134.5	127.1		1.0	262.6		134.5	127.1	1.0	
Motor Gasoline		68.8	376.3	15,779.7		199.8	16,424.7					16,424.7
Residual Fuel		62.4	102.7	764.2	180.7	165.7	1,275.7	604.8				670.9
Other Petroleum												
AvGas Blend Components			(0.8)				(0.8)					(0.8)
Crude Oil												
MoGas Blend Components												
Misc. Products			151.8			55.2	207.1		151.8		55.2	
Naphtha (<401 deg. F)			471.9				471.9		471.9			
Other Oil (>401 deg. F)			424.8				424.8		424.8			
Pentanes Plus			127.5				127.5		97.7			29.9
Petroleum Coke		0.3	799.0		138.6		937.9		195.4			742.4
Still Gas			1,455.0				1,455.0		133.9			1,321.1
Special Naphtha			46.2				46.2		46.2			
Unfinished Oils			(77.8)				(77.8)					(77.8)
Waxes			12.2				12.2		12.2			
Geothermal					**51.9**		**51.9**					**51.9**
TOTAL (All Fuels)	**6,055.5**	**3,938.3**	**16,040.1**	**25,861.3**	**25,776.4**	**625.9**	**78,297.5**	**1,678.1**	**4,486.3**	**127.1**	**56.3**	**71,949.8**

[a] Expressed as gross calorific values (i.e., higher heating values).
[b] Adjustments are subtracted from total consumption estimates and include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).
NE (Not Estimated)

Table A- 11: 2009 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*
	Adjusted Consumption (TBtu)[a]							**Emissions[b] (Tg CO$_2$ Eq.) from Energy Use**						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**6.8**	**61.5**	**880.8**	**NE**	**18,296.2**	**38.2**	**19,283.4**	**0.6**	**5.8**	**83.4**	**NE**	**1,747.6**	**3.5**	**1,841.0**
Residential Coal	6.8						6.8	0.6						0.6
Commercial Coal		61.5					61.5		5.8					5.8
Industrial Other Coal			880.8				880.8			83.4				83.4
Transportation Coal				NE										NE
Electric Power Coal					18,296.2		18,296.2					1,747.6		1,747.6
U.S. Territory Coal (bit)						38.2	38.2						3.5	3.5
Natural Gas	**4,852.1**	**3,168.3**	**6,887.2**	**684.2**	**7,038.5**	**27.4**	**22,657.8**	**257.2**	**167.9**	**365.0**	**36.3**	**373.1**	**1.5**	**1,200.9**
Total Petroleum	**1,196.5**	**708.5**	**3,785.9**	**23,371.9**	**389.8**	**504.0**	**29,956.7**	**81.4**	**50.3**	**282.0**	**1,683.4**	**32.9**	**36.7**	**2,166.7**
Asphalt & Road Oil														
Aviation Gasoline				26.6			26.6				1.8			1.8
Distillate Fuel Oil	591.7	406.3	1,068.1	5,442.7	70.6	74.3	7,653.6	43.8	30.0	79.0	402.5	5.2	5.5	566.0
Jet Fuel				1,922.3		41.7	1,964.0				138.8		3.0	141.8
Kerosene	26.2	5.3	4.9			7.6	43.9	1.9	0.4	0.4			0.6	3.2
LPG	578.7	165.4	357.9	41.2		14.9	1,158.1	35.7	10.2	22.1	2.5		0.9	71.5
Lubricants														
Motor Gasoline		68.8	376.3	15,779.7		199.8	16,424.7		4.9	26.8	1,125.7		14.3	1,171.7
Residual Fuel		62.4	102.7	159.4	180.7	165.7	670.9		4.7	7.7	12.0	13.6	12.4	50.4
Other Petroleum														
AvGas Blend Components			(0.8)				(0.8)			(0.1)				(0.1)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			29.9				29.9			2.1				2.1
Petroleum Coke		0.3	603.6		138.6		742.4		0.0	61.6		14.2		75.8
Still Gas			1,321.1				1,321.1			88.1				88.1
Special Naphtha														
Unfinished Oils			(77.8)				(77.8)			(5.8)				(5.8)
Waxes														
Geothermal					51.9		51.9					0.4		0.4
TOTAL (All Fuels)	**6,055.5**	**3,938.3**	**11,553.8**	**24,056.2**	**25,776.4**	**569.6**	**71,949.8**	**339.2**	**224.0**	**730.4**	**1,719.7**	**2,154.0**	**41.7**	**5,209.0**

[a] Expressed as gross calorific values (i.e., higher heating values).

[b] Adjustments are subtracted from total consumption estimates and include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).

NE (Not Estimated)

Table A-12: 2008 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
		Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO$_2$ Eq.) from Energy Use						
Fuel Type		Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal		**7.7**	**69.1**	**1,083.4**	**NE**	**20,513.0**	**35.7**	**21,708.7**	**0.7**	**6.5**	**102.6**	**NE**	**1,959.4**	**3.3**	**2,072.5**
Residential Coal		7.7						7.7	0.7						0.7
Commercial Coal			69.1					69.1		6.5					6.5
Industrial Other Coal				1,083.4				1,083.4			102.6				102.6
Transportation Coal					NE										NE
Electric Power Coal						20,513.0		20,513.0					1,959.4		1,959.4
U.S. Territory Coal (bit)							35.7	35.7						3.3	3.3
Natural Gas		**4,989.4**	**3,211.3**	**7,377.7**	**694.5**	**6,828.9**	**29.3**	**23,130.9**	**264.4**	**170.2**	**391.0**	**36.8**	**361.9**	**1.6**	**1,226.0**
Total Petroleum		**1,214.7**	**669.3**	**4,165.2**	**24,319.9**	**467.7**	**478.6**	**31,315.4**	**83.1**	**47.4**	**309.3**	**1,753.1**	**39.2**	**35.0**	**2,267.1**
Asphalt & Road Oil															
Aviation Gasoline					28.3			28.3				2.0			2.0
Distillate Fuel Oil		640.7	355.9	1,197.9	5,996.5	73.1	94.3	8,358.3	47.4	26.3	88.6	443.5	5.4	7.0	618.2
Jet Fuel					2,147.3		34.9	2,182.2				155.1		2.5	157.6
Kerosene		21.3	4.3	4.0			5.8	35.3	1.6	0.3	0.3			0.4	2.6
LPG		552.7	158.0	382.0	39.4		15.7	1,147.8	34.1	9.7	23.6	2.4		1.0	70.8
Lubricants															
Motor Gasoline			77.7	424.9	15,843.4		134.0	16,480.1		5.5	30.3	1,130.3		9.6	1,175.7
Residual Fuel			73.2	135.6	265.0	240.4	193.9	908.1		5.5	10.2	19.9	18.1	14.6	68.2
Other Petroleum															
AvGas Blend Components				0.1				0.1			0.0				0.0
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus				35.8				35.8			2.5				2.5
Petroleum Coke			0.3	615.6		154.2		770.1		0.0	62.9		15.7		78.6
Still Gas				1,423.0				1,423.0			94.9				94.9
Special Naphtha															
Unfinished Oils				(53.7)				(53.7)			(4.0)				(4.0)
Waxes															
Geothermal						51.0		51.0					0.4		0.4
TOTAL (All Fuels)		**6,211.7**	**3,949.7**	**12,626.2**	**25,014.4**	**27,860.5**	**543.5**	**76,206.1**	**348.2**	**224.2**	**802.9**	**1,789.9**	**2,360.9**	**39.8**	**5,565.9**

[a] Expressed as gross calorific values (i.e., higher heating values).
[b] Adjustments are subtracted from total consumption estimates and include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).
NE (Not Estimated)

Table A-13: 2007 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO_2 Eq.) from Energy Use						
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal	**7.8**	**70.0**	**1,130.3**	**NE**	**20,807.7**	**46.5**	**22,062.4**	**0.7**	**6.7**	**107.0**	**NE**	**1,987.3**	**4.3**	**2,106.0**
Residential Coal	7.8						7.8	0.7						0.7
Commercial Coal		70.0					70.0		6.7					6.7
Industrial Other Coal			1,130.3				1,130.3			107.0				107.0
Transportation Coal				NE										NE
Electric Power Coal					20,807.7		20,807.7					1,987.3		1,987.3
U.S. Territory Coal (bit)						46.5	46.5						4.3	4.3
Natural Gas	**4,849.6**	**3,094.1**	**7,339.6**	**665.4**	**7,005.2**	**26.8**	**22,980.6**	**257.0**	**164.0**	**389.0**	**35.3**	**371.3**	**1.4**	**1,218.0**
Total Petroleum	**1,224.9**	**680.7**	**4,679.9**	**25,685.8**	**657.1**	**551.7**	**33,480.1**	**84.6**	**48.7**	**346.0**	**1,858.7**	**53.9**	**40.4**	**2,432.4**
Asphalt & Road Oil														
Aviation Gasoline				31.6			31.6				2.2			2.2
Distillate Fuel Oil	697.3	368.7	1,185.5	6,439.7	89.3	136.5	8,917.0	51.6	27.3	87.7	476.3	6.6	10.1	659.5
Jet Fuel				2,336.3		55.5	2,391.8				168.7		4.0	172.7
Kerosene	43.9	9.2	13.4			5.2	71.8	3.2	0.7	1.0			0.4	5.3
LPG	483.7	121.4	563.7	21.9		11.6	1,202.3	29.8	7.5	34.8	1.4		0.7	74.2
Lubricants														
Motor Gasoline		105.6	528.7	16,470.1		157.0	17,261.4		7.6	37.9	1,181.2		11.3	1,238.0
Residual Fuel		75.4	130.4	386.1	396.6	185.9	1,174.4		5.7	9.8	29.0	29.8	14.0	88.2
Other Petroleum														
AvGas Blend Components			1.8				1.8			0.1				0.1
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			42.0				42.0			2.9				2.9
Petroleum Coke		0.4	666.7		171.2		838.3		0.0	68.1		17.5		85.6
Still Gas			1,482.6				1,482.6			98.9				98.9
Special Naphtha														
Unfinished Oils			65.2				65.2			4.8				4.8
Waxes														
Geothermal					49.9		49.9					0.4		0.4
TOTAL (All Fuels)	**6,082.2**	**3,844.8**	**13,149.8**	**26,351.2**	**28,520.0**	**625.0**	**78,572.9**	**342.4**	**219.4**	**842.0**	**1,894.0**	**2,412.8**	**46.1**	**5,756.7**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).

[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

NE (Not Estimated)

Table A-14: 2006 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO_2 Eq.) from Energy Use						
Fuel Type		Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal		**6.4**	**64.8**	**1,188.3**	**NE**	**20,461.9**	**36.9**	**21,758.2**	**0.6**	**6.2**	**112.6**	**NE**	**1,953.7**	**3.4**	**2,076.5**
Residential Coal		6.4						6.4	0.6						0.6
Commercial Coal			64.8					64.8		6.2					6.2
Industrial Other Coal				1,188.3				1,188.3			112.6				112.6
Transportation Coal					NE			NE							NE
Electric Power Coal						20,461.9		20,461.9					1,953.7		1,953.7
U.S. Territory Coal (bit)							36.9	36.9						3.4	3.4
Natural Gas		**4,475.9**	**2,901.7**	**7,125.0**	**625.0**	**6,375.1**	**26.1**	**21,528.8**	**237.3**	**153.8**	**377.7**	**33.1**	**338.0**	**1.4**	**1,141.3**
Total Petroleum		**1,204.9**	**677.7**	**4,842.3**	**25,589.8**	**648.1**	**620.9**	**33,583.6**	**83.6**	**48.5**	**357.9**	**1,845.0**	**54.4**	**45.5**	**2,434.9**
Asphalt & Road Oil															
Aviation Gasoline					33.4			33.4				2.3			2.3
Distillate Fuel Oil		693.0	390.5	1,199.4	6,358.6	73.7	90.2	8,805.3	51.3	28.9	88.7	470.3	5.4	6.7	651.2
Jet Fuel					2,347.1		76.1	2,423.2				169.5		5.5	175.0
Kerosene		66.4	15.2	29.6			4.4	115.5	4.9	1.1	2.2			0.3	8.5
LPG		445.5	123.2	587.5	27.5		6.6	1,190.2	27.5	7.6	36.3	1.7		0.4	73.5
Lubricants															
Motor Gasoline			73.4	567.0	16,516.8		188.8	17,345.9		5.2	40.4	1,178.2		13.5	1,237.4
Residual Fuel			75.3	176.4	306.3	360.5	254.8	1,173.3		5.7	13.2	23.0	27.1	19.1	88.1
Other Petroleum															
AvGas Blend Components				0.6				0.6			0.0				0.0
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus				32.8				32.8			2.3				2.3
Petroleum Coke			0.3	682.5		213.9		896.7		0.0	69.7		21.8		91.6
Still Gas				1,496.1				1,496.1			99.8				99.8
Special Naphtha															
Unfinished Oils				70.3				70.3			5.2				5.2
Waxes															
Geothermal						**49.7**		**49.7**					**0.4**		**0.4**
TOTAL (All Fuels)		**5,687.2**	**3,644.2**	**13,155.6**	**26,214.7**	**27,534.8**	**683.9**	**76,920.4**	**321.5**	**208.6**	**848.2**	**1,878.1**	**2,346.4**	**50.3**	**5,653.1**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).

[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

NE (Not Estimated)

Table A-15: 2005 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*
	Adjusted Consumption (TBtu)[a]							**Emissions[b] (Tg CO$_2$ Eq.) from Energy Use**						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**8.4**	**97.0**	**1,219.1**	**NE**	**20,737.2**	**32.7**	**22,094.5**	**0.8**	**9.3**	**115.3**	**NE**	**1,983.8**	**3.0**	**2,112.3**
Residential Coal	8.4						8.4	0.8						0.8
Commercial Coal		97.0					97.0		9.3					9.3
Industrial Other Coal			1,219.1				1,219.1			115.3				115.3
Transportation Coal				NE			NE							NE
Electric Power Coal					20,737.2		20,737.2					1,983.8		1,983.8
U.S. Territory Coal (bit)						32.7	32.7						3.0	3.0
Natural Gas	**4,946.4**	**3,073.2**	**7,184.9**	**623.9**	**6,014.5**	**24.3**	**21,867.2**	**262.2**	**162.9**	**380.8**	**33.1**	**318.8**	**1.3**	**1,159.0**
Total Petroleum	**1,369.2**	**716.0**	**4,401.3**	**25,932.6**	**1,234.5**	**623.3**	**34,276.9**	**94.9**	**51.3**	**326.9**	**1,863.5**	**99.2**	**45.7**	**2,481.5**
Asphalt & Road Oil														
Aviation Gasoline				35.4			35.4				2.4			2.4
Distillate Fuel Oil	772.6	404.7	1,124.5	6,193.8	114.6	121.3	8,731.6	57.1	29.9	83.2	458.1	8.5	9.0	645.8
Jet Fuel				2,689.2		66.0	2,755.2				194.2		4.8	199.0
Kerosene	83.8	21.6	39.1			5.8	150.2	6.1	1.6	2.9			0.4	11.0
LPG	512.9	131.4	521.0	28.2		0.8	1,194.2	31.7	8.1	32.2	1.7		0.0	73.7
Lubricants														
Motor Gasoline		42.2	328.4	16,729.6		194.3	17,294.4		3.0	23.3	1,187.8		13.8	1,227.9
Residual Fuel		115.8	223.2	256.4	876.5	235.2	1,707.2		8.7	16.8	19.3	65.8	17.7	128.2
Other Petroleum														
AvGas Blend Components			8.3				8.3			0.6				0.6
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			45.9				45.9			3.2				3.2
Petroleum Coke		0.3	678.6		243.5		922.3		0.0	69.3		24.9		94.2
Still Gas			1,429.4				1,429.4			95.4				95.4
Special Naphtha														
Unfinished Oils			2.8				2.8			0.2				0.2
Waxes														
Geothermal					**50.1**		**50.1**					**0.4**		**0.4**
TOTAL (All Fuels)	**6,324.0**	**3,886.2**	**12,805.3**	**26,556.5**	**28,036.4**	**680.4**	**78,288.8**	**357.9**	**223.5**	**823.1**	**1,896.6**	**2,402.1**	**50.0**	**5,753.2**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).

[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

NE (Not Estimated)

Table A-16: 2004 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |

Fuel Type	Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO_2 Eq.) from Energy Use						
	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal	**11.4**	**102.9**	**1,262.0**	**NE**	**20,305.0**	**32.0**	**21,713.3**	**1.1**	**9.8**	**118.3**	**NE**	**1,943.1**	**2.9**	**2,075.1**
Residential Coal	11.4						11.4	1.1						1.1
Commercial Coal		102.9					102.9		9.8					9.8
Industrial Other Coal			1,262.0				1,262.0			118.3				118.3
Transportation Coal				NE			NE							NE
Electric Power Coal					20,305.0		20,305.0					1,943.1		1,943.1
U.S. Territory Coal (bit)						32.0	32.0						2.9	2.9
Natural Gas	**4,980.8**	**3,201.0**	**7,802.3**	**602.0**	**5,594.9**	**24.6**	**22,205.6**	**264.1**	**169.7**	**413.7**	**31.9**	**296.7**	**1.3**	**1,177.5**
Total Petroleum	**1,474.6**	**766.7**	**4,282.6**	**25,529.7**	**1,212.4**	**653.6**	**33,919.5**	**102.7**	**54.9**	**317.7**	**1,834.9**	**96.9**	**47.9**	**2,455.0**
Asphalt & Road Oil														
Aviation Gasoline				31.2			31.2				2.2			2.2
Distillate Fuel Oil	878.1	447.0	1,136.6	5,917.7	111.3	134.4	8,625.2	64.9	33.1	84.1	437.7	8.2	9.9	637.9
Jet Fuel				2,525.0		68.8	2,593.7				182.4		5.0	187.3
Kerosene	84.8	20.5	28.2			6.0	139.5	6.2	1.5	2.1			0.4	10.2
LPG	511.7	152.0	564.8	19.1		0.8	1,248.4	31.6	9.4	34.9	1.2		0.0	77.1
Lubricants														
Motor Gasoline		24.4	203.4	16,850.3		198.6	17,276.7		1.7	14.5	1,197.6		14.1	1,227.9
Residual Fuel		122.5	195.3	186.4	879.0	245.0	1,628.2		9.2	14.7	14.0	66.0	18.4	122.3
Other Petroleum														
AvGas Blend Components			10.6				10.6			0.7				0.7
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			52.1				52.1			3.6				3.6
Petroleum Coke		0.3	683.9		222.1		906.2		0.0	69.8		22.7		92.5
Still Gas			1,483.3				1,483.3			99.0				99.0
Special Naphtha														
Unfinished Oils			(75.6)				(75.6)			(5.6)				(5.6)
Waxes														
Geothermal					50.5		50.5					0.4		0.4
TOTAL (All Fuels)	**6,466.8**	**4,070.6**	**13,346.9**	**26,131.6**	**27,162.9**	**710.2**	**77,889.0**	**367.9**	**234.4**	**849.6**	**1,866.8**	**2,337.0**	**52.2**	**5,708.0**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-17: 2003 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
		Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO$_2$ Eq.) from Energy Use						
Fuel Type		Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal		**12.2**	**82.0**	**1,248.8**	**NE**	**20,184.7**	**33.9**	**21,561.7**	**1.2**	**7.8**	**117.0**	**NE**	**1,931.0**	**3.1**	**2,060.1**
Residential Coal		12.2						12.2	1.2						1.2
Commercial Coal			82.0					82.0		7.8					7.8
Industrial Other Coal				1,248.8				1,248.8			117.0				117.0
Transportation Coal					NE										NE
Electric Power Coal						20,184.7		20,184.7					1,931.0		1,931.0
U.S. Territory Coal (bit)							33.9	33.9						3.1	3.1
Natural Gas		**5,209.4**	**3,260.9**	**7,806.1**	**627.4**	**5,246.2**	**26.9**	**22,177.0**	**275.9**	**172.7**	**413.4**	**33.2**	**277.8**	**1.4**	**1,174.3**
Total Petroleum		**1,466.1**	**762.1**	**4,018.7**	**24,937.8**	**1,205.0**	**621.8**	**33,011.5**	**101.8**	**54.5**	**299.3**	**1,790.4**	**95.0**	**45.3**	**2,386.3**
Asphalt & Road Oil															
Aviation Gasoline					30.2			30.2				2.1			2.1
Distillate Fuel Oil		851.3	453.1	1,054.1	5,710.9	161.0	120.5	8,350.8	63.0	33.5	78.0	422.4	11.9	8.9	617.6
Jet Fuel					2,480.8		76.1	2,556.9				179.2		5.5	184.7
Kerosene		70.3	18.6	24.1			10.7	123.7	5.1	1.4	1.8			0.8	9.1
LPG		544.5	156.9	484.6	16.5		10.5	1,213.0	33.7	9.7	30.0	1.0		0.7	75.0
Lubricants															
Motor Gasoline			22.0	119.2	16,600.2		210.1	16,951.6		1.6	8.5	1,178.3		14.9	1,203.2
Residual Fuel			111.1	171.7	99.1	869.4	193.9	1,445.2		8.3	12.9	7.4	65.3	14.6	108.5
Other Petroleum															
AvGas Blend Components				7.5				7.5			0.5				0.5
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus				51.7				51.7			3.6				3.6
Petroleum Coke			0.3	678.9		174.7		853.9		0.0	69.3		17.8		87.2
Still Gas				1,477.3				1,477.3			98.6				98.6
Special Naphtha															
Unfinished Oils				(50.4)				(50.4)			(3.7)				(3.7)
Waxes															
Geothermal						49.2		49.2					0.4		0.4
TOTAL (All Fuels)		**6,687.8**	**4,104.9**	**13,073.5**	**25,565.3**	**26,685.2**	**682.6**	**76,799.3**	**378.8**	**235.0**	**829.6**	**1,823.6**	**2,304.2**	**49.9**	**5,621.1**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).

[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

NE (Not Estimated)

Table A-18: 2002 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |

		Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO₂ Eq.) from Energy Use						
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal	**12.2**	**89.8**	**1,243.7**	**NE**	**19,782.8**	**10.8**	**21,139.3**	**1.2**	**8.6**	**116.6**	**NE**	**1,889.9**	**1.0**	**2,017.2**
Residential Coal	12.2						12.2	1.2						1.2
Commercial Coal		89.8					89.8		8.6					8.6
Industrial Other Coal			1,243.7				1,243.7			116.6				116.6
Transportation Coal				NE										NE
Electric Power Coal					19,782.8		19,782.8					1,889.9		1,889.9
U.S. Territory Coal (bit)						10.8	10.8						1.0	1.0
Natural Gas	**5,014.5**	**3,225.0**	**8,100.0**	**701.6**	**5,766.8**	**22.8**	**22,830.7**	**265.8**	**170.9**	**429.3**	**37.2**	**305.7**	**1.2**	**1,210.1**
Total Petroleum	**1,358.9**	**645.4**	**3,860.0**	**24,844.0**	**961.3**	**556.8**	**32,226.5**	**93.9**	**46.1**	**287.5**	**1,785.1**	**76.8**	**40.6**	**2,329.9**
Asphalt & Road Oil														
Aviation Gasoline				33.7			33.7				2.3			2.3
Distillate Fuel Oil	761.8	393.4	1,048.4	5,595.9	127.4	92.8	8,019.7	56.3	29.1	77.5	413.9	9.4	6.9	593.1
Jet Fuel				2,448.5		61.8	2,510.2				176.8		4.5	181.3
Kerosene	59.9	15.9	13.8			8.2	97.9	4.4	1.2	1.0			0.6	7.2
LPG	537.1	140.8	539.3	14.3		11.2	1,242.7	33.2	8.7	33.3	0.9		0.7	76.8
Lubricants														
Motor Gasoline		15.2	104.2	16,523.7		189.4	16,832.5		1.1	7.4	1,174.1		13.5	1,196.0
Residual Fuel		79.8	146.1	227.9	658.7	193.6	1,306.1		6.0	11.0	17.1	49.5	14.5	98.1
Other Petroleum														
AvGas Blend Components			7.5				7.5			0.5				0.5
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			52.4				52.4			3.7				3.7
Petroleum Coke		0.2	680.7		175.2		856.1		0.0	69.5		17.9		87.4
Still Gas			1,403.3				1,403.3			93.6				93.6
Special Naphtha														
Unfinished Oils			(135.7)				(135.7)			(10.1)				(10.1)
Waxes														
Geothermal					49.4		49.4					0.4		0.4
TOTAL (All Fuels)	**6,385.6**	**3,960.3**	**13,203.7**	**25,545.6**	**26,560.3**	**590.5**	**76,245.9**	**360.9**	**225.6**	**833.4**	**1,822.3**	**2,272.7**	**42.8**	**5,557.6**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-19: 2001 Energy Consumption Data and CO$_2$ Emissions from Fossil Fuel Combustion by Fuel Type

	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO$_2$ Eq.) from Energy Use						
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal	**12.0**	**96.9**	**1,358.4**	**NE**	**19,613.7**	**3.8**	**21,084.8**	**1.1**	**9.2**	**127.8**	**NE**	**1,869.8**	**0.4**	**2,008.4**
Residential Coal	12.0						12.0	1.1						1.1
Commercial Coal		96.9					96.9		9.2					9.2
Industrial Other Coal			1,358.4				1,358.4			127.8				127.8
Transportation Coal				NE										NE
Electric Power Coal					19,613.7		19,613.7					1,869.8		1,869.8
U.S. Territory Coal (bit)						3.8	3.8						0.4	0.4
Natural Gas	**4,889.0**	**3,097.3**	**7,933.2**	**658.0**	**5,458.1**	**22.9**	**22,058.5**	**259.1**	**164.2**	**420.5**	**34.9**	**289.3**	**1.2**	**1,169.1**
Total Petroleum	**1,463.0**	**718.6**	**3,932.7**	**24,428.5**	**1,276.6**	**632.2**	**32,451.6**	**101.8**	**51.5**	**293.4**	**1,752.8**	**98.5**	**46.2**	**2,344.0**
Asphalt & Road Oil														
Aviation Gasoline				34.9			34.9				2.4			2.4
Distillate Fuel Oil	842.2	471.4	1,181.8	5,417.0	170.5	109.4	8,192.3	62.3	34.9	87.4	400.6	12.6	8.1	605.9
Jet Fuel				2,605.2		98.9	2,704.0				188.1		7.1	195.3
Kerosene	95.1	31.4	23.2			0.9	150.6	7.0	2.3	1.7			0.1	11.0
LPG	525.7	142.7	461.0	13.7		7.0	1,150.1	32.5	8.8	28.5	0.8		0.4	71.1
Lubricants														
Motor Gasoline		3.1	24.3	16,198.3		187.6	16,413.2		0.2	1.7	1,148.7		13.3	1,164.0
Residual Fuel		69.9	156.1	159.5	1,002.8	228.4	1,616.7		5.2	11.7	12.0	75.3	17.2	121.4
Other Petroleum														
AvGas Blend Components			6.1				6.1			0.4				0.4
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			61.6				61.6			4.3				4.3
Petroleum Coke		0.2	663.4		103.2		766.8		0.0	67.7		10.5		78.3
Still Gas			1,430.7				1,430.7			95.5				95.5
Special Naphtha														
Unfinished Oils			(75.4)				(75.4)			(5.6)				(5.6)
Waxes														
Geothermal					46.9		46.9						0.4	0.4
TOTAL (All Fuels)	**6,364.0**	**3,912.7**	**13,224.3**	**25,086.6**	**26,395.2**	**658.9**	**75,641.7**	**362.0**	**224.9**	**841.7**	**1,787.6**	**2,257.9**	**47.8**	**5,521.9**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).

[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

NE (Not Estimated)

Table A-20: 2000 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Fuel Type	Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO_2 Eq.) from Energy Use						
		Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal		**11.4**	**91.9**	**1,348.8**	**NE**	**20,220.2**	**10.3**	**21,682.4**	**1.1**	**8.8**	**127.3**	**NE**	**1,927.4**	**0.9**	**2,065.5**
Residential Coal		11.4						11.4	1.1						1.1
Commercial Coal			91.9					91.9		8.8					8.8
Industrial Other Coal				1,348.8				1,348.8			127.3				127.3
Transportation Coal					NE										NE
Electric Power Coal						20,220.2		20,220.2					1,927.4		1,927.4
U.S. Territory Coal (bit)							10.3	10.3						0.9	0.9
Natural Gas		**5,104.6**	**3,251.6**	**8,619.2**	**672.0**	**5,293.4**	**12.7**	**22,953.5**	**270.7**	**172.5**	**457.2**	**35.6**	**280.8**	**0.7**	**1,217.4**
Total Petroleum		**1,427.5**	**694.0**	**3,586.6**	**24,715.2**	**1,144.3**	**471.7**	**32,039.3**	**98.8**	**49.6**	**266.6**	**1,773.9**	**88.4**	**34.2**	**2,311.6**
Asphalt & Road Oil															
Aviation Gasoline					36.3			36.3				2.5			2.5
Distillate Fuel Oil		778.0	422.2	1,003.7	5,442.4	174.8	71.3	7,892.5	57.5	31.2	74.2	402.5	12.9	5.3	583.7
Jet Fuel					2,766.4		74.1	2,840.5				199.8		5.3	205.1
Kerosene		94.6	29.7	15.6			2.4	142.2	6.9	2.2	1.1			0.2	10.4
LPG		554.9	150.4	562.6	11.9		8.0	1,287.8	34.4	9.3	34.9	0.7		0.5	79.8
Lubricants															
Motor Gasoline					16,014.8		185.1	16,199.8				1,135.0		13.1	1,148.1
Residual Fuel			91.6	190.3	443.5	870.8	130.9	1,727.1		6.9	14.3	33.3	65.4	9.8	129.7
Other Petroleum															
AvGas Blend Components				3.8				3.8			0.3				0.3
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus				106.5				106.5			7.5				7.5
Petroleum Coke			0.2	669.5		98.6		768.3		0.0	68.4		10.1		78.5
Still Gas				1,435.6				1,435.6			95.8				95.8
Special Naphtha															
Unfinished Oils				(401.2)				(401.2)			(29.7)				(29.7)
Waxes															
Geothermal						**48.1**		**48.1**					**0.4**		**0.4**
TOTAL (All Fuels)		**6,543.5**	**4,037.4**	**13,554.5**	**25,387.2**	**26,706.0**	**494.6**	**76,723.2**	**370.7**	**230.8**	**851.1**	**1,809.5**	**2,296.9**	**35.9**	**5,594.8**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-21: 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*
	Adjusted Consumption (TBtu)[a]							**Emissions**[b] **(Tg CO$_2$ Eq.) from Energy Use**						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**14.0**	**102.5**	**1,372.8**	**NE**	**19,279.5**	**10.2**	**20,779.0**	**1.3**	**9.8**	**129.9**	**NE**	**1,836.4**	**0.9**	**1,978.3**
Residential Coal	14.0						14.0	1.3						1.3
Commercial Coal		102.5					102.5		9.8					9.8
Industrial Other Coal			1,372.8				1,372.8			129.9				129.9
Transportation Coal				NE										NE
Electric Power Coal					19,279.5		19,279.5					1,836.4		1,836.4
U.S. Territory Coal (bit)						10.2	10.2						0.9	0.9
Natural Gas	**4,834.9**	**3,115.0**	**8,401.6**	**675.3**	**4,902.1**		**21,929.0**	**256.3**	**165.1**	**445.4**	**35.8**	**259.9**		**1,162.6**
Total Petroleum	**1,342.1**	**613.9**	**3,465.8**	**24,071.1**	**1,211.4**	**461.0**	**31,165.3**	**92.8**	**43.8**	**260.0**	**1,725.9**	**93.8**	**33.5**	**2,249.9**
Asphalt & Road Oil														
Aviation Gasoline				39.2			39.2				2.7			2.7
Distillate Fuel Oil	705.0	373.4	983.4	5,251.3	140.1	79.4	7,532.6	52.1	27.6	72.7	388.4	10.4	5.9	557.1
Jet Fuel				2,677.5		59.5	2,737.1				193.4		4.3	197.7
Kerosene	111.2	26.9	12.8			3.7	154.7	8.1	2.0	0.9			0.3	11.3
LPG	526.0	140.2	395.9	14.3		8.3	1,084.6	32.5	8.7	24.5	0.9		0.5	67.1
Lubricants														
Motor Gasoline				15,913.1		164.0	16,077.2				1,127.4		11.6	1,139.0
Residual Fuel		73.3	154.0	175.7	958.7	146.0	1,507.8		5.5	11.6	13.2	72.0	11.0	113.2
Other Petroleum														
AvGas Blend Components			6.4				6.4			0.4				0.4
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			103.5				103.5			7.2				7.2
Petroleum Coke		0.1	676.5		112.5		789.1		0.0	69.1		11.5		80.6
Still Gas			1,421.1				1,421.1			94.8				94.8
Special Naphtha														
Unfinished Oils			(287.9)				(287.9)			(21.3)				(21.3)
Waxes														
Geothermal					**50.6**		**50.6**					**0.4**		**0.4**
TOTAL (All Fuels)	**6,191.0**	**3,831.5**	**13,240.1**	**24,746.4**	**25,443.6**	**471.2**	**73,923.8**	**350.5**	**218.7**	**835.3**	**1,761.7**	**2,190.5**	**34.5**	**5,391.1**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).

[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

NE (Not Estimated)

Table A-22: 1998 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO₂ Eq.) from Energy Use						
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal	**11.5**	**93.4**	**1,470.8**	**NE**	**19,215.7**	**10.5**	**20,802.0**	**1.1**	**8.9**	**139.1**	**NE**	**1,828.2**	**1.0**	**1,978.3**
Residential Coal	11.5						11.5	1.1						1.1
Commercial Coal		93.4					93.4		8.9					8.9
Industrial Other Coal			1,470.8				1,470.8			139.1				139.1
Transportation Coal				NE										NE
Electric Power Coal					19,215.7		19,215.7					1,828.2		1,828.2
U.S. Territory Coal (bit)						10.5	10.5						1.0	1.0
Natural Gas	**4,646.1**	**3,083.0**	**8,826.5**	**666.1**	**4,674.9**		**21,896.6**	**246.0**	**163.3**	**467.4**	**35.3**	**247.6**		**1,159.5**
Total Petroleum	**1,207.3**	**609.1**	**3,379.3**	**23,154.5**	**1,306.2**	**445.4**	**30,102.0**	**84.0**	**43.7**	**254.7**	**1,661.9**	**101.3**	**32.4**	**2,178.0**
Asphalt & Road Oil														
Aviation Gasoline				35.5			35.5				2.5			2.5
Distillate Fuel Oil	675.1	375.1	1,027.9	4,955.2	135.7	71.9	7,240.8	49.9	27.7	76.0	366.5	10.0	5.3	535.5
Jet Fuel				2,483.9		59.9	2,543.7				179.4		4.3	183.7
Kerosene	108.3	31.2	22.1			6.3	167.8	7.9	2.3	1.6			0.5	12.3
LPG	423.9	117.6	271.6	17.6		5.9	836.7	26.1	7.2	16.7	1.1		0.4	51.6
Lubricants														
Motor Gasoline				15,583.4		160.3	15,743.8				1,106.6		11.4	1,118.0
Residual Fuel		85.2	173.3	78.9	1,047.0	141.1	1,525.5		6.4	13.0	5.9	78.6	10.6	114.6
Other Petroleum														
AvGas Blend Components			4.0				4.0			0.3				0.3
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			89.7				89.7			6.3				6.3
Petroleum Coke		0.1	667.5		123.6		791.2		0.0	68.2		12.6		80.8
Still Gas			1,437.3				1,437.3			95.9				95.9
Special Naphtha														
Unfinished Oils			(313.9)				(313.9)			(23.3)				(23.3)
Waxes														
Geothermal					50.4		50.4					0.4		0.4
TOTAL (All Fuels)	**5,865.0**	**3,785.5**	**13,676.6**	**23,820.6**	**25,247.2**	**456.0**	**72,850.9**	**331.1**	**215.9**	**861.2**	**1,697.2**	**2,177.4**	**33.4**	**5,316.2**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-23: 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
		Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO$_2$ Eq.) from Energy Use						
Fuel Type		Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal		**16.0**	**129.4**	**1,457.0**	**NE**	**18,904.5**	**10.4**	**20,517.4**	**1.5**	**12.3**	**137.6**	**NE**	**1,797.0**	**1.0**	**1,949.4**
Residential Coal		16.0						16.0	1.5						1.5
Commercial Coal			129.4					129.4		12.3					12.3
Industrial Other Coal				1,457.0				1,457.0			137.6				137.6
Transportation Coal					NE										NE
Electric Power Coal						18,904.5		18,904.5					1,797.0		1,797.0
U.S. Territory Coal (bit)							10.4	10.4						1.0	1.0
Natural Gas		**5,092.9**	**3,285.3**	**9,052.1**	**780.3**	**4,125.5**		**22,336.2**	**270.1**	**174.2**	**480.0**	**41.4**	**218.8**		**1,184.4**
Total Petroleum		**1,333.5**	**655.1**	**3,754.9**	**22,649.5**	**926.8**	**445.3**	**29,765.2**	**93.0**	**47.1**	**279.8**	**1,625.3**	**72.2**	**32.4**	**2,149.8**
Asphalt & Road Oil															
Aviation Gasoline					39.7			39.7				2.7			2.7
Distillate Fuel Oil		785.9	398.9	1,053.7	4,802.2	110.6	81.6	7,232.7	58.1	29.5	77.9	355.2	8.2	6.0	534.9
Jet Fuel					2,509.5		62.1	2,571.6				181.2		4.5	185.7
Kerosene		92.9	24.6	18.8			4.0	140.3	6.8	1.8	1.4			0.3	10.3
LPG		454.8	120.2	429.9	14.2		6.5	1,025.7	28.1	7.4	26.5	0.9		0.4	63.3
Lubricants															
Motor Gasoline					15,147.5		160.0	15,307.5				1,075.0		11.4	1,086.4
Residual Fuel			111.2	235.6	136.5	714.6	131.1	1,329.0		8.4	17.7	10.3	53.7	9.8	99.8
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															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus				30.0				30.0			2.1				2.1
Petroleum Coke			0.1	631.1		101.6		732.8		0.0	64.4		10.4		74.8
Still Gas				1,445.1				1,445.1			96.4				96.4
Special Naphtha															
Unfinished Oils				(102.9)				(102.9)			(7.6)				(7.6)
Waxes															
Geothermal						**50.2**		**50.2**					**0.4**		**0.4**
TOTAL (All Fuels)		**6,442.5**	**4,069.8**	**14,264.1**	**23,429.8**	**24,007.1**	**455.7**	**72,669.1**	**364.6**	**233.6**	**897.4**	**1,666.6**	**2,088.4**	**33.4**	**5,284.0**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).

[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

NE (Not Estimated)

Table A-24: 1996 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO₂ Eq.) from Energy Use						
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal	**16.6**	**121.6**	**1,454.9**	**NE**	**18,429.0**	**10.3**	**20,032.4**	**1.6**	**11.6**	**137.4**	**NE**	**1,752.4**	**1.0**	**1,903.9**
Residential Coal	16.6						16.6	1.6						1.6
Commercial Coal		121.6					121.6		11.6					11.6
Industrial Other Coal			1,454.9				1,454.9			137.4				137.4
Transportation Coal				NE										NE
Electric Power Coal					18,429.0		18,429.0					1,752.4		1,752.4
U.S. Territory Coal (bit)						10.3	10.3						1.0	1.0
Natural Gas	**5,354.4**	**3,226.3**	**9,048.6**	**736.9**	**3,862.4**		**22,228.7**	**283.9**	**171.1**	**479.8**	**39.1**	**204.8**		**1,178.7**
Total Petroleum	**1,396.6**	**718.3**	**3,760.8**	**22,406.2**	**817.4**	**434.6**	**29,533.9**	**97.5**	**51.8**	**280.6**	**1,608.0**	**63.4**	**31.6**	**2,132.8**
Asphalt & Road Oil														
Aviation Gasoline				37.4			37.4				2.6			2.6
Distillate Fuel Oil	839.0	437.6	1,046.7	4,599.0	109.4	76.5	7,108.1	62.1	32.4	77.4	340.1	8.1	5.7	525.7
Jet Fuel				2,459.9		78.5	2,538.4				177.7		5.7	183.3
Kerosene	88.8	21.0	18.3			3.0	131.1	6.5	1.5	1.3			0.2	9.6
LPG	468.7	122.4	401.7	15.6		7.3	1,015.8	28.9	7.5	24.8	1.0		0.5	62.6
Lubricants														
Motor Gasoline				14,979.4		151.4	15,130.8				1,063.0		10.7	1,073.8
Residual Fuel		137.2	281.7	314.9	628.4	118.0	1,480.1		10.3	21.2	23.6	47.2	8.9	111.1
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														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			38.5				38.5			2.7				2.7
Petroleum Coke		0.1	629.0		79.6		708.7		0.0	64.2		8.1		72.4
Still Gas			1,437.1				1,437.1			95.9				95.9
Special Naphtha														
Unfinished Oils			(112.8)				(112.8)			(8.4)				(8.4)
Waxes														
Geothermal					48.9		48.9					0.4		0.4
TOTAL (All Fuels)	**6,767.5**	**4,066.2**	**14,264.4**	**23,143.1**	**23,157.7**	**445.0**	**71,843.9**	**383.0**	**234.5**	**897.8**	**1,647.1**	**2,021.0**	**32.5**	**5,215.9**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-25: 1995 Energy Consumption Data and CO$_2$ Emissions from Fossil Fuel Combustion by Fuel Type

	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO$_2$ Eq.) from Energy Use						
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal	**17.5**	**116.8**	**1,526.9**	**NE**	**17,466.3**	**10.2**	**19,137.7**	**1.7**	**11.2**	**144.4**	**NE**	**1,660.7**	**0.9**	**1,819.0**
Residential Coal	17.5						17.5	1.7						1.7
Commercial Coal		116.8					116.8		11.2					11.2
Industrial Other Coal			1,526.9				1,526.9			144.4				144.4
Transportation Coal				NE			NE							NE
Electric Power Coal					17,466.3		17,466.3					1,660.7		1,660.7
U.S. Territory Coal (bit)						10.2	10.2						0.9	0.9
Natural Gas	**4,954.2**	**3,096.0**	**8,736.2**	**724.0**	**4,302.0**		**21,812.3**	**262.7**	**164.2**	**463.3**	**38.4**	**228.1**		**1,156.6**
Total Petroleum	**1,260.9**	**694.0**	**3,417.3**	**21,916.2**	**754.6**	**461.8**	**28,504.7**	**88.3**	**50.1**	**255.0**	**1,569.8**	**58.7**	**33.6**	**2,055.6**
Asphalt & Road Oil														
Aviation Gasoline				39.6			39.6				2.7			2.7
Distillate Fuel Oil	791.8	419.1	966.7	4,383.3	108.1	89.5	6,758.4	58.6	31.0	71.5	324.2	8.0	6.6	499.8
Jet Fuel				2,409.8		75.7	2,485.5				170.9		5.4	176.3
Kerosene	74.3	22.1	15.4			3.6	115.4	5.4	1.6	1.1			0.3	8.4
LPG	394.8	108.7	403.4	17.7		5.6	930.2	24.4	6.7	24.9	1.1		0.3	57.4
Lubricants														
Motor Gasoline		2.5	27.2	14,678.5		146.7	14,854.9		0.2	1.9	1,041.8		10.4	1,054.3
Residual Fuel		141.5	284.7	387.3	566.0	140.7	1,520.1		10.6	21.4	29.1	42.5	10.6	114.2
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														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			34.5				34.5			2.4				2.4
Petroleum Coke		0.1	609.1		80.6		689.8		0.0	62.2		8.2		70.4
Still Gas			1,377.3				1,377.3			91.9				91.9
Special Naphtha														
Unfinished Oils			(320.9)				(320.9)			(23.8)				(23.8)
Waxes														
Geothermal					45.6		45.6					0.3		0.3
TOTAL (All Fuels)	**6,232.5**	**3,906.8**	**13,680.4**	**22,640.1**	**22,568.5**	**472.0**	**69,500.3**	**352.7**	**225.5**	**862.7**	**1,608.2**	**1,947.9**	**34.5**	**5,031.5**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).

[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

NE (Not Estimated)

Table A-26: 1994 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO$_2$ Eq.) from Energy Use						
Fuel Type		**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal		**20.8**	**118.1**	**1,594.9**	**NE**	**17,260.9**	**10.0**	**19,004.7**	**2.0**	**11.3**	**150.7**	**NE**	**1,638.8**	**0.9**	**1,803.7**
Residential Coal		20.8						20.8	2.0						2.0
Commercial Coal			118.1					118.1		11.3					11.3
Industrial Other Coal				1,594.9				1,594.9			150.7				150.7
Transportation Coal					NE										NE
Electric Power Coal						17,260.9		17,260.9					1,638.8		1,638.8
U.S. Territory Coal (bit)							10.0	10.0						0.9	0.9
Natural Gas		**4,959.8**	**2,962.0**	**8,290.4**	**708.5**	**3,977.3**		**20,898.0**	**262.9**	**157.0**	**439.4**	**37.6**	**210.8**		**1,107.6**
Total Petroleum		**1,305.3**	**745.9**	**3,631.6**	**21,379.1**	**1,058.8**	**506.3**	**28,627.0**	**91.8**	**54.0**	**270.3**	**1,531.3**	**81.3**	**36.9**	**2,065.6**
Asphalt & Road Oil															
Aviation Gasoline					38.1			38.1				2.6			2.6
Distillate Fuel Oil		856.7	447.1	975.8	4,187.0	120.1	118.8	6,705.5	63.4	33.1	72.2	309.7	8.9	8.8	495.9
Jet Fuel					2,360.6		65.8	2,426.4				167.5		4.7	172.2
Kerosene		64.9	19.5	16.9			3.0	104.3	4.8	1.4	1.2			0.2	7.6
LPG		383.7	107.3	423.1	34.0		7.3	955.3	23.7	6.6	26.1	2.1		0.4	59.0
Lubricants															
Motor Gasoline					14,401.3		147.4	14,548.7				1,022.5		10.5	1,033.0
Residual Fuel			171.9	368.4	358.1	869.0	164.1	1,931.5		12.9	27.7	26.9	65.3	12.3	145.0
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															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus				80.8				80.8			5.7				5.7
Petroleum Coke			0.1	607.9		69.7		677.7		0.0	62.1		7.1		69.2
Still Gas				1,413.2				1,413.2			94.3				94.3
Special Naphtha															
Unfinished Oils				(279.2)				(279.2)			(20.7)				(20.7)
Waxes															
Geothermal						**53.0**		**53.0**					**0.4**		**0.4**
TOTAL (All Fuels)		**6,286.0**	**3,826.0**	**13,516.8**	**22,087.7**	**22,350.0**	**516.3**	**68,582.8**	**356.7**	**222.3**	**860.4**	**1,568.8**	**1,931.2**	**37.8**	**4,977.4**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-27: 1993 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO₂ Eq.) from Energy Use						
Fuel Type		Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal		**25.7**	**117.3**	**1,585.0**	**NE**	**17,195.9**	**9.6**	**18,933.5**	**2.5**	**11.3**	**149.8**	**NE**	**1,632.5**	**0.9**	**1,796.9**
Residential Coal		25.7						25.7	2.5						2.5
Commercial Coal			117.3					117.3		11.3					11.3
Industrial Other Coal				1,585.0				1,585.0			149.8				149.8
Transportation Coal					NE			NE							NE
Electric Power Coal						17,195.9		17,195.9					1,632.5		1,632.5
U.S. Territory Coal (bit)							9.6	9.6						0.9	0.9
Natural Gas		**5,063.3**	**2,923.3**	**8,281.4**	**644.7**	**3,537.5**		**20,450.1**	**268.4**	**155.0**	**439.0**	**34.2**	**187.5**		**1,084.2**
Total Petroleum		**1,348.5**	**743.4**	**3,508.4**	**20,859.5**	**1,123.8**	**459.9**	**28,043.3**	**94.9**	**53.8**	**261.9**	**1,497.8**	**86.4**	**33.6**	**2,028.4**
Asphalt & Road Oil															
Aviation Gasoline					38.4			38.4				2.7			2.7
Distillate Fuel Oil		883.3	447.2	990.1	3,889.4	86.5	104.9	6,401.3	65.3	33.1	73.2	287.6	6.4	7.8	473.4
Jet Fuel					2,306.9		62.1	2,369.0				163.8		4.4	168.3
Kerosene		75.6	14.0	13.1			3.8	106.5	5.5	1.0	1.0			0.3	7.8
LPG		389.6	109.2	412.2	20.2		4.9	936.2	24.0	6.7	25.4	1.2		0.3	57.8
Lubricants															
Motor Gasoline					14,237.0		128.3	14,365.3				1,014.8		9.1	1,023.9
Residual Fuel			172.7	391.2	367.5	958.6	155.9	2,046.0		13.0	29.4	27.6	72.0	11.7	153.6
Other Petroleum															
AvGas Blend Components				0.1				0.1			0.0				0.0
Crude Oil				21.2				21.2			1.6				1.6
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus				56.4				56.4			3.9				3.9
Petroleum Coke			0.2	618.4		78.6		697.2		0.0	63.1		8.0		71.2
Still Gas				1,401.8				1,401.8			93.5				93.5
Special Naphtha															
Unfinished Oils				(396.0)				(396.0)			(29.3)				(29.3)
Waxes															
Geothermal						57.3		57.3					0.4		0.4
TOTAL (All Fuels)		**6,437.5**	**3,783.9**	**13,374.7**	**21,504.2**	**21,914.5**	**469.5**	**67,484.3**	**365.8**	**220.1**	**850.6**	**1,531.9**	**1,906.9**	**34.5**	**4,909.8**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-28: 1992 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO$_2$ Eq.) from Energy Use						
Fuel Type		Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal		**25.6**	**116.6**	**1,554.1**	**NE**	**16,465.6**	**8.8**	**18,170.6**	**2.5**	**11.3**	**147.4**	**NE**	**1,569.6**	**0.8**	**1,731.5**
Residential Coal		25.6						25.6	2.5						2.5
Commercial Coal			116.6					116.6		11.3					11.3
Industrial Other Coal				1,554.1				1,554.1			147.4				147.4
Transportation Coal					NE										NE
Electric Power Coal						16,465.6		16,465.6					1,569.6		1,569.6
U.S. Territory Coal (bit)							8.8	8.8						0.8	0.8
Natural Gas		**4,804.6**	**2,871.2**	**8,129.3**	**608.1**	**3,511.5**		**19,924.7**	**254.5**	**152.1**	**430.7**	**32.2**	**186.0**		**1,055.6**
Total Petroleum		**1,365.8**	**788.9**	**3,850.2**	**20,366.5**	**990.7**	**444.9**	**27,807.1**	**96.5**	**57.3**	**284.9**	**1,465.0**	**75.5**	**32.5**	**2,011.6**
Asphalt & Road Oil															
Aviation Gasoline					41.1			41.1				2.8			2.8
Distillate Fuel Oil		931.4	481.7	1,028.5	3,665.7	73.5	91.8	6,272.7	68.9	35.6	76.1	271.1	5.4	6.8	463.9
Jet Fuel					2,267.7		61.3	2,329.0				161.2		4.4	165.6
Kerosene		65.0	11.1	9.8			3.3	89.2	4.8	0.8	0.7			0.2	6.5
LPG		369.4	106.9	441.8	19.4		11.9	949.4	22.8	6.6	27.3	1.2		0.7	58.7
Lubricants															
Motor Gasoline					13,972.5		122.1	14,094.7				998.6		8.7	1,007.4
Residual Fuel			189.1	328.1	400.1	872.2	154.6	1,944.0		14.2	24.6	30.0	65.5	11.6	146.0
Other Petroleum															
AvGas Blend Components				0.2				0.2			0.0				0.0
Crude Oil				27.4				27.4			2.0				2.0
MoGas Blend Components				75.7				75.7			5.4				5.4
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus				261.0				261.0			18.3				18.3
Petroleum Coke			0.1	596.9		45.0		642.0		0.0	61.0		4.6		65.6
Still Gas				1,435.7				1,435.7			95.8				95.8
Special Naphtha															
Unfinished Oils				(354.8)				(354.8)			(26.3)				(26.3)
Waxes															
Geothermal						**55.1**		**55.1**					**0.4**		**0.4**
TOTAL (All Fuels)		**6,196.0**	**3,776.7**	**13,533.6**	**20,974.6**	**21,022.9**	**453.7**	**65,957.5**	**353.5**	**220.6**	**863.0**	**1,497.3**	**1,831.5**	**33.3**	**4,799.1**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).

[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

NE (Not Estimated)

Table A-29: 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
	Fuel Type	Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO$_2$ Eq.) from Energy Use						
		Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal		**25.4**	**115.5**	**1,602.2**	**NE**	**16,249.7**	**7.7**	**18,000.5**	**2.4**	**11.1**	**152.1**	**NE**	**1,548.2**	**0.7**	**1,714.5**
Residential Coal		25.4						25.4	2.4						2.4
Commercial Coal			115.5					115.5		11.1					11.1
Industrial Other Coal				1,602.2				1,602.2			152.1				152.1
Transportation Coal					NE										NE
Electric Power Coal						16,249.7		16,249.7					1,548.2		1,548.2
U.S. Territory Coal (bit)							7.7	7.7						0.7	0.7
Natural Gas		**4,667.2**	**2,795.4**	**7,828.1**	**620.3**	**3,377.4**		**19,288.4**	**247.3**	**148.1**	**414.7**	**32.9**	**178.9**		**1,021.9**
Total Petroleum		**1,381.5**	**903.6**	**3,578.0**	**19,671.2**	**1,198.3**	**425.4**	**27,158.0**	**97.5**	**65.6**	**265.2**	**1,411.6**	**90.7**	**30.9**	**1,961.4**
Asphalt & Road Oil															
Aviation Gasoline					41.7			41.7				2.9			2.9
Distillate Fuel Oil		931.0	517.7	1,050.8	3,449.7	83.6	71.4	6,104.1	68.9	38.3	77.7	255.1	6.2	5.3	451.4
Jet Fuel					2,329.0		78.2	2,407.2				165.7		5.6	171.2
Kerosene		72.3	12.1	11.4			2.8	98.6	5.3	0.9	0.8			0.2	7.2
LPG		378.1	108.2	342.2	21.1		13.8	863.5	23.3	6.7	21.1	1.3		0.9	53.3
Lubricants															
Motor Gasoline			53.7	122.0	13,605.2		124.7	13,905.6		3.8	8.7	969.7		8.9	991.1
Residual Fuel			211.9	270.9	224.4	1,085.3	134.6	1,927.2		15.9	20.3	16.9	81.5	10.1	144.7
Other Petroleum															
AvGas Blend Components				(0.1)				(0.1)			(0.0)				(0.0)
Crude Oil				38.9				38.9			2.9				2.9
MoGas Blend Components				(25.9)				(25.9)			(1.8)				(1.8)
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus				249.2				249.2			17.5				17.5
Petroleum Coke				564.2		29.3		593.5			57.6		3.0		60.6
Still Gas				1,404.5				1,404.5			93.7				93.7
Special Naphtha															
Unfinished Oils				(450.2)				(450.2)			(33.3)				(33.3)
Waxes															
Geothermal						54.5		54.5					0.4		0.4
TOTAL (All Fuels)		**6,074.0**	**3,814.5**	**13,008.3**	**20,291.5**	**20,879.8**	**433.2**	**64,501.4**	**347.2**	**224.8**	**832.0**	**1,444.4**	**1,818.2**	**31.6**	**4,698.2**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A- 30: 1990 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Fuel Type	Adjusted Consumption (TBtu)[a]							Emissions[b] (Tg CO$_2$ Eq.) from Energy Use						
	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total
Total Coal	**31.1**	**124.5**	**1,640.1**	**NE**	**16,261.0**	**7.0**	**18,063.6**	**3.0**	**12.0**	**155.3**	**NE**	**1,547.6**	**0.6**	**1,718.4**
Residential Coal	31.1						31.1	3.0						3.0
Commercial Coal		124.5					124.5		12.0					12.0
Industrial Other Coal			1,640.1				1,640.1			155.3				155.3
Transportation Coal				NE										NE
Electric Power Coal					16,261.0		16,261.0					1,547.6		1,547.6
U.S. Territory Coal (bit)						7.0	7.0						0.6	0.6
Natural Gas	**4,490.9**	**2,682.2**	**7,720.8**	**679.9**	**3,308.5**		**18,882.3**	**238.0**	**142.1**	**409.1**	**36.0**	**175.3**		**1,000.6**
Total Petroleum	**1,375.2**	**891.4**	**3,810.9**	**20,213.2**	**1,289.4**	**374.8**	**27,955.0**	**97.4**	**64.9**	**282.1**	**1,449.9**	**97.5**	**27.2**	**2,019.0**
Asphalt & Road Oil														
Aviation Gasoline				45.0			45.0				3.1			3.1
Distillate Fuel Oil	959.2	525.4	1,098.5	3,554.8	96.5	74.0	6,308.4	70.9	38.9	81.2	262.9	7.1	5.5	466.5
Jet Fuel				2,477.2		61.0	2,538.2				176.2		4.3	180.5
Kerosene	63.9	11.8	12.3			2.6	90.6	4.7	0.9	0.9			0.2	6.6
LPG	352.1	102.3	380.2	22.9		14.4	871.9	21.8	6.3	23.5	1.4		0.9	53.9
Lubricants														
Motor Gasoline		22.1	36.8	13,813.0		101.0	13,972.8		1.6	2.6	983.7		7.2	995.1
Residual Fuel		229.8	364.1	300.3	1,162.6	121.8	2,178.7		17.3	27.3	22.6	87.3	9.2	163.6
Other Petroleum														
AvGas Blend Components			0.2				0.2			0.0				0.0
Crude Oil			50.9				50.9			3.8				3.8
MoGas Blend Components			53.7				53.7			3.8				3.8
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			167.8				167.8			11.7				11.7
Petroleum Coke			563.5		30.4		593.9			57.5		3.1		60.6
Still Gas			1,451.9				1,451.9			96.9				96.9
Special Naphtha														
Unfinished Oils			(369.0)				(369.0)			(27.3)				(27.3)
Waxes														
Geothermal					**52.7**		**52.7**					**0.4**		**0.4**
TOTAL (All Fuels)	**5,897.2**	**3,698.1**	**13,171.7**	**20,893.1**	**20,911.6**	**381.9**	**64,953.5**	**338.3**	**219.0**	**846.5**	**1,485.9**	**1,820.8**	**27.9**	**4,738.4**

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-31), and international bunker fuel consumption (see Table A-32).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-31: Unadjusted Non-Energy Fuel Consumption (TBtu)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Industry	**4,509.4**	**5,194.9**	**5,270.5**	**5,493.3**	**5,723.5**	**5,981.5**	**5,607.6**	**5,266.7**	**5,350.5**	**5,308.0**	**5,845.9**	**5,532.4**	**5,510.7**	**5,324.7**	**4,855.6**	**4,486.3**
Industrial Coking Coal	+	37.2	23.5	0.0	10.4	39.5	53.0	24.3	39.8	51.2	167.1	79.8	62.3	1.7	28.4	6.1
Industrial Other Coal	8.2	11.3	11.4	11.2	10.4	11.1	12.4	11.3	12.0	11.9	11.9	11.9	12.4	12.4	12.4	12.4
Natural Gas to Chemical Plants, Other Uses	301.7	357.2	360.3	386.7	426.6	436.6	438.4	407.7	380.7	384.4	403.8	411.3	416.8	432.1	406.0	388.4
Asphalt & Road Oil	1,170.2	1,178.2	1,175.9	1,223.6	1,262.6	1,324.4	1,275.7	1,256.9	1,240.0	1,219.5	1,303.8	1,323.2	1,261.2	1,197.0	1,012.0	873.1
LPG	1,201.4	1,586.9	1,652.0	1,670.4	1,744.4	1,820.7	1,665.4	1,553.4	1,620.3	1,545.1	1,576.4	1,488.1	1,516.8	1,542.2	1,442.1	1,520.5
Lubricants	186.3	177.8	172.5	182.3	190.8	192.8	189.9	174.0	171.9	159.0	161.0	160.2	156.1	161.2	149.6	134.5
Pentanes Plus	82.6	303.4	316.5	298.9	204.3	261.4	236.7	201.6	171.4	169.1	170.4	150.3	107.3	137.4	117.2	97.7
Naphtha (<401 deg. F)	347.8	373.0	479.3	536.4	584.0	502.1	613.5	493.7	582.6	613.0	749.4	698.7	628.9	562.5	477.2	471.9
Other Oil (>401 deg. F)	753.9	801.0	729.6	861.3	818.7	811.1	722.2	662.4	632.1	699.4	779.5	708.0	790.6	744.1	647.8	424.8
Still Gas	21.3	40.1	0.0	2.1	0.0	16.1	12.6	35.8	57.8	59.0	62.9	67.7	57.2	44.2	47.3	133.9
Petroleum Coke	150.7	112.2	127.8	96.3	191.0	259.3	126.6	194.2	161.4	145.8	249.7	210.5	251.5	239.2	252.1	195.4
Special Naphtha	107.1	70.8	74.5	72.3	107.3	145.4	97.4	78.5	102.4	80.5	51.0	62.5	70.1	78.0	84.9	46.2
Other (Wax/Misc.)																
Distillate Fuel Oil	7.0	8.0	9.2	10.4	11.7	11.7	11.7	11.7	11.7	13.1	14.6	16.0	17.5	17.5	17.5	17.5
Waxes	33.3	40.6	48.7	43.7	42.4	37.4	33.1	36.3	32.2	31.0	30.8	31.4	26.1	21.9	19.1	12.2
Miscellaneous Products	137.8	97.1	89.0	97.8	119.0	111.9	119.2	124.9	134.2	126.0	113.4	112.8	136.0	133.5	142.0	151.8
Transportation	**176.0**	**167.9**	**163.0**	**172.1**	**180.2**	**182.1**	**179.4**	**164.3**	**162.4**	**150.1**	**152.1**	**151.3**	**147.4**	**152.2**	**141.3**	**127.1**
Lubricants	176.0	167.9	163.0	172.1	180.2	182.1	179.4	164.3	162.4	150.1	152.1	151.3	147.4	152.2	141.3	127.1
U.S. Territories	**86.7**	**90.8**	**121.7**	**131.6**	**135.0**	**139.3**	**152.2**	**80.3**	**140.2**	**123.5**	**110.8**	**121.9**	**133.4**	**108.4**	**126.7**	**56.3**
Lubricants	0.7	2.0	1.5	2.5	1.3	1.4	3.1	0.0	3.0	4.9	5.1	4.6	6.2	5.9	2.7	1.0
Other Petroleum (Misc. Prod.)	86.0	88.8	120.2	129.1	133.8	138.0	149.1	80.3	137.2	118.6	105.7	117.3	127.2	102.5	124.1	55.2
Total	**4,772.1**	**5,453.6**	**5,555.1**	**5,797.0**	**6,038.7**	**6,302.9**	**5,939.1**	**5,511.3**	**5,653.0**	**5,581.6**	**6,108.7**	**5,805.7**	**5,791.5**	**5,585.4**	**5,123.6**	**4,669.7**

Note: These values are unadjusted non-energy fuel use provided by EIA. They have not yet been adjusted to remove petroleum feedstock exports and processes accounted for in the Industrial Processes Chapter.
+ Does not exceed 0.05 TBtu.

Table A-32: International Bunker Fuel Consumption (TBtu)

Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Marine Residual Fuel Oil	715.7	523.2	536.4	575.2	594.8	489.7	444.1	426.0	448.9	471.8	553.1	581.0	599.4	607.5	654.6	604.8
Marine Distillate Fuel Oil & Other	158.0	125.7	114.1	125.5	158.8	113.6	85.9	72.4	82.6	103.9	143.6	126.9	119.3	111.3	122.2	112.3
Aviation Jet Fuel	652.3	722.4	814.3	798.7	872.9	784.3	813.9	820.8	891.9	784.6	857.6	785.6	1,032.3	1,021.3	1,045.5	961.0
Total	**1,526.0**	**1,371.4**	**1,464.8**	**1,499.4**	**1,626.5**	**1,387.6**	**1,343.9**	**1,319.3**	**1,423.3**	**1,360.3**	**1,554.2**	**1,493.5**	**1,750.9**	**1,740.2**	**1,822.3**	**1,678.1**

Table A- 33: Key Assumptions for Estimating CO₂ Emissions

Fuel Type	C Content Coefficient (Tg C/QBtu)
Coal	
Residential Coal	[a]
Commercial Coal	[a]
Industrial Coking Coal	[a]
Industrial Other Coal	[a]
Electric Power Coal	[a]
U.S. Territory Coal (bit)	25.14
Pipeline Natural Gas	**[a]**
Flare Gas [a]	15.31
Petroleum	
Asphalt & Road Oil	20.55
Aviation Gasoline	18.86
Distillate Fuel Oil No. 1	19.98
Distillate Fuel Oil No. 2[b]	20.17
Distillate Fuel Oil No. 4	20.47
Jet Fuel	[a]
Kerosene	19.96
LPG (energy use)	[a]
LPG (non-energy use)	[a]
Lubricants	20.20
Motor Gasoline	[a]
Residual Fuel Oil No. 5	19.89
Residual Fuel Oil No. 6[b]	20.48
Other Petroleum	
AvGas Blend Components	18.87
Crude Oil	[a]
MoGas Blend Components	[a]
Misc. Products	[a]
Misc. Products (Territories)	[a]
Naphtha (<401 deg. F)	18.55
Other Oil (>401 deg. F)	20.17
Pentanes Plus	19.10
Petroleum Coke	27.85
Still Gas	18.20
Special Naphtha	19.74
Unfinished Oils	[a]
Waxes	19.80
Geothermal	**2.05**

[a] Flare gas is not used in the CO₂ from fossil fuel combustion calculations and is presented for informational purposes only.
[b] Distillate fuel oil No.2 and residual fuel oil No. 6 are used in the CO₂ from fossil fuel combustion calculations, and other oil types are presented for informational purposes only. An additional discussion on the derivation of these carbon content coefficients is presented in Annex 2.2.
Sources: C coefficients from EIA (2009b) and EPA 2010a.
[a] These coefficients vary annually due to fluctuations in fuel quality (see Table A- 34)

Table A- 34: Annually Variable C Content Coefficients by Year (Tg C/QBtu)

Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Residential Coal	26.20	26.13	26.04	25.90	26.07	25.98	26.01	26.00	25.98	26.04	25.91	26.09	26.29	25.94	25.71*	25.71*
Commercial Coal	26.20	26.13	26.04	25.90	26.07	25.98	26.01	26.00	25.98	26.04	25.91	26.09	26.29	25.94	25.71	25.71
Industrial Coking Coal	25.53	25.57	25.56	25.59	25.62	25.59	25.63	25.63	25.65	25.63	25.63	25.60	25.60	25.61	25.61	25.61
Industrial Other Coal	25.82	25.80	25.75	25.75	25.79	25.80	25.74	25.66	25.57	25.55	25.56	25.80	25.84	25.82	25.82	25.82
Electric Power Coal	25.96	25.93	25.93	25.93	25.95	25.98	26.00	26.00	26.05	26.09	26.10	26.09	26.04	26.05	26.05	26.05
Pipeline Natural Gas	14.45	14.46	14.46	14.46	14.44	14.46	14.47	14.46	14.46	14.44	14.46	14.46	14.46	14.46	14.46	14.46
LPG (energy use)	16.86	16.82	16.82	16.84	16.81	16.86	16.89	16.87	16.85	16.86	16.84	16.84	16.83	16.82	16.83	16.83
LPG (non-energy use)	17.06	17.09	17.10	17.08	17.08	17.07	17.09	17.10	17.09	17.09	17.07	17.06	17.06	17.05	17.06	17.06
Motor Gasoline	19.42	19.36	19.35	19.36	19.37	19.32	19.33	19.34	19.38	19.36	19.38	19.36	19.45	19.56	19.46	19.46
Jet Fuel	19.40	19.34	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70
MoGas Blend Components	19.42	19.36	19.35	19.36	19.37	19.32	19.33	19.34	19.38	19.36	19.38	19.36	19.45	19.56	19.46	19.46
Misc. Products	20.15	20.21	20.23	20.22	20.22	20.17	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31
Unfinished Oils	20.15	20.21	20.23	20.22	20.22	20.17	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31
Crude Oil	20.15	20.21	20.23	20.22	20.22	20.17	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31

*U.S. EIA discontinued collection of residential sector coal consumption data in 2008, because consumption of coal in the residential sector is extremely limited. Therefore, the number cited here is developed from commercial/institutional consumption.
Source: EPA (2010a)

Table A-35: Electricity Consumption by End-Use Sector (Billion Kilowatt-Hours)

End-Use Sector	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Residential	924	1,043	1,083	1,076	1,130	,145	1,192	1,202	1,265	1,276	1,292	1,359	1,352	1,392	1,380	1,363
Commercial	838	953	980	1,027	1,078	1,104	1,159	1,191	1,205	1,199	1,230	1,275	1,300	1,336	1,336	1,323
Industrial	1,070	1,163	1,186	1,194	1,212	1,230	1,235	1,159	,156	1,181	1,186	1,169	1,158	1,187	1,183	1,048
Transportation	5	5	5	5	5	5	5	6	6	7	7	8	7	8	8	8
Total	**2,837**	**3,164**	**3,254**	**3,302**	**3,425**	**3,484**	**3,592**	**3,557**	**3,632**	**3,662**	**3,716**	**3,811**	**3,817**	**3,924**	**3,906**	**3,741**

Note: Does not include the U.S. territories.
Source: EIA (2010b)

2.2. Methodology for Estimating the Carbon Content of Fossil Fuels

This sub-annex presents the background and methodology for estimating the carbon (C) content of fossil fuels combusted in the United States. The C content of a particular fossil fuel represents the maximum potential emissions to the atmosphere if all C in the fuel is oxidized during combustion. The C content coefficients used in past editions of this report were developed using methods first outlined in the U.S. Energy Information Administration's (EIA) *Emissions of Greenhouse Gases in the United States: 1987-1992* (1994) and were developed primarily by EIA. For this report, EPA has updated many of the C content coefficients based on carbon dioxide emission factors developed for the Mandatory Reporting of Greenhouse Gases Rule, signed in September 2009 (EPA, 2009b, 2010). This sub-annex describes an updated methodology for estimating the C content of natural gas, and presents a time-series analysis of changes in U.S. C content coefficients for coal, petroleum products and natural gas. A summary of C content coefficients used in this report appears in Table A- 36.

Though the methods for estimating C contents for coal, natural gas, and petroleum products differ in their details, they each follow the same basic approach. First, because C coefficients are presented in terms of mass per unit energy (i.e., teragrams C per quadrillion Btu or Tg C/QBtu), those fuels that are typically described in volumetric units (petroleum products and natural gas) are converted to units of mass using an estimated density. Second, C contents are derived from fuel sample data, using descriptive statistics to estimate the C share of the fuel by weight. The heat content of the fuel is then estimated based on the sample data, or where sample data are unavailable or unrepresentative, by default values that reflect the characteristics of the fuel as defined by market requirements. A discussion of each fuel appears below.

The C content of coal is described first because approximately one-third of all U.S. C emissions from fossil fuel combustion are associated with coal consumption. The methods and sources for estimating the C content of natural gas are provided next. Approximately one-fifth of U.S. greenhouse gas emissions from fossil fuel combustion are attributable to natural gas consumption. Finally, this sub-annex examines C contents of petroleum products. U.S. energy consumption statistics account for more than 20 different petroleum products.

Table A- 36: Carbon Content Coefficients Used in this Report (Tg Carbon/QBtu)

Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Coal																
Residential Coal[a]	26.20	26.13	26.04	25.90	26.07	25.98	26.01	26.00	25.98	26.04	25.91	26.09	26.29	25.94	25.71*	25.71*
Commercial Coal[a]	26.20	26.13	26.04	25.90	26.07	25.98	26.01	26.00	25.98	26.04	25.91	26.09	26.29	25.94	25.71	25.71
Industrial Coking Coal[a]	25.53	25.57	25.56	25.59	25.62	25.59	25.63	25.63	25.65	25.63	25.63	25.60	25.60	25.61	25.61	25.61
Industrial Other Coal[a]	25.82	25.80	25.75	25.75	25.79	25.80	25.74	25.66	25.57	25.55	25.56	25.80	25.84	25.82	25.82	25.82
Utility Coal[a,b]	25.96	25.93	25.93	25.93	25.95	25.98	26.00	26.00	26.05	26.09	26.10	26.09	26.04	26.05	26.05	26.05
Pipeline Natural Gas[c]	**14.45**	**14.46**	**14.46**	**14.46**	**14.44**	**14.46**	**14.47**	**14.46**	**14.46**	**14.44**	**14.46**	**14.46**	**14.46**	**14.46**	**14.46**	**14.46**
Flare Gas	15.31	15.31	15.31	15.31	15.31	15.31	15.31	15.31	15.31	15.31	15.31	15.31	15.31	15.31	15.31	15.31
Petroleum																
Asphalt and Road Oil	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55
Aviation Gasoline	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86
Distillate Fuel Oil No. 1	19.98	19.98	19.98	19.98	19.98	19.98	19.98	19.98	19.98	19.98	19.98	19.98	19.98	19.98	19.98	19.98
Distillate Fuel Oil No. 2	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17
Distillate Fuel Oil No. 4	20.47	20.47	20.47	20.47	20.47	20.47	20.47	20.47	20.47	20.47	20.47	20.47	20.47	20.47	20.47	20.47
Jet Fuel[a]	19.73	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70
Kerosene	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96
LPG (energy use)[c]	16.86	16.82	16.82	16.84	16.81	16.86	16.89	16.87	16.85	16.86	16.84	16.84	16.83	16.82	16.83	16.83
LPG (non-energy use)[c]	17.06	17.09	17.10	17.08	17.08	17.07	17.09	17.10	17.09	17.09	17.07	17.06	17.06	17.05	17.06	17.06
Lubricants	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20
Motor Gasoline[c]	19.42	19.36	19.35	19.36	19.37	19.32	19.33	19.34	19.38	19.36	19.38	19.36	19.45	19.56	19.46	19.46
Residual Fuel No. 5	19.89	19.89	19.89	19.89	19.89	19.89	19.89	19.89	19.89	19.89	19.89	19.89	19.89	19.89	19.89	19.89
Residual Fuel No. 6	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48
Other Petroleum																
Av Gas Blend Comp.	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
Mo Gas Blend Comp[c]	19.42	19.36	19.35	19.36	19.37	19.32	19.33	19.34	19.38	19.36	19.38	19.36	19.45	19.56	19.46	19.46
Crude Oil[c]	20.15	20.21	20.23	20.22	20.22	20.17	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31
Misc. Products[c]	20.15	20.21	20.23	20.22	20.22	20.17	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31
Misc. Products (Terr.)	20.15	20.21	20.23	20.22	20.22	20.17	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31
Naphtha (<401 deg. F)	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55
Other oil (>401 deg. F)	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17
Pentanes Plus	19.10	19.10	19.10	19.10	19.10	19.10	19.10	19.10	19.10	19.10	19.10	19.10	19.10	19.10	19.10	19.10
Petroleum Coke	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85
Still Gas	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20
Special Naphtha	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74
Unfinished Oils[c]	20.15	20.21	20.23	20.22	20.22	20.17	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31
Waxes	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80
Other Wax and Misc.	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80
Geothermal	**2.05**	**2.05**	**2.05**	**2.05**	**2.05**	**2.05**	**2.05**	**2.05**	**2.05**	**2.05**	**2.05**	**2.05**	**2.05**	**2.05**	**2.05**	**2.05**

*U.S. EIA discontinued collection of residential sector coal consumption data in 2008, because consumption of coal in the residential sector is extremely limited. Therefore, the number cited here is developed from commercial/institutional consumption.

[a] C contents vary annually based on changes in annual mix of production and end-use consumption of coal from each producing state.

[b] C content for utility coal used in the electric power calculations. All coefficients based on higher heating value. Higher heating value (gross heating value) is the total amount of heat released when a fuel is burned. Coal, crude oil, and natural gas all include chemical compounds of carbon and hydrogen. When those fuels are burned, the carbon and hydrogen combine with oxygen in the air to produce CO_2 and water. Some of the energy released in burning goes into transforming the water into steam and is usually lost. The amount of heat spent in transforming the water into steam is counted as part of

gross heat content. Lower heating value (net heating value), in contrast, does not include the heat spent in transforming the water into steam. Using a simplified methodology based on International Energy Agency defaults, higher heating value can be converted to lower heating value for coal and petroleum products by multiplying by 0.95 and for natural gas by multiplying by 0.90. Carbon content coefficients are presented in higher heating value because U.S. energy statistics are reported by higher heating value.
ᶜC contents vary annually based on changes in fuel composition.

Coal

Approximately one-third of all U.S. CO_2 emissions from fossil fuel combustion are associated with coal consumption. Although the IPCC guidelines provide C contents for coal according to rank, it was necessary to develop C content coefficients by consuming sector to match the format in which coal consumption is reported by EIA. Because the C content of coal varies by the state in which it was mined and by coal rank, and because the sources of coal for each consuming sector vary by year, the weighted average C content for coal combusted in each consuming sector also varies over time. A time series of C contents by coal rank and consuming sector appears in Table A- 37.[6]

Methodology

The methodology for developing C contents for coal by consuming sector consists of four steps. An additional step has been taken to calculate C contents by coal rank to facilitate comparison with IPCC default values.

Step 1. Determine carbon contents by rank and by state of origin

C contents by rank and state of origin are estimated on the basis of 7,092 coal samples, 6,588 of which were collected by the U.S. Geological Survey (USGS 1998) and 504 samples that come from the Pennsylvania State University database (PSU 2010). These coal samples are classified according to rank and state of origin. For each rank in each state, the average heat content and C content of the coal samples are calculated based on the proximate (heat) and ultimate (percent carbon) analyses of the samples. Dividing the C content (reported in pounds CO_2) by the heat content (reported in million Btu or MMBtu) yields an average C content coefficient. This coefficient is then converted into units of Tg C/QBtu.

Step 2. Determine weighted average carbon content by state

C contents by rank and origin calculated in Step 1 are then weighted by the annual share of state production that was each rank. State production by rank is obtained from the EIA. This step yields a single carbon content per state that varies annually based on production. However, most coal-producing states produce only one rank of coal. For these states the weighted factor equals the carbon content calculated in Step 1 and is constant across the time series.

Step 3. Allocate sectoral consumption by state of origin

U.S. energy statistics[7] through 2007 provide data on the origin of coal used in four areas: 1) the electric power industry, 2) industrial coking, 3) all other industrial uses, and 4) the residential and commercial end-use sectors.[8] Because U.S. energy statistics do not provide the distribution of coal rank consumed by each consuming sector, it is assumed that each sector consumes a representative mixture of coal ranks from a particular state that matches the mixture of all coal produced in that state during the year. Thus, the weighted state-level factor developed in Step 2 is applied.

Step 4. Weight sectoral carbon contents to reflect the rank and state of origin of coal consumed

Sectoral C contents are calculated by multiplying the share of coal purchased from each state by the state's weighted C content estimated in Step 2. The resulting partial C contents are then totaled across all states to generate a national sectoral C content.

$$C_{sector} = S_{state1} \times C_{state1} + S_{state2} \times C_{state2} + \ldots + S_{state50} \times C_{state50}$$

Where,

C_{sector} = The C content by consuming sector;

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[6] For a comparison to earlier estimated carbon contents please see *Chronology and Explanation of Changes in Individual Carbon Content Coefficients of Fossil Fuels* near the end of this annex.

[7] U.S. Energy Information Administration (EIA). *Coal Distribution – Annual* (2001-2008); and *Coal Industry Annual* (1990-2000).

[8] Beginning in 2008, the EIA collects and reports data on commercial and institutional coal consumption, rather than residential and commercial consumption. Thus, the residential / commercial coal coefficient reported in Table A- 36 for 2009 represents the mix of coal consumed by commercial and institutional users. Currently, only an extremely small amount of coal is consumed in the U.S. Residential Sector.

S_{state} = The portion of consuming sector coal consumption attributed to production from a given state;
C_{state} = The estimated weighted C content of all ranks produced in a given state.

Table A- 37: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank (Tg C/QBtu) (1990-2009)

Consuming Sector	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Electric Power	25.96	25.93	25.93	25.93	25.95	25.98	26.00	26.00	26.05	26.09	26.10	26.09	26.04	26.05	26.05	26.05
Industrial Coking	25.53	25.57	25.56	25.59	25.62	25.59	25.63	25.63	25.65	25.63	25.63	25.60	25.60	25.61	25.61	25.61
Other Industrial	25.82	25.80	25.75	25.75	25.79	25.80	25.74	25.66	25.57	25.55	25.56	25.80	25.84	25.82	25.82	25.82
Residential/ Commercial	26.20	26.13	26.04	25.90	26.07	25.98	26.01	26.00	25.98	26.04	25.91	26.09	26.29	25.94	25.71	25.71
Coal Rank																
Anthracite	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28
Bituminous	25.38	25.42	25.43	25.43	25.43	25.44	25.45	25.46	25.46	25.45	25.45	25.45	25.45	25.45	25.44	25.44
Sub-bituminous	26.50	26.50	26.50	26.50	26.50	26.50	26.49	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50
Lignite	26.58	26.59	26.58	26.59	26.59	26.60	26.61	26.62	26.63	26.62	26.62	26.62	26.62	26.64	26.65	26.65

[a] In 2008, the EIA began collecting consumption data for commercial and institutional consumption rather than commercial and residential consumption.

Sources: C content coefficients calculated from USGS (1998) and PSU (2010); data presented in EPA (2010b).

Step 5. Develop national-level carbon contents by rank for comparison to IPCC defaults

Although not used to calculate emissions, national-level C contents by rank are more easily compared to C contents of other countries than are sectoral C contents. This step requires weighting the state-level C contents by rank developed under Step 1 by overall coal production by state and rank. Each state-level C content by rank is multiplied by the share of national production of that rank that each state represents. The resulting partial C contents are then summed across all states to generate an overall C content for each rank.

$$N_{rank} = P_{rank1} \times C_{rank1} + P_{rank2} \times C_{rank2} + \ldots + P_{rankn} \times C_{rankn}$$

Where,

N_{rank} = The national C content by rank;
P_{rank} = The portion of U.S. coal production of a given rank attributed to each state; and
C_{rank} = The estimated C content of a given rank in each state.

Data Sources

The ultimate analysis of coal samples was based on the 7,092 coal samples, 6,588 of which are from USGS (1998) and 504 that come from the Pennsylvania State University Coal Database (PSU 2010). Data contained in the USGS's CoalQual Database are derived primarily from samples taken between 1973 and 1989, and were largely reported in State Geological Surveys. Data in the PSU Coal Database are mainly from samples collected by PSU since 1967 and are housed at the PSU Sample Bank. Only the subset of PSU samples that are whole-seam channel samples are included in the development of carbon factors in order to increase data accuracy.

Data on coal consumption by sector and state of origin, as well as coal production by state and rank, were obtained from EIA. The EIA's *Annual Coal Report* is the source for state coal production by rank from 2001-2008. In prior years, the EIA reported this data in its *Coal Industry Annual*. Data for coal consumption by state of origin and consuming sector for 2001 to 2008 was obtained from the EIA's *Coal Distribution – Annual*. For 1990-2000, end-use data was obtained from the *Coal Industry Annual*.

Uncertainty

C contents vary considerably by state. Bituminous coal production and sub-bituminous coal production represented 47.3 percent and 46.1 percent of total U.S. supply in 2008, respectively. State average C content coefficients for bituminous coal vary from a low of 85.59 kg CO_2 per MMBtu in Texas to a high of 105.21 kg CO_2 per MMBtu in Montana. However, Texas bituminous coal is considered anomalous,[9] has not been produced since 2004 and production since 1990 peaked at just 446,000 short tons in 1996. The next lowest average emission factor for bituminous coal is found in Western Kentucky (91.36 kg CO_2 per MMBtu). In 2000, Montana produced no bituminous coal and Western Kentucky production accounted for just 4.5 percent of overall bituminous production. In 2008, more than 60 percent of bituminous coal was produced in three states: West Virginia, Kentucky (predominantly from the Eastern production region), and Pennsylvania, and this share has remained fairly constant since 1990. These three states show a variation in C content for bituminous coals of ±0.7 percent, based on more than 2,000 samples (see Table A-38).

Similarly, the C content coefficients for sub-bituminous coal range from 91.29 kg CO_2 per MMBtu in Utah to 98.10 kg CO_2 per MMBtu in Alaska. However, Utah has no recorded production of sub-bituminous coal since 1990. Production of sub-bituminous coal in Alaska has made up less than 0.7 percent of total sub-bituminous production since 1990, with even this small share declining over time. Wyoming has represented between 75 percent and 87 percent of total sub-bituminous coal production in the United States in each year since 1990. Thus, the C content coefficient for Wyoming (97.22 kg CO_2 per MMBtu), based on 455 samples, dominates the national average.

The interquartile range of C content coefficients among samples of sub-bituminous coal in Wyoming was ±1.5 percent from the mean. Similarly, this range among samples of bituminous coal from West Virginia, Kentucky, and Pennsylvania was ±1.2 percent or less for each state. The large number of samples and the low variability within the sample set of the states that represent the predominant source of supply of U.S. coal suggest that the uncertainty in this factor is very low, on the order of ±1.0 percent.

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[9] See, for example: San Filipo, 1999. USGS. (U.S. Geological Survey Open-File Report 99-301), Ch. 4.

For comparison, J. Quick (2010) completed an analysis similar in methodology to that used here, in order to generate national average carbon emission factors as well as county-level factors. This study's rank-based national average factors have a maximum deviation from the factors developed here by EPA of -0.55 percent, which is for lignite (range: -0.55 to +0.1 percent). This corroboration further supports the assertion of minimal uncertainty in the application of the rank-based factors derived for the purposes of this Inventory.

Table A-38: Variability in Carbon Content Coefficients by Rank Across States (Kilograms CO_2 Per MMBtu)

State	Number of Samples	Bituminous	Sub-bituminous	Anthracite	Lignite
Alabama	951	92.84	-	-	99.10
Alaska	91	98.33	98.10	-	98.65
Arizona	15	93.94	97.34	-	-
Arkansas	80	96.36	-	-	94.97
Colorado	318	94.37	96.52	-	101.10
Georgia	35	95.01	-	-	-
Idaho	1	-	94.90	-	-
Illinois	57	92.33	-	-	-
Indiana	146	92.65	-	-	-
Iowa	100	91.87	-	-	-
Kansas	29	90.91	-	-	-
Kentucky	897	92.61	-	-	-
Louisiana	1	-	-	-	96.01
Maryland	47	94.29	-	-	-
Massachusetts	3	-	-	114.82	-
Michigan	3	92.88	-	-	-
Mississippi	8	-	-	-	98.19
Missouri	111	91.71	-	-	-
Montana	309	105.21	97.73	103.60	99.40
Nevada	2	94.41	-	-	99.86
New Mexico	185	94.29	94.89	103.92	-
North Dakota	202	-	93.97	-	99.48
Ohio	674	91.84	-	-	-
Oklahoma	63	92.33	-	-	-
Pennsylvania	861	93.33	-	103.68	-
Tennessee	61	92.82	-	-	-
Texas	64	85.59	94.19	-	94.47
Utah	169	95.75	91.29	-	-
Virginia	470	93.51	-	98.54	-
Washington	18	94.53	97.36	102.53	106.55
West Virginia	612	93.84	-	-	-
Wyoming	503	94.80	97.22	-	-
U.S. Average	**7,092**	**93.13**	**96.94**	**104.29**	**98.63**

Notes: - Indicates No Sample Data Available.
Sources: Calculated from USGS (1998), and PSU (2010); data presented in EPA (2010).

Natural Gas

Natural gas is predominantly composed of methane, which is 75 percent C by weight and contains 14.2 Tg C/QBtu (higher heating value), but it may also contain many other compounds that can lower or raise its overall C content. These other compounds may be divided into two classes: 1) natural gas liquids (NGLs), and 2) non-hydrocarbon gases. The most common NGLs are ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and, to a lesser extent, pentane (C_5H_{12}) and hexane (C_6H_{14}). Because the NGLs have more C atoms than methane (which has only one), their presence increases the overall C content of natural gas. NGLs have a commercial value greater than that of methane, and therefore are usually separated from raw natural gas at gas processing plants and sold as separate products. Ethane is typically used as a petrochemical feedstock, propane and butane have diverse uses, and natural gasoline[10] contributes to the gasoline/naphtha "octane pool," used primarily to make motor gasoline.

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[10] A term used in the gas processing industry to refer to a mixture of liquid hydrocarbons (mostly pentanes and heavier hydrocarbons) extracted from natural gas.

Raw natural gas can also contain varying amounts of non-hydrocarbon gases, such as CO_2, nitrogen, helium and other noble gases, and hydrogen sulfide. The share of non-hydrocarbon gases is usually less than 5 percent of the total, but there are individual natural gas reservoirs where the share can be much larger. The treatment of non-hydrocarbon gases in raw gas varies. Hydrogen sulfide is always removed. Inert gases are removed if their presence is substantial enough to reduce the energy content of the gas below pipeline specifications (see Step 1, below). Otherwise, inert gases will usually be left in the natural gas. Because the raw gas that is usually flared (see Step 2, below) contains NGLs and CO_2, it will typically have a higher overall C content than gas that has been processed and moved to end-use customers via transmission and distribution pipelines.

Methodology

The methodology for estimating the C contents of pipeline and flared natural gas can be described in five steps.

Step 1. Define pipeline-quality natural gas

In the United States, pipeline-quality natural gas is required to have an energy content greater than 970 Btu per cubic foot, but less than 1,100 Btu per cubic foot. Hydrogen sulfide content must be negligible. Typical pipeline-quality natural gas is about 95 percent methane, 3 percent NGLs, and 2 percent non-hydrocarbon gases, of which approximately half is CO_2.

However, there remains a range of gas compositions that are consistent with pipeline specifications. The minimum C content coefficient for natural gas would match that for pure methane, which equates to an energy content of 1,005 Btu per standard cubic foot. Gas compositions with higher or lower Btu content tend to have higher C emission factors, because the "low" Btu gas has a higher content of inert gases (including CO_2 offset with more NGLs), while "high" Btu gas tends to have more NGLs.

Step 2. Define flared gas

Every year, a certain amount of natural gas is flared in the United States. There are several reasons that gas is flared:

- There may be no market for some batches of natural gas, the amount may be too small or too variable, or the quality might be too poor to justify treating the gas and transporting it to market (such is the case when gas contains large shares of CO_2). Most natural gas that is flared for these reasons is "rich" associated gas, with relatively high energy content, high NGL content, and a high C content.

- Gas treatment plants may flare substantial volumes of natural gas because of "process upsets," because the gas is "off spec," or possibly as part of an emissions control system. Gas flared at processing plants may be of variable quality.

Data on the energy content of flare gas, as reported by states to EIA, indicate an average energy content of 1,130 Btu per standard cubic foot (EIA 1994). Flare gas may have an even higher energy content than reported by EIA since rich associated gas can have energy contents as high as 1,300 to 1,400 Btu per cubic foot.

Step 3. Determine a relationship between carbon content and heat content

A relationship between C content and heat content may be used to develop a C content coefficient for natural gas consumed in the United States. In 1994, EIA examined the composition (including C contents) of 6,743 samples of pipeline-quality natural gas from utilities and/or pipeline companies in 26 cities located in 19 states. To demonstrate that these samples were representative of actual natural gas "as consumed" in the United States, their heat content was compared to that of the national average. For the most recent year, the average heat content of natural gas consumed in the United States was 1,029 Btu per cubic foot, and has varied by less than 1 percent (1,027 to 1,029 Btu per cubic foot) over the past 5 years. Meanwhile, the average heat content of the 6,743 samples was 1,027 Btu per cubic foot, and the median heat content was 1,031 Btu per cubic foot. Thus, the average heat content of the sample set falls well within the typical range of natural gas consumed in the United States, suggesting that these samples continue to be representative of natural gas "as consumed" in the United States. The average and median composition of these samples appear in Table A-39.

Table A-39: Composition of Natural Gas (Percent)

Compound	Average	Median
Methane	93.07	95.00
Ethane	3.21	2.79
Propane	0.59	0.48
Higher Hydrocarbons	0.32	0.30
Non-hydrocarbons	2.81	1.43
Higher Heating Value (Btu per cubic foot)	1,027	1,031

Source: Gas Technology Institute (1992).

Carbon contents were calculated for a series of sub-samples based on their CO_2 content and heat content. Carbon contents were calculated for the groups of samples with less than 1.0 percent (n=5,181) and less than 1.5 percent CO_2 only (n=6,522) and those with less than 1.0 or 1.5 percent CO_2 and less than 1,050 Btu/cf (n= 4,888 and 6,166, respectively). These stratifications were chosen to exclude samples with CO_2 content and heat contents outside the range of pipeline-quality natural gas. In addition, hexane was removed from the samples since it is usually stripped out of raw natural gas before delivery because it is a valuable natural gas liquid used as a feedstock for gasoline. The average carbon contents for the four separate sub-samples are shown below in Table A-40.

Table A-40: Carbon Content of Pipeline-Quality Natural Gas by CO_2 and Heat Content (Tg C/QBtu)

Sample	Average Carbon Content
Full Sample	14.48
< 1.0% CO_2	14.43
< 1.5% CO_2	14.47
< 1.0 % CO_2 and <1,050 Btu/cf	14.42
< 1.5 % CO_2 and <1,050 Btu/cf	14.47

Source: EPA (2010).

Step 4. Apply carbon content coefficients developed in Step 3 to pipeline natural gas

A regression analysis was performed on the sub-samples in to further examine the relationship between carbon content and heat content. The regression used carbon content as the dependent variable and heat content as the independent variable. The resulting R-squared values[11] for each of the sub-samples ranged from 0.79 for samples with less than 1.5% CO_2 and under 1,050 Btu/cf to 0.91 for samples containing less than 1.0% CO_2 only. However, the sub-sample with less than 1.5% CO_2 and 1,050 Btu/cf was chosen as the representative sample for two reasons. First, it most accurately reflects the range of CO_2 content and heat content of pipeline quality natural gas. Secondly, the R-squared value, although it is the lowest of the sub-groups tested, remains relatively high. This high R-squared indicates a low percentage of variation in C content as related to heat content. The regression for this sub-sample resulted in the following equation:

$$C \text{ Content} = (0.011 \times \text{Heat Content}) + 3.5341$$

This equation was used to estimate the annual predicted carbon content of natural gas from 1990 to 2009 based on the EIA's national average pipeline-quality gas heat content for each year. The table of average carbon contents for each year is shown below in Table A-41.

Table A-41: Carbon Content Coefficients for Natural Gas (Tg Carbon/QBtu)

Fuel Type	1990		1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Natural Gas	14.45		14.46	14.46	14.46	14.44	14.46	14.47	14.46	14.46	14.44	14.46	14.46	14.46	14.46	14.46	14.46

Source: EPA (2010)

Step 5. Apply carbon content coefficients developed in Step 3 to flare gas

Selecting a C content coefficient for flare gas was much more difficult than for pipeline natural gas, because of the uncertainty of its composition and of the combustion efficiency of the flare. Because EIA estimates the heat content of flare gas at 1,130 Btu per cubic foot, the average C content for samples with more than 1,100 Btu per cubic foot (n=18) was chosen as the relevant sub-sample from which to calculate a flare gas carbon content. It should be noted that the sample dataset did not include any samples with more than 1,130 Btu per cubic foot.

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[11] R-squared represents the percentage of variation in the dependent variable (in this case carbon content) explained by variation in the independent variables.

Hexane was not removed from flare gas samples since it is assumed that natural gas liquids are present in samples with higher heat contents. Carbon contents were calculated for each sample with a heat content of more than 1,100 Btu per cubic foot. The simple average carbon content for the sample sub-set representing flare gas is shown below in Table A-42.

Table A-42: Carbon Content of Flare Gas (Tg C/QBtu)

Relevant Sub-Sample	Average Carbon Content
>1,100 Btu/cf	15.31

Source: EPA (2010)

Data Sources

Natural gas samples were obtained from the Gas Technology Institute (1992). Average heat content data for natural gas consumed in the United States was taken from EIA (2009a).

Uncertainty

The assignment of C content coefficients for natural gas, and particularly for flare gas, requires more subjective judgment than the methodology used for coal. This subjective judgment may introduce additional uncertainty.

Figure A-1 shows the relationship between the calculated C content for each natural gas sample and its energy content. This figure illustrates the relatively restricted range of variation in both the energy content (which varies by about 6 percent from average) and the C emission coefficient of natural gas (which varies by about 5 percent). Thus, the knowledge that gas has been sold via pipeline to an end-use consumer allows its C emission coefficient to be predicted with an accuracy of ±5.0 percent.

Figure A-1: Carbon Content for Samples of Pipeline-Quality Natural Gas Included in the Gas Technology Institute Database

Natural gas suppliers may achieve the same overall energy content from a wide variety of methane, higher hydrocarbon, and non-hydrocarbon gas combinations. Thus, the plot reveals large variations in C content for a single Btu value. In fact, the variation in C content for a single Btu value may be nearly as great as the variation for the whole sample. As a result, while energy content has some predictive value, the specific energy content does not substantially improve the accuracy of an estimated C content coefficient beyond the ±5.0 percent offered with the knowledge that it is of pipeline-quality.

The plot of C content also reveals other interesting anomalies. Samples with the lowest emissions coefficients tend to have energy contents of about 1,000 Btu per cubic foot. They are composed of almost pure methane. Samples with a greater proportion of NGLs (e.g., ethane, propane, and butane) tend to have energy contents greater than 1,000 Btu per cubic foot, along with higher emissions coefficients. Samples with a greater proportion of inert gases tend to have lower energy content, but they usually contain carbon dioxide as one of the inert gases and, consequently, also tend to have higher emission coefficients (see left side of Figure A-1).

For the full sample (n=6,743), the average C content of a cubic foot of gas was 14.48 Tg C/QBtu (see Table A-41). Additionally, a regression analysis using the full sample produced a predicted C content of 14.49 Tg C/QBtu based on a heat content of 1,029 btu/cf (the average heat content in the U.S. for the most recent year). However, these two values include an upward influence on the resulting carbon content that is caused by inclusion in the sample set of the samples that contain large amounts of inert carbon dioxide and those samples with more than 1,050 Btu per cubic foot that contain an unusually large amount of NGLs. Because typical gas consumed in the United States does not contain such a large amount of carbon dioxide or natural gas liquids, a carbon content of 14.47 Tg C/QBtu, based on samples with less than 1.5 percent carbon dioxide and less than 1,050 Btu per cubic foot, better represents the pipeline-quality fuels typically consumed.

Petroleum

There are four critical determinants of the C content coefficient for a petroleum-based fuel:

- The density of the fuel (e.g., the weight in kilograms of one barrel of fuel);

- The fraction by mass of the product that consists of hydrocarbons, and the fraction of non-hydrocarbon impurities;

- The specific types of 'families' of hydrocarbons that make up the hydrocarbon portion of the fuel; and

- The heat content of the fuel.

$$C_{fuel} = (D_{fuel} \times S_{fuel}) / E_{fuel}$$

Where,

C_{fuel} = The C content coefficient of the fuel;
D_{fuel} = The density of the fuel;
S_{fuel} = The share of the fuel that is C; and
E_{fuel} = The heat content of the fuel.

Most of the density, carbon share or heat contents applied to calculate the carbon coefficients for petroleum products that are described in this sub-Annex and applied to this emissions inventory have been updated for this edition of the report. These changes have been made where necessary to increase the accuracy of the underlying data or to align the petroleum properties data used in this report with that developed for use in the Mandatory Reporting of Greenhouse Gases Rule (EPA 2009b).

Petroleum products vary between 5.6 degrees API gravity (dense products such as asphalt and road oil) and 247 degrees (ethane).[12] This is a range in density of 60 to 150 kilograms per barrel, or ±50 percent. The variation in C content, however, is much smaller (±5 to 7 percent) for products produced by standard distillation refining: ethane is 80 percent C by weight, while petroleum coke is 90 to 92 percent C. This tightly bound range of C contents can be explained by basic petroleum chemistry (see below). Additional refining can increase carbon contents. Calcined coke, for example, is formed by heat treating petroleum coke to about 1600 degrees Kelvin (calcining), to expel volatile materials and increase the percentage of elemental carbon. This product can contain as much as 97 to 99 percent carbon. Calcined coke is mainly used in the aluminum and steel industry to produce carbon anodes.

Petroleum Chemistry

Crude oil and petroleum products are typically mixtures of several hundred distinct compounds, predominantly hydrocarbons. All hydrocarbons contain hydrogen and C in various proportions. When crude oil is distilled into petroleum products, it is sorted into fractions by the boiling temperature of these hundreds of organic compounds. Boiling temperature is strongly correlated with the number of C atoms in each molecule. Petroleum products consisting of relatively simple molecules and few C atoms have low boiling temperatures, while larger molecules with more C atoms have higher boiling temperatures.

Products that boil off at higher temperatures are usually more dense, which implies greater C content as well. Petroleum products with higher C contents, in general, have lower energy content per unit mass and higher energy content per unit volume than products with lower C contents. Empirical research led to the establishment of a set of quantitative relationships between density, energy content per unit weight and volume, and C and hydrogen content. Figure A-2 compares C content coefficients calculated on the basis of the derived formula with actual C content coefficients for a range of crude oils, fuel oils, petroleum products, and pure hydrocarbons. The actual fuel samples were drawn from the sources described below in the discussions of individual petroleum products.

Figure A-2: Estimated and Actual Relationships Between Petroleum Carbon Content Coefficients and Hydrocarbon Density

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[12] API gravity is an arbitrary scale expressing the gravity or density of liquid petroleum products, as established by the American Petroleum Institute (API). The measuring scale is calibrated in terms of degrees API. The higher the API gravity, the lighter the compound. Light crude oils generally exceed 38 degrees API and heavy crude oils are all crude oils with an API gravity of 22 degrees or below. Intermediate crude oils fall in the range of 22 degrees to 38 degrees API gravity. API gravity can be calculated with the following formula: API Gravity = (141.5/Specific Gravity) – 131.5. Specific gravity is the density of a material relative to that of water. At standard temperature and pressure, there are 62.36 pounds of water per cubic foot, or 8.337 pounds water per gallon.

The derived empirical relationship between C content per unit heat and density is based on the types of hydrocarbons most frequently encountered. Petroleum fuels can vary from this relationship due to non-hydrocarbon impurities and variations in molecular structure among classes of hydrocarbons. In the absence of more exact information, this empirical relationship offers a good indication of C content.

Non-hydrocarbon Impurities

Most fuels contain a certain share of non-hydrocarbon material. This is also primarily true of crude oils and fuel oils. The most common impurity is sulfur, which typically accounts for between 0.5 and 4 percent of the mass of most crude oils, and can form an even higher percentage of heavy fuel oils. Some crude oils and fuel oils also contain appreciable quantities of oxygen and nitrogen, typically in the form of asphaltenes or various acids. The nitrogen and oxygen content of crude oils can range from near zero to a few percent by weight. Lighter petroleum products have much lower levels of impurities, because the refining process tends to concentrate all of the non-hydrocarbons in the residual oil fraction. Light products usually contain less than 0.5 percent non-hydrocarbons by mass. Thus, the C content of heavy fuel oils can often be several percent lower than that of lighter fuels, due entirely to the presence of non-hydrocarbons.

Variations in Hydrocarbon Classes

Hydrocarbons can be divided into five general categories, each with a distinctive relationship between density and C content and physical properties. Refiners tend to control the mix of hydrocarbon types in particular products in order to give petroleum products distinct properties. The main classes of hydrocarbons are described below.

Paraffins. Paraffins are the most common constituent of crude oil, usually comprising 60 percent by mass. Paraffins are straight-chain hydrocarbons with the general formula C_nH_{2n+2}. Paraffins include ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and octane (C_8H_{18}). As the chemical formula suggests, the C content of the paraffins increases with their C number: ethane is 79.89 percent C by weight, octane 84.12 percent. As the size of paraffin molecules increases, the C content approaches the limiting value of 85.7 percent asymptotical (see Figure A-3).

Cycloparaffins. Cycloparaffins are similar to paraffins, except that the C molecules form ring structures rather than straight chains, and consequently require two fewer hydrogen molecules than paraffins. Cycloparaffins always have the general formula C_nH_{2n} and are 85.63 percent C by mass, regardless of molecular size.

Olefins. Olefins are a very reactive and unstable form of paraffin: a straight chain with two carbon atoms double bonded together (thus are unsaturated) compared to the carbon atoms in a paraffin (which are saturated with hydrogen).. They are never found in crude oil but are created in moderate quantities by the refining process. Gasoline, for example, may contain between 2 and 20 percent olefins. They also have the general formula C_nH_{2n}, and hence are also always 85.63 percent C by weight. Propylene (C_3H_6), a common intermediate petrochemical product, is an olefin.

Aromatics. Aromatics are very reactive hydrocarbons that are relatively uncommon in crude oil (10 percent or less). Light aromatics increase the octane level in gasoline, and consequently are deliberately created by catalytic reforming of heavy naphtha. Aromatics also take the form of ring structures with some double bonds between C atoms. The most common aromatics are benzene (C_6H_6), toluene (C_7H_8), and xylene (C_8H_{10}). The general formula for aromatics is C_nH_{2n-6}. Benzene is 92.26 percent C by mass, while xylene is 90.51 percent C by mass and toluene is 91.25 percent C by mass. Unlike the other hydrocarbon families, the C content of aromatics declines asymptotically toward 85.7 percent with increasing C number and density (see Figure A-3).

Polynuclear Aromatics. Polynuclear aromatics are large molecules with a multiple ring structure and few hydrogen atoms, such as naphthalene ($C_{10}H_8$ and 93.71 percent C by mass) and anthracene ($C_{14}H_{10}$ and 97.7 percent C). They are relatively rare but do appear in heavier petroleum products.

Figure A-3 illustrates the share of C by weight for each class of hydrocarbon. Hydrocarbon molecules containing 2 to 4 C atoms are all natural gas liquids; hydrocarbons with 5 to 10 C atoms are predominantly found in naphtha and gasoline; and hydrocarbon compounds with 12 to 20 C atoms comprise "middle distillates," which are used to make diesel fuel, kerosene and jet fuel. Larger molecules which can be vacuum distilled may be used as lubricants, waxes, and residual fuel oil or cracked and blended into the gasoline or distillate pools.

Figure A-3: Carbon Content of Pure Hydrocarbons as a Function of Carbon Number

If one knows nothing about the composition of a particular petroleum product, assuming that it is 85.7 percent C by mass is not an unreasonable first approximation. Since denser products have higher C numbers, this guess would be most likely to be correct for crude oils and fuel oils. The C content of lighter products is more affected by the shares of paraffins and aromatics in the blend.

Energy Content of Petroleum Products

The exact energy content (gross heat of combustion) of petroleum products is not generally known. EIA estimates energy consumption in Btu on the basis of a set of industry-standard conversion factors. These conversion factors are generally accurate to within 3 to 5 percent.

Individual Petroleum Products

The United States maintains data on the consumption of more than 20 separate petroleum products and product categories. The C contents, heat contents, and density for each product are provided below in Table A-43. A description of the methods and data sources for estimating the key parameters for each individual petroleum product appears below.

Table A-43: Carbon Content Coefficients and Underlying Data for Petroleum Products

Fuel	2008 Carbon Content (Tg C/QBtu)	Gross Heat of Combustion (MMBtu/Barrel)	Density (API Gravity)	Percent Carbon
Motor Gasoline	19.46	a	a	a
LPG(total)	16.97	b	b	b
LPG (energy use)	16.83	b	b	b
LPG (non-energy use)	17.06	b	b	b
Jet Fuel	19.70	5.670	42.0	86.30
Distillate Fuel No. 1	19.98	5.822	35.3	86.40
Distillate Fuel No. 2	20.17	5.809	35.8	87.30
Distillate Fuel No. 4	20.47	6.135	23.2	86.47
Residual Fuel No. 5	19.89	5.879	33.0	85.67
Residual Fuel No. 6	20.48	6.317	15.5	84.67
Asphalt and Road Oil	20.55	6.636	5.6	83.47
Lubricants	20.20	6.065	25.7	85.80
Naphtha (< 400 deg. F)[c]	18.55	5.248	62.4	84.11
Other Oils (>400 deg. F)[c]	20.17	5.825	35.8	87.30
Aviation Gas	18.86	5.048	69.0	85.00
Kerosene	19.96	5.825	35.3	86.40
Petroleum Coke	27.85	6.024	-	92.28
Special Naphtha	19.74	5.248	52.0	84.75
Petroleum Waxes	19.80	5.537	43.3	85.30
Still Gas	18.20	6.000	-	77.70
Crude Oil	20.31	5.800	31.2	85.49
Unfinished Oils	20.31	5.825	31.2	85.49
Miscellaneous Products	20.31	5.796	31.2	85.49
Pentanes Plus	19.10	4.620	81.3	83.63

[a] Calculation of the carbon content coefficient for motor gasoline in 2008 uses separate higher heating values for conventional and reformulated gasoline of 5.253 and 5.150, respectively (EIA 2008a). Densities and carbon shares (percent carbon) are annually variable and separated by both fuel formulation and grade, see Motor Gasoline and Blending Components, below, for details.
[b] LPG is a blend of multiple paraffinic hydrocarbons: ethane, propane, isobutane, and normal butane, each with their own heat content, density and C content, see Table A-46.
[c] Petrochemical feedstocks have been split into naphthas and other oils for this inventory report. Parameters presented are for naphthas with a boiling temperature less than 400 degrees Fahrenheit. Other oils are petrochemical feedstocks with higher boiling points. They are assumed to have the same characteristics as distillate fuel oil no. 2.
- No sample data available
Sources: EIA (1994), EIA (2009a), EPA (2009b), and EPA (2010).

Motor Gasoline and Motor Gasoline Blending Components

Motor gasoline is a complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in spark-ignition engines.[13] "Motor Gasoline" includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline; but excludes aviation gasoline.

Gasoline is the most widely used petroleum product in the United States, and its combustion accounts for nearly 20 percent of all U.S. CO_2 emissions. EIA collects consumption data (i.e., "petroleum products supplied" to end-users) for several types of finished gasoline over the 1990-2008 time period: regular, mid-grade and premium conventional gasoline (all years) and regular, mid-grade and premium reformulated gasoline (November 1994 to 2008). Leaded and oxygenated gasoline are not separately included in the data used for this report.[14]

The American Society for Testing and Materials (ASTM) standards permit a broad range of densities for gasoline, ranging from 50 to 70 degrees API gravity, or 111.52 to 112.65 kilograms per barrel (EIA 1994), which implies a range of possible C and energy contents per barrel. Table A- 44 reflects changes in the density of gasoline over time and across grades and formulations of gasoline through 2008.

Table A- 44: Motor Gasoline Density, 1990 – 2009 (Degrees API)

Fuel Grade	1990		1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Conventional - Winter Grade																	
Low Octane	62.0		59.8	60.6	61.5	61.8	61.6	61.6	61.7	61.6	61.8	62.4	62.6	62.7	63.1	63.0	63.0
High Octane	59.0		58.0	58.5	59.3	60.0	60.3	59.7	59.1	59.0	59.9	60.7	60.9	60.0	60.3	60.9	60.9
Conventional - Summer Grade																	
Low Octane	58.2		56.1	56.9	57.1	57.6	57.7	56.8	57.2	56.5	56.8	57.4	57.9	57.8	57.5	58.6	58.6
High Octane	55.5		55.1	55.3	56.4	55.7	57.4	55.8	55.5	55.7	56.0	57.0	57.0	57.4	56.9	58.0	58.0
Reformulated - Winter Grade																	
Low Octane	NA		61.9	62.3	62.1	62.7	62.7	62.7	62.6	61.9	62.1	62.7	62.8	62.3	62.1	62.4	62.4
High Octane	NA		59.9	60.8	62.1	61.4	61.0	61.1	61.0	61.8	61.9	61.8	61.8	61.7	62.1	62.5	62.5
Reformulated - Summer Grade																	
Low Octane	NA		58.5	58.0	58.8	58.4	58.4	58.4	58.8	58.2	59.1	58.1	58.4	58.7	58.5	59.1	59.1
High Octane	NA		56.7	57.8	58.4	58.5	57.8	58.3	58.2	58.0	58.7	58.9	58.1	59.0	59.3	59.8	59.8

Notes: NA – Not Applicable, fuel type was not analyzed.
Source: National Institute of Petroleum and Energy Research (1990 through 2009).

The density of motor gasoline increased across all grades through 1994, partly as a result of the leaded gasoline phase-out. In order to maintain the "anti-knock" quality and octane ratings of gasoline in the absence of lead, the portion of aromatic hydrocarbons blended into gasoline through the refining process was increased. As discussed above, aromatic hydrocarbons have a lower ratio of hydrogen to C than other hydrocarbons typically found in gasoline, and therefore increase fuel density.

The trend in gasoline density was reversed beginning in 1996 with the development of fuel additives that raised oxygen content. In 1995, a requirement for reformulated gasoline in non-attainment areas implemented under the Clean Air Act Amendments further changed the composition of gasoline consumed in the United States. Through 2005, methyl tertiary butyl ether (MTBE), ethanol, ethyl tertiary butyl ether (ETBE) and tertiary amyl methyl ether (TAME) were added to reformulated and sometimes to conventional gasoline to boost its oxygen content, reduce its toxics impacts and increase its octane. The increased oxygen reduced the emissions of carbon monoxide and unburned hydrocarbons. These oxygen-rich blending components are also much lower in C than standard gasoline. The average gallon of reformulated gasoline consumed in 2005 contained over 10 percent MTBE and 0.6 percent TAME (by volume). The characteristics of reformulated fuel additives appear in Table A-45.

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[13] Motor gasoline, as defined in ASTM Specification D 4814 or Federal Specification VV-G-1690C, is characterized as having a boiling range of 122 degrees to 158 degrees Fahrenheit at the 10-percent recovery point to 365 degrees to 374 degrees Fahrenheit at the 90-percent recovery point.

[14] Oxygenated gasoline volumes are included in the conventional gasoline data provided by EIA from 2007 onwards. Leaded gasoline was included in total gasoline by EIA until October 1993.

Table A-45: Characteristics of Major Reformulated Fuel Additives

Additive	Density (Degrees API)	Carbon Share (Percent)
MTBE	58.6	68.13
ETBE	58.5	70.53
TAME	51.2	70.53
DIPE	62.7	70.53
Ethanol (100%)	45.8	52.14

Source: EPA, 2009b.

Since 2005, due to concerns about the potential environmental consequences of the use of MTBE in fuels, there has been a shift away from the addition of MTBE, TAME, ETBE and DIPE and towards the use of ethanol as a fuel oxygenate.[15] Ethanol, also called ethyl alcohol, is an anhydrous alcohol with molecular formula C_2H_5OH. Ethanol has a lower carbon share than other oxygenates, approximately 52 percent compared to about 70 percent for MTBE and TAME. The density of ethanol was calculated by fitting density data at 10 degree intervals to a polynomial of order two and then using the fit to interpolate the value of the density at 15 degrees Celsius. A common fuel mixture of 10 percent denatured ethanol (denatured by 2% hydrocarbons) and 90 percent gasoline, known as E10, is widely used in the U.S. and does not require any modification to vehicle engines or fuel systems. The average gallon of reformulated alcohol blend gasoline in 2008 contained 8.6 percent ethanol (by volume). As of 2010, ten States require the use of ethanol-blended fuel.[16] Ethanol blends up to E85 (85 percent ethanol, 15 percent gasoline) are in use in the United States but can only be used in specially designed vehicles called flexible fuel vehicles (FFVs). Most ethanol fuel in the United States is produced using corn as feedstock,[17] although production pathways utilizing agricultural waste, woody biomass and other resources are in development.

Methodology

Step 1. Disaggregate U.S. gasoline consumption by grade and type

Separate monthly data for U.S. sales to end users of finished gasoline by product grade and season for both standard gasoline and reformulated gasoline were obtained from the EIA.

Step 2. Develop carbon content coefficients for each grade and type

Annual C content coefficients for each gasoline grade, type and season are derived from four parameters for each constituent of the finished gasoline blend: the volumetric share of each constituent,[18] the density of the constituent, share of the constituent[19] that is C; and the energy content of a gallon of the relevant formulation of gasoline. The percent by mass of each constituent of each gasoline type was calculated using percent by volume data from NIPER and the density of each constituent. The ether additives listed in Table A-45 are accounted for in both reformulated fuels and conventional fuels, to the extent that they were present in the fuel. From 2006 onward, reformulated fuel mass percentages are calculated from their constituents, net of the share provided by ethanol. C content coefficients were then derived from the calculated percent by mass values by weighting the carbon share of each constituent by its contribution to the total mass of the finished motor gasoline product.

Step 3. Weight overall gasoline carbon content coefficient for consumption of each grade and type

The C content for each grade, type and season of fuel is multiplied by the share of annual consumption represented by the grade and fuel type during the relevant time period. Individual coefficients are then summed and totaled to yield an overall C content coefficient for each year.

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[15] The annual motor gasoline carbon contents that are applied for this inventory do not include the carbon contributed by the ethanol contained in reformulated fuels. Ethanol is a biofuel, and net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change and Forestry.

[16] Ethanol.org. http://www.ethanol.org/index.php?id=79&parentid=26. Retrieved 2-19-2010.

[17] "Ethanol Market Penetration". Alternative Fuels and Advanced Vehicles Data Center, US DOE. http://www.afdc.energy.gov/afdc/ethanol/market.html. Retrieved 2-19-2010.

[18] Calculations account for the properties of the individual constituents of gasoline, including, as applicable to the fuel grade and type: aromatics (excluding benzene), olefins, benzene, saturates, MTBE, TAME, ETBE, DIPE and ethanol.

[19] Saturates are assumed to be octane and aromatics are assumed to be toluene.

<u>Data Sources</u>

Data for the density of motor gasoline were derived from the National Institute for Petroleum and Energy Research (NIPER) (1990 through 2009). Data on the characteristics of reformulated gasoline, including C share, were also taken from NIPER (1990 through 2009).

Standard heat contents for motor gasoline of 5.253 MMBtu per barrel conventional gasoline and 5.150 MMBtu per barrel reformulated gasoline[20] were adopted from EIA (2009a).

<u>Uncertainty</u>

The uncertainty underlying the C content coefficients for motor gasoline has three underlying sources: the uncertainty in the averages published by NIPER, uncertainty in the C shares assumed in the EPA's analysis to be representative of the constituent hydrocarbon classes within gasoline (aromatics, olefins and saturates) and uncertainty in the heat contents applied.

A variable number of samples are used each year to determine the average percent by volume share of each hydrocarbon within each grade, season and formulation of gasoline that are obtained from NIPER. The total number of samples analyzed for each seasonal NIPER report varies from approximately 730 to over 1,800 samples over the period from 1990 through 2008. The number of samples analyzed that underlie the calculation of the average make-up of each seasonal formulation and grade varies from approximately 50 to over 400, with the greatest number of samples each season being of conventional, regular or premium gasoline. Further, not all sample data submitted to NIPER contains data for each of the properties, such that the number of samples underlying each constituent average value for each season, grade and formulation may be variable within the single gasoline type (e.g., of the 1,073 samples for which some data was obtained for gasoline sold in Winter 1995-1996, benzene content was provided for all samples, while olefin, aromatic and saturate content was provided for just 736 of those samples).

The distribution of sample origin collected for the NIPER report and the calculation of national averages are not reflective of sales volumes. The publication of simple, rather than sales-weighted averages to represent national average values increases the uncertainty in their application to the calculation of carbon content factors for the purposes of this inventory. Further, data for each sample is submitted voluntarily, which may also affect their representativeness.

Additionally, because the simple average constituent shares are calculated based upon data that have been renormalized to account for the share of ethers and alcohols, total average volume shares may not equal 100 percent.

The simple average for each hydrocarbon constituent is contained within a range of values that are as wide as +74.5/-63 percent of the mean across the Winter 2007-2008 and +49.6/-51.3 percent across the Summer 2008 samples of conventional, regular grade gasoline. However, these wide ranges exist for benzene, which generally accounts for only 1 percent, by volume, of each gallon. In contrast, saturates, the class of hydrocarbon that contribute the largest share, by volume, ranges only +6.4/-6.5 percent for the same set of Winter samples and +15.7/-8.8 percent for the Summer samples.

Secondly, EPA's calculation of C content factors for each gasoline type includes the following assumptions: for the purposes of assigning a carbon share to each compound in the blend, aromatic content (other than benzene) is assumed to be toluene and saturated hydrocarbons are assumed to be octane. All olefins have the same carbon share because they all have a molecular formula in the form C_nH_{2n}, so the C share applied to the olefin portion of the total gasoline blend does not increase the level of uncertainty in the calculation. These assumptions are based upon the use of octane and octane isomers as the primary saturates and toluene as the primary non-benzene aromatic in U.S. motor gasoline blends. The octane rating of a particular blend is based upon the equivalent iso-octane to heptane ratio, which is achieved through significant octane content relative to the other saturates. Aside from benzene, U.S. gasolines will include toluene as a major aromatic component, so toluene may be assumed a reasonable representative of total non-benzene aromatic content (EPA 2009a).

For each hydrocarbon category, the assumed C content lies within a range of possible values for all such hydrocarbons. Among saturated hydrocarbons, the C share of octane (84.12 percent) is at the high end of the range while ethane is represents the low end of the range (79.89 percent C). Total saturates constitute from 40 to 95 percent by volume of a given gasoline blend. For aromatics, toluene (91.25 percent C) lies in the middle of the possible range. This range is bounded by cumene (89.94 percent C) and naphthalene (93.71 percent C). Total aromatics may make up between 3 and 50 percent by volume of any given gasoline blend. The range of these potential values contributes to the uncertainty surrounding the final calculated carbon factors.

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[20] The reformulated gasoline heat content is applied to both reformulated blends containing ethers and those containing ethanol.

However, as demonstrated above in Figure A-3, the amount of variation in C content of gasoline is restricted by the compounds in the fuel to ±4 percent. Further, despite variation in sampling survey response, sample size and annually variable fuel formulation requirements, the observed variation in the annual weighted motor gasoline coefficients estimated for this inventory is ±0.8 percent over 1990 through 2008.

The third primary contributor to uncertainty is the assumed heat content. The heat contents are industry standards established many years ago. The heat contents are standard conversion factors used by EIA to convert volumetric energy data to energy units. Because the heat contents of fuels change over time, without necessarily and directly altering their volume, the conversion of known volumetric data to energy units may introduce bias. Thus, a more precise approach to estimating emissions factors would be to calculate C content per unit of volume, rather than per unit of energy. Adopting this approach, however, makes it difficult to compare U.S. C content coefficients with those of other nations.

The changes in density of motor gasoline over the last decade suggest that the heat content of the fuels is also changing. However, that change within any season grade has been less than 1 percent over the decade. Of greater concern is the use of a standardized heat content across grades that show a variation in density of ±1.5 percent from the mean for conventional gasoline and ±1.0 percent for reformulated fuels.

Jet Fuel

Jet fuel is a refined petroleum product used in jet aircraft engines. There are two classes of jet fuel used in the United States: "naphtha-based" jet fuels and "kerosene-based" jet fuels. In 1989, 13 percent of U.S. consumption was naphtha-based fuel, with the remainder kerosene-based jet fuel. In 1993, the U.S. Department of Defense began a conversion from naphtha-based JP-4 jet fuel to kerosene-based jet fuel, because of the possibility of increased demand for reformulated motor gasoline limiting refinery production of naphtha-based jet fuel. By 1996, naphtha-based jet fuel represented less than one-half of one percent of all jet fuel consumption. The C content coefficient for jet fuel used in this report prior to 1996 represents a consumption-weighted combination of the naphtha-based and kerosene-based coefficients. From 1996 to 2008, only the kerosene-based portion of total consumption is considered significant.

Methodology

Step 1. Estimate the carbon content for naphtha-based jet fuels

Because naphtha-based jet fuels are used on a limited basis in the United States, sample data on its characteristics are limited. The density of naphtha-based jet fuel (49 degrees) was estimated as the central point of the acceptable API gravity range published by ASTM. The heat content of the fuel was assumed to be 5.355 MMBtu per barrel based on EIA industry standards. The C fraction was derived from an estimated hydrogen content of 14.1 percent (Martel and Angello 1977), and an estimated content of sulfur and other non-hydrocarbons of 0.1 percent.

Step 2. Estimate the carbon content for kerosene-based jet fuels

The density of kerosene-based jet fuels was estimated at 42 degrees API and the carbon share at 86.3 percent. The density estimate was based on 38 fuel samples examined by NIPER. Carbon share was estimated on the basis of a hydrogen content of 13.6 percent found in fuel samples taken in 1959 and reported by Martel and Angello, and on an assumed sulfur content of 0.1 percent. The EIA's standard heat content of 5.670 MMBtu per barrel was adopted for kerosene-based jet fuel.

Step 3. Weight the overall jet fuel carbon content coefficient for consumption of each type of fuel (1990-1995 only)

For years 1990 through1995, the C content for each jet fuel type (naphtha-based, kerosene-based) is multiplied by the share of overall consumption of that fuel type, as reported by EIA (2009a). Individual coefficients are then summed and totaled to yield an overall C content coefficient. Only the kerosene-based C coefficient is reflected in the overall jet fuel coefficient for 1996 through 2008.

Data Sources

Data on the C content of naphtha-based jet fuel was taken from C.R. Martel and L.C. Angello (1977). Data on the density of naphtha-based jet fuel was taken from ASTM (1985). Standard heat contents for kerosene and naphtha-based jet fuels were adopted from EIA (2009a). Data on the C content of kerosene-based jet fuel is based on C.R. Martel and L.C. Angello (1977) and the density is derived from NIPER (1993).

Uncertainty

Variability in jet fuel is relatively small with the average C share of kerosene-based jet fuel varying by less than ±1 percent and the density varying by ±1 percent. This is because the ratio of fuel mass to useful energy must be tightly bounded to maximize safety and range. There is more uncertainty associated with the density and C share of naphtha-based jet fuel because sample data were unavailable and default values were used. This uncertainty has only a small impact on the overall uncertainty of the C content coefficient for jet fuels, however, because naphtha-based jet fuel represents a small and declining share of total jet fuel consumption in the United States and is treated as negligible when calculating carbon content factors for 1996 onwards.

Distillate Fuel

Distillate fuel is a general classification for diesel fuels and fuel oils. Products known as No. 1, No. 2, and No. 4 diesel fuel are used in on-highway diesel engines, such as those in trucks and automobiles, as well as off-highway engines, such as those in railroad locomotives and agricultural machinery. No. 1, No. 2, and No. 4 fuel oils are also used for space heating and electric power generation.

Methodology

For this inventory, separate C coefficients have been estimated for each of the three distillates, although the level of aggregation of U.S. energy statistics requires that a single coefficient is used to represent all three grades in inventory calculations. In past inventories, the emission coefficient was only determined for distillate No. 2. Distillate No. 2 remains the representative grade applied to the distillate class for calculation purposes. Coefficients developed for Nos. 1 and 4 distillate are provided for informational purposes. The C share each distillate is drawn from Perry's Chemical Engineers' Handbook, 8th Ed. (Green & Perry 2008). Each C share was combined with individual heat contents of 5.822, 5.809 and 6.135 MMBtu per barrel, respectively for distillates No. 1, No. 2 and No. 4, and densities of 35.3, 35.8 and 23.2 degrees API to calculate C coefficients for each distillate type.

Data Sources

Densities for distillate Nos. 1 and 2 were derived from Alliance of Automobile Manufacturers, Diesel Survey – Winter 2008 (AAM 2009). Densities are based on four, and 144 samples, respectively. The density of distillate fuel oil No. 4 is taken from Perry's Chemical Engineer's Handbook, 8th Ed. (Green & Perry, 2008), Table 24-6.

Heat contents are adopted from EPA (2009b). And carbon shares for each distillate are from Perry's Chemical Engineers' Handbook (Green & Perry 2008), Table 24-6.

Uncertainty

The primary source of uncertainty for the estimated C content of distillate fuel is the selection of No. 2 distillate as the typical distillate fuel oil or diesel fuel. No.2 fuel oil is generally consumed for home heating. No.1 distillate is generally less dense and if it is consumed in large portions for mobile sources, the application of the C content estimated for No. 2 for this report is likely to be too high when applied to both Nos. 1 and 2 distillates. The opposite is true of the application of a coefficient based upon the properties of No. 2 to the consumption of No. 4 distillate, which is of a significantly higher density and thus, has a higher C coefficient despite its lower C share. The overall effect on uncertainty from applying a single factor will depend on the relative annual consumption of each distillate.

The densities applied to the calculation of each carbon factor are an underlying a source of uncertainty. While the density of No. 1 distillate is based upon just four samples, the factor applied to all distillates in the inventory estimates (that for No. 2 oil) is based on a much larger sample size (144). Given the range of densities for these three distillate fuel classes (0.1342 to 0.1452 MT/bbl at 60°F), the uncertainty associated with the assumed density of distillate fuels is predominately a result of the use of No. 2 to represent all distillate consumption. There is also a small amount of uncertainty in the No. 2 distillate density itself. This is due to the possible variation across seasonal diesel formulations and fuel grades and between stationary and transport applications within the No. 2 distillate classification. The range of the density of the samples of No. 2 diesel (regular grade, 15ppm sulfur) is ±2.5 percent from the mean, while the range in density across the small sample set of No. 1 diesel is -2.1 to +1.6 percent of the mean. Samples from AAM (2009) of Premium No. 2 diesel (n=5) and higher sulfur (500 ppm S) regular diesel (n=2), which are also consumed in the U.S., each have nominally higher average densities (+1.3 percent and +0.6 percent, respectively) than do the low-sulfur regular diesel samples that underlie the density applied in this inventory.

The use of the 144 AAM samples to define the density of No. 2 distillate (and those four samples used to define that of No. 1 distillate) may introduce additional uncertainty because the samples were collected from just one season of on-road fuel production (Winter 2008). Despite the limited sample frame, the average No. 2 density calculated from the samples is applied to the calculation of a uniform C coefficient applicable for all years of the inventory and for all types of distillate consumption. The ASTM standards for each grade of diesel fuel oil do not include a required range in which the density must lie, and the density (as well as heat content and carbon share) may vary according to the additives in each seasonal blend and the sulfur content of each sub-grade.

However, previous studies also show relatively low variation in density across samples of No. 2 and across all distillates, supporting the application of a single No. 2 density to all U.S. distillate consumption. The average density calculated from samples analyzed by the EIA in 1994 (n=7) differs only very slightly from the value applied for the purposes of this inventory (-0.12 percent for No. 2 distillate). Further, the difference between the mean density applied to this inventory (No. 2 only) and that calculated from EIA samples of all distillates, regardless of grade, is also near zero (-0.06 percent, based on n=14, of distillates Nos. 1, 2 and 4 combined).

A C share of 87.30 percent is applied to No. 2 distillate, while No. 1 and No. 4 have C shares estimated at 86.40 and 86.47 percent, respectively. Again, the application of parameters specific to No. 2 to the consumption of all three distillates contributes to an increased level of uncertainty in the overall coefficient and emissions estimate and its broad application. For comparison, four No. 1 fuel oil samples obtained by EIA (1994) contained an average of 86.19 percent C, while seven samples No. 2 fuel oil from the same EIA analysis showed an average of 86.60 percent C. Additionally, three samples of No. 4 distillate indicate an average C share of 85.81 percent. The range of C share observed across the seven No. 2 samples is 86.1 to 87.5 percent, and across all samples (all three grades, n=14) the range is 85.3 to 87.5 percent C. There also exists an uncertainty of ±1 percent in the share of C in No. 2 based on the limited sample size.

Residual Fuel

Residual fuel is a general classification for the heavier oils, known as No. 5 and No. 6 fuel oils, that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. Residual fuel conforms to ASTM Specifications D 396 and D 975 and Federal Specification VV-F-815C. No. 5, a residual fuel oil of medium viscosity, is also known as Navy Special and is defined in Military Specification MIL-F-859E, including Amendment 2 (NATO Symbol F-770). It is used in steam-powered vessels in government service and inshore power plants. No. 6 fuel oil includes Bunker C fuel oil and is used for the production of electric power, space heating, vessel bunkering, and various industrial purposes.

In the United States, electric utilities purchase about one-third of the residual oil consumed. A somewhat larger share is used for vessel bunkering, and the balance is used in the commercial and industrial sectors. The residual oil (defined as No. 6 fuel oil) consumed by electric utilities has an energy content of 6.287 MMBtu per barrel (EIA 2008a) and an average sulfur content of 1 percent (EIA 2001). This implies a density of about 17 degrees API.

Methodology

Because U.S. energy consumption statistics are available only as an aggregate of Nos. 5 and 6 residual oil, a single coefficient must be used to represent the full residual fuel category. As in earlier editions of this report, residual fuel oil has been defined as No. 6 fuel oil, due to the majority of residual consumed in the United States being No. 6. However, for this report, a separate coefficient for fuel oil No. 5 has also been developed for informational purposes. Densities of 33.0 and 15.5 degrees API were adopted when developing the C content coefficients for Nos. 5 and 6, respectively (Wauquier, J.-P., ed. 1995; Green & Perry, ed. 2008).

The estimated C share of fuel oil No. 5 is 85.67 percent, based on an average of 12 ultimate analyses of samples of fuel oil (EIA 1994). An average share of C in No. 6 residual oil of 84.67 percent by mass was used, based on Perry's, 8th Ed. (Green & Perry 2008).

Data Sources

Data on the C share and density of residual fuel oil No. 6 were obtained from Green & Perry, ed. (2008).

Data on the C share of fuel oil No. 5 was adopted from EIA (1994), and the density of No. 5 was obtained from Wauquier, J.-P., ed. (1995).

Heat contents for both Nos. 5 and 6 fuel oil are adopted from EPA (2009b).

Uncertainty

Beyond the application of a C factor based upon No. 6 oil to all residual oil consumption, the largest source of uncertainty in estimating the C content of residual fuel centers on the estimates of density. Fuel oils are likely to differ depending on the application of the fuel (i.e., power generation or as a marine vessel fuel). Slight differences between the density of residual fuel used by utilities and that used in mobile applications are likely attributable to non-sulfur impurities, which reduce the energy content of the fuel, but do not greatly affect the density of the product. Impurities of several percent are commonly observed in residual oil. The extent of the presence of impurities has a greater effect on the uncertainty of C share estimation than it does on density. This is because these impurities do provide some Btu content to the fuel, but they are absent of carbon. Fuel oils with significant sulfur, nitrogen and heavy metals contents would have a different total carbon share than a fuel oil that is closer to pure hydrocarbon. This contributes to the uncertainty of the estimation of an average C share and C coefficient for these varied fuels.

The 12 samples of residual oil (EIA 1994) cover a density range from 4.3 percent below to 8.2 percent above the mean density. The observed range of C share in these samples is -2.5 to +1.8 percent of the mean. Overall, the uncertainty associated with the C content of residual fuel is probably ±1 percent.

Liquefied Petroleum Gases (LPG)

EIA identifies four categories of paraffinic hydrocarbons as LPG: ethane, propane, isobutane, and n-butane. Because each of these compounds is a pure paraffinic hydrocarbon, their C shares are easily derived by taking into account the atomic weight of C (12.01) and the atomic weight of hydrogen (1.01). Thus, for example, the C share of propane, C_3H_8, is 81.71 percent. The densities and heat contents of the compounds are also well known, allowing C content coefficients to be calculated directly. Table A-46 summarizes the physical characteristic of LPG.

Table A-46: Physical Characteristics of Liquefied Petroleum Gases

Compound	Chemical Formula	Density (Barrels Per Metric Ton)	Carbon Content (Percent)	Energy Content (MMBtu/Barrel)	Carbon Content Coefficient (Tg C/QBtu)
Ethane	C_2H_6	11.55	79.89	3.082	17.16
Propane	C_3H_8	12.76	81.71	3.836	16.76
Isobutane	C_4H_{10}	11.42	82.66	3.974	17.77
n-butane	C_4H_{10}	10.98	82.66	4.326	17.75

Source: Densities – CRC Handbook of Chemistry and Physics (2008/09); Carbon Contents – derived from the atomic weights of the elements; Energy Contents – EPA (2009b). All values are for the compound in liquid form. The density and energy content of ethane are for refrigerated ethane (-89 degrees C). Values for n-butane are for pressurized butane (-25 degrees C).

Methodology

Step 1. Assign carbon content coefficients to each pure paraffinic compound

Based on their known physical characteristics, a C content coefficient is assigned to each compound contained in the U.S. energy statistics category, Liquefied Petroleum Gases.

Step 2. Weight individual LPG coefficients for share of fuel use consumption

A C content coefficient for LPG used as fuel is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics.

Step 3. Weight individual LPG coefficients for share of non-fuel use consumption

The mix of LPG consumed for non-fuel use differs significantly from the mix of LPG that is combusted. While the majority of LPG consumed for fuel use is propane, ethane is the largest component of LPG used for non-fuel applications. A C content coefficient for LPG used for non-fuel applications is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics.

Step 4. Weight the carbon content coefficients for fuel use and non-fuel use by their respective shares of consumption

The changing shares of LPG fuel use and non-fuel use consumption appear below in Table A- 47.

Data Sources

Data on C share was derived via calculations based on atomic weights of each element of the four individual compounds Densities are from the CRC Handbook of Chemistry and Physics, 89th Ed.. The energy content of each LPG is

from the EPA (2009b). LPG consumption was based on data obtained from API (1990 through 2008) and EIA (2009b). Non-fuel use of LPG was obtained from API (1990 through 2008).

Uncertainty

Because LPG consists of pure paraffinic compounds whose density, heat content and C share are physical constants, there is limited uncertainty associated with the C content coefficient for this petroleum product. Any uncertainty is associated with the collection of data tabulating fuel- and non-fuel consumption in U.S. energy statistics. This uncertainty is likely less than ±3 percent.

Table A- 47: Consumption and Carbon Content Coefficients of Liquefied Petroleum Gases, 1990-2009

	1990		1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Energy Consumption (QBtu)																	
Fuel Use	**0.88**		**0.94**	**1.02**	**1.04**	**0.84**	**1.08**	**1.31**	**1.16**	**1.25**	**1.22**	**1.26**	**1.21**	**1.19**	**1.20**	**1.13**	**1.13**
Ethane	0.04		0.03	0.04	0.07	0.00	0.01	0.10	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.06	0.07
Propane	0.77		0.86	0.94	0.92	0.80	0.97	1.07	1.00	1.10	1.07	1.12	1.08	1.07	1.09	1.02	1.02
Butane	0.06		0.03	0.03	0.03	0.02	0.06	0.07	0.06	0.05	0.06	0.06	0.05	0.05	0.05	0.05	0.03
Isobutane	0.01		0.02	0.02	0.02	0.02	0.05	0.06	0.04	0.04	0.03	0.01	0.01	0.01	0.00	0.00	0.01
Non-Fuel Use	**1.35**		**1.78**	**1.87**	**1.88**	**1.96**	**2.06**	**1.90**	**1.77**	**1.85**	**1.75**	**1.80**	**1.70**	**1.74**	**1.78**	**1.67**	**1.80**
Ethane	0.71		0.89	0.97	0.93	0.96	1.08	1.04	0.96	1.00	0.92	0.97	0.91	0.98	1.03	0.95	1.12
Propane	0.51		0.67	0.64	0.71	0.77	0.77	0.65	0.59	0.64	0.63	0.66	0.63	0.63	0.64	0.60	0.60
Butane	0.11		0.15	0.15	0.13	0.12	0.12	0.11	0.13	0.12	0.13	0.13	0.12	0.12	0.11	0.12	0.08
Isobutane	0.02		0.08	0.10	0.11	0.12	0.09	0.09	0.09	0.08	0.07	0.03	0.03	0.02	0.01	0.00	0.01
Carbon Content (Tg C/QBtu)																	
Fuel Use	16.86		16.82	16.82	16.84	16.81	16.86	16.89	16.87	16.85	16.86	16.84	16.84	16.83	16.82	16.83	16.82
Non-Fuel Use	17.06		17.09	17.10	17.08	17.08	17.07	17.09	17.10	17.09	17.09	17.07	17.06	17.06	17.05	17.06	17.06

Sources: Fuel use of LPG based on data from EIA (2009b) and API (1990 through 2007). Non-fuel use of LPG from API (1990 through 2008). Volumes converted using the energy contents provided in Table A-46. C contents from EPA (2010).

Aviation Gasoline

Aviation gasoline is used in piston-powered airplane engines. It is a complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in aviation reciprocating engines. Fuel specifications are provided in ASTM Specification D910 and Military Specification MIL-G-5572. Aviation gas is a relatively minor contributor to greenhouse gas emissions compared to other petroleum products, representing approximately 0.1 percent of all consumption.

The ASTM standards for boiling and freezing points in aviation gasoline effectively limit the aromatics content to a maximum of 25 percent (ASTM D910). Because weight is critical in the operation of an airplane, aviation gas must have as many Btu per pound (implying a lower density) as possible, given other requirements of piston engines such as high anti-knock quality.

Methodology

A C content coefficient for aviation gasoline was calculated on the basis of the EIA standard heat content of 5.048 MMBtu per barrel. This implies a density of approximately 69 degrees API gravity or 5.884 pounds per gallon, based on the relationship between heat content and density of petroleum liquids, as described in *Thermal Properties of Petroleum Products* (DOC 1929). To estimate the share of C in the fuel, it was assumed that aviation gasoline is 87.5 percent iso-octane, 9.0 percent toluene, and 3.5 percent xylene. The maximum allowable sulfur content in aviation gasoline is 0.05 percent, and the maximum allowable lead content is 0.1 percent. These amounts were judged negligible and excluded for the purposes of this analysis. This yielded a C share of 85.00 percent and a C content coefficient of 18.86 Tg C/QBtu.

Data Sources

Data sources include ASTM (1985). A standard heat content for aviation gas was adopted from EIA (2009a).

Uncertainty

The relationship used to calculate density from heat content has an accuracy of five percent at 1 atm. The uncertainty associated with the C content coefficient for aviation gasoline is larger than that for other liquid petroleum products examined because no ultimate analyses of samples are available. Given the requirements for safe operation of

piston-powered aircraft the composition of aviation gas is well bounded and the uncertainty of the C content coefficient is likely to be ±5 percent.

Still Gas

Still gas, or refinery gas, is composed of light hydrocarbon gases that are released as petroleum is processed in a refinery. The composition of still gas is highly variable, depending primarily on the nature of the refining process and secondarily on the composition of the product being processed. Petroleum refineries produce still gas from many different processes. Still gas can be used as a fuel or feedstock within the refinery, sold as a petrochemical feedstock, or purified and sold as pipeline-quality natural gas. For the purposes of this inventory, the coefficient derived here is only applied to still gas that is consumed as a fuel. In general, still gas tends to include large amounts of free hydrogen and methane, as well as smaller amounts of heavier hydrocarbons. Because different refinery operations result in different gaseous byproducts, it is difficult to determine what represents typical still gas.

Methodology

The properties of still gas used to calculate the carbon content are taken from the literature. The carbon share of still gas was calculated from its net calorific value and carbon content from IPCC (2006). This calculation yields a carbon share of 77.7 percent. The density of still gas was estimated to be 0.1405 metric tons per barrel based on its heat content (from EIA 2008a) and the relationship between heat content and density that is described by the U.S. Department of Commerce, Bureau of Standards (DOC 1929).

Data Sources

The carbon share of still gas is calculated from data provided by IPCC (2006). Density is estimated at 0.1405 metric tons per barrel, approximately 28.3 degrees API, based on the heat content of 6.00 MMbtu/barrel of still gas from EIA (2009a).

Uncertainty

The EIA obtained data on four samples of still gas. Table A-48 below shows the composition of those samples.

Table A-48: Composition, Energy Content, and Carbon Content Coefficient for Four Samples of Still Gas

Sample	Hydrogen (%)	Methane (%)	Ethane (%)	Propane (%)	Btu Per Cubic Foot	Carbon Content (Tg C/QBtu)
One	12.7	28.1	17.1	11.9	1,388	17.51
Two	34.7	20.5	20.5	6.7	1,143	14.33
Three	72.0	12.8	10.3	3.8	672	10.23
Four	17.0	31.0	16.2	2.4	1,100	15.99

Sources: EIA (2008b).

Because the composition of still gas is highly heterogeneous, the C content coefficient for this product is highly uncertain. Gas streams with a large free hydrogen content are likely to be used as refinery or chemical feedstocks. Therefore, the sample cited above with the very high H content of 72 percent (and the lowest calculated C content) is less likely to be representative of the still gas streams to which the calculated coefficient is applied. The C content coefficient used for this report is probably at the high end of the plausible range given that it is higher than the greatest sample-based C content in Table A-48.

Asphalt

Asphalt is used to pave roads. Because most of its C is retained in those roads, it is a small source of carbon dioxide emissions. It is derived from a class of hydrocarbons called "asphaltenes," which are abundant in some crude oils but not in others. Asphaltenes have oxygen and nitrogen atoms bound into their molecular structure, so that they tend to have lower C contents than do other hydrocarbons.

Methodology

Ultimate analyses of twelve samples of asphalts showed an average C content of 83.47 percent. The EIA standard Btu content for asphalt of 6.636 MMBtu per barrel was assumed. The ASTM petroleum measurement tables show a density of 5.6 degrees API or 8.605 pounds per gallon for asphalt. Together, these variables generate C content coefficient of 20.55 Tg C/QBtu.

A standard heat content for asphalt was adopted from EIA (2009a). The density of asphalt was determined by the ASTM (1985). C share is adopted from analyses in EIA (2008b).

Uncertainty

The share of C in asphalt ranges from 79 to 88 percent by weight. Also present in the mixture are hydrogen and sulfur, with shares by weight ranging from seven to 13 percent for hydrogen, and from trace levels to eight percent for sulfur. Because C share and total heat content in asphalts do vary systematically, the overall C content coefficient is likely to be accurate to ±5 percent.

Lubricants

Lubricants are substances used to reduce friction between bearing surfaces, or incorporated into processing materials used in the manufacture of other products, or used as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Lubricants include all grades of lubricating oils, from spindle oil to cylinder oil to those used in greases. Lubricant consumption is dominated by motor oil for automobiles, but there is a large range of product compositions and end uses within this category.

Methodology

The ASTM Petroleum Measurement tables give the density of lubricants at 25.6 degrees API, or 0.1428 metric tons per barrel. Ultimate analysis of a single sample of motor oil yielded a C content of 85.80 percent. A standard heat content of 6.065 MMBtu per barrel was adopted from EIA. These factors produce a C content coefficient of 20.20 Tg C/QBtu.

Data Sources

A standard heat content was adopted from the EIA (2009a). The carbon content of lubricants is adopted from ultimate analysis of one sample of motor oil (EPA 2009a). The density of lubricating oils was determined by ASTM (1985).

Uncertainty

Uncertainty in the estimated C content coefficient for lubricants is driven by the large range of product compositions and end uses in this category combined with an inability to establish the shares of the various products captured under this category in U.S. energy statistics. Because lubricants may be produced from either the distillate or residual fractions during refineries, the possible C content coefficients range from 19.89 Tg C/QBtu to 21.48 Tg C/QBtu or an uncertainty band from –1.5 percent to + 1.4 percent of the estimated value.

Petrochemical Feedstocks

U.S. energy statistics distinguish between two different kinds of petrochemical feedstocks: those with a boiling temperature below 400 degrees Fahrenheit, generally called "naphtha," and those with a boiling temperature 401 degrees Fahrenheit and above, referred to as "other oils" for the purposes of this inventory.

Methodology

The C content of these petrochemical feedstocks are estimated independently according to the following steps.

Step 1. Estimate the carbon content coefficient for naphtha

Because reformed naphtha is used to make motor gasoline (hydrogen is released to raise aromatics content and octane rating), "straight-run" naphtha is assumed to be used as a petrochemical feedstock. Ultimate analyses of five samples of naphtha were examined and showed an average C share of 84.11 percent. A density of 62.4 degrees API gravity was taken from the Handbook of Petroleum Refining Processes, 3rd ed. The standard EIA heat content of 5.248 MMBtu per barrel is used to estimate a C content coefficient of 18.55 Tg C/QBtu.

Step 2. Estimate the carbon content coefficient for petrochemical feedstocks with a boiling temperature 400 degrees Fahrenheit and above ("other oils")

The boiling temperature of this product places it into the "middle distillate" fraction in the refining process, and EIA estimates that these petrochemical feedstocks have the same heat content as distillate fuel No. 2. Thus, the C content

coefficient of 20.17 Tg C/QBtu used for distillate fuel No. 2 is also adopted for this portion of the petrochemical feedstocks category.

<u>Data Sources</u>

Naphthas: Data on the C content was taken from Unzelman (1992). Density is from Meyers (2004). A standard heat content for naphthas was adopted from EIA (2009a). Other oils: See Distillate Fuel, Distillate No.2.

<u>Uncertainty</u>

Petrochemical feedstocks are not so much distinguished on the basis of chemical composition as on the identity of the purchaser, who are presumed to be a chemical company or a petrochemical unit co-located on the refinery grounds. Naphthas are defined, for the purposes of U.S. energy statistics, as those naphtha products destined for use as a petrochemical feedstock. Because naphthas are also commonly used to produce motor gasoline, there exists a considerable degree of uncertainty about the exact composition of petrochemical feedstocks.

Different naphthas are distinguished by their density and by the share of paraffins, isoparaffins, olefins, naphthenes and aromatics contained in the oil. Naphtha from the same crude oil fraction may have vastly different properties depending on the source of the crude. Two different samples of Egyptian crude, for example, produced two straight run naphthas having naphthene and paraffin contents (percent volume) that differ by 18.1 and 17.5 percent, respectively (Matar and Hatch, 2000).

Naphthas are typically used either as a petrochemical feedstock or a gasoline feedstock, with lighter paraffinic naphthas going to petrochemical production. Naphthas that are rich in aromatics and naphthenes tend to be reformed or blended into gasoline. Thus, the product category encompasses a range of possible fuel compositions, creating a range of possible C shares and densities. The uncertainty associated with the calculated C content of naphthas is primarily a function of the uncertainty that underlies the average carbon share calculation, which is based on a limited number of samples. Two additional samples cited by the EIA (1994) have a range of 83.80 to 84.42 percent C.

The uncertainty of the carbon content for other oils is based upon the assumption of distillate oil No. 2 as a product representative of the ill-defined classification of "other oils," and from the calculation of the C content of No. 2 itself (see "Distillate Fuels," above). While No. 2 distillate is used as a proxy for "other oils" for the purposes of this inventory's carbon coefficient, important differences exist between these two petroleum products, contributing some uncertainty to the cross-application. Other oils are defined herein as those "oils with a boiling range equal to or greater than 401°F that are generally intended for use as a petrochemical feedstock and are not defined elsewhere." For comparison, various material safety data sheets (MSDSs) published by producers of distillate No. 2 indicate a boiling range for this product of 320-700 degrees Fahrenheit. The relatively open definition of the classification "other oils" leaves room for potentially significant variation in the heating value, density and carbon share properties of each feedstock oil having a boiling point above 400 degrees Fahrenheit, creating a large band of uncertainty beyond that associated with the C factor for distillate No. 2.

Kerosene

A light petroleum distillate that is used in space heaters, cook stoves, and water heaters and is suitable for use as a light source when burned in wick-fed lamps, kerosene is drawn from the same petroleum fraction as jet fuel. Kerosene is generally comparable to No.1 distillate oil.

<u>Methodology</u>

The average density and C share of kerosene are assumed to be the same as those for distillate No. 1 since the physical characteristics of the products are very similar. Thus, a density of 35.3 degrees API and average C share of 86.40 percent were applied to a standard heat content for distillate No. 1 of 5.825 MMBtu per barrel to yield a C content coefficient of 19.96 Tg C/QBtu.

<u>Data Sources</u>

A standard heat content for distillate No.1 was adopted from EIA (2009a).

<u>Uncertainty</u>

Uncertainty in the estimated C content for kerosene is driven by the selection of distillate No. 1 as a proxy for kerosene. If kerosene is more like kerosene-based jet fuel, the true C content coefficient is likely to be some 1.3 percent lower. If kerosene is more aptly compared to No. 2 distillate oil, then the true C content coefficient is likely to be about

1.1 percent higher. While kerosene is a light petroleum distillate, like distillate No. 1, the two oil classes are do have some variation in their properties. For example, the boiling range of kerosene is 250-550 degrees Fahrenheit, whereas No. 1 oils typically boil over a range from 350-615 degrees Fahrenheit. The properties of individual kerosenes will vary with their use and particular crude origin, as well. Both kerosene and fuel oil No. 1 are primarily composed of hydrocarbons having 9 to 16 carbon atoms per molecule. However, kerosene is a straight-run No. 1 fuel oil, additional cracking processes and additives contribute to the range of possible fuels that make up the broader distillate No. 1 oil category.

Petroleum Coke

Petroleum coke is the solid residue by-product of the extensive processing of crude oil. It is a coal-like solid, usually has a C content greater than 90 percent, and is used as a boiler fuel and industrial raw material.

Methodology

Ultimate analyses of two samples of petroleum coke showed an average C share of 92.28 percent. The ASTM standard density of 9.543 pounds per gallon was adopted and the EIA standard energy content of 6.024 MMBtu per barrel assumed. Together, these factors produced an estimated C content coefficient of 27.85 Tg C/QBtu.

Data Sources

C content was derived from two samples from Martin, S.W. (1960). The density of petroleum coke was taken from the ASTM (1985). A standard heat content for petroleum coke was adopted from EIA (2009a).

Uncertainty

The uncertainty associated with the estimated C content coefficient of petroleum coke can be traced to two factors: the use of only two samples to establish C contents and a standard heat content which may be too low. Together, these uncertainties are likely to bias the C content coefficient upwards by as much as 6 percent.

Special Naphtha

Special naphtha is defined as a light petroleum product to be used for solvent applications, including commercial hexane and four classes of solvent: Stoddard solvent, used in dry cleaning; high flash point solvent, used as an industrial paint because of its slow evaporative characteristics; odorless solvent, most often used for residential paints; and high solvency mineral spirits, used for architectural finishes. These products differ in both density and C percentage, requiring the development of multiple coefficients.

Methodology

The method for estimating the C content coefficient of special naphtha includes three steps.

Step 1. Estimate the carbon content coefficient for hexane

Hexane is a pure paraffin containing 6 C atoms and 14 hydrogen atoms; thus, it is 83.63 percent C. Its density is 83.7 degrees API or 5.477 pounds per gallon and its derived C content coefficient is 21.40 Tg C/QBtu.

Step 2. Estimate the carbon contents of non-hexane special naphthas

The hydrocarbon compounds in special naphthas are assumed to be either paraffinic or aromatic (see discussion above). The portion of aromatics in odorless solvents is estimated at less than 1 percent, Stoddard and high flash point solvents contain 15 percent aromatics and high solvency mineral spirits contain 30 percent aromatics (Boldt and Hall 1977). These assumptions, when combined with the relevant densities, yield the C content factors contained in Table A-49, below.

Table A-49: Characteristics of Non-hexane Special Naphthas

Special Naphtha	Aromatic Content (Percent)	Density (Degrees API)	Carbon Share (Percent Mass)	Carbon Content (Tg C/QBtu)
Odorless Solvent	1	55.0	84.51	19.41
Stoddard Solvent	15	47.9	84.44	20.11
High Flash Point	15	47.6	84.70	20.17
Mineral Spirits	30	43.6	85.83	20.99

Sources: EIA (2008b) and Boldt and Hall (1977).

Step 3. Develop weighted carbon content coefficient based on consumption of each special naphtha

EIA reports only a single consumption figure for special naphtha. The C contents of the five special naphthas are weighted according to the following formula: approximately 10 percent of all special naphtha consumed is hexane; the remaining 90 percent is assumed to be distributed evenly among the four other solvents. The resulting emissions coefficient for special naphthas is 19.74 Tg C/QBtu.

Data Sources

A standard heat content for special naphtha was adopted from EIA (2009a). Density and aromatic contents were adopted from Boldt and Hall (1977).

Uncertainty

The principal uncertainty associated with the estimated C content coefficient for special naphtha is the allocation of overall consumption across individual solvents. The overall uncertainty is bounded on the low end by the C content of odorless solvent and on the upper end by the C content of hexane. This implies an uncertainty band of –1.7 percent to +8.4 percent.

Petroleum Waxes

The ASTM standards define petroleum wax as a product separated from petroleum that is solid or semi-solid at 77 degrees Fahrenheit (25 degrees Celsius). The two classes of petroleum wax are paraffin waxes and microcrystalline waxes. They differ in the number of C atoms and the type of hydrocarbon compounds. Microcrystalline waxes have longer C chains and more variation in their chemical bonds than paraffin waxes.

Methodology

The method for estimating the C content coefficient for petroleum waxes includes three steps.

Step 1. Estimate the carbon content of paraffin waxes

For the purposes of this analysis, paraffin waxes are assumed to be composed of 100 percent paraffinic compounds with a chain of 25 C atoms. The resulting C share for paraffinic wax is 85.23 percent and the density is estimated at 45 degrees API or 6.684 pounds per gallon.

Step 2. Estimate the carbon content of microcrystalline waxes

Microcrystalline waxes are assumed to consist of 50 percent paraffinic and 50 percent cycloparaffinic compounds with a chain of 40 C atoms, yielding a C share of 85.56 percent. The density of microcrystalline waxes is estimated at 36.7 degrees API, based on a sample of 10 microcrystalline waxes found in the *Petroleum Products Handbook*.

Step 3. Develop a carbon content coefficient for petroleum waxes by weighting the density and carbon content of paraffinic and microcrystalline waxes

A weighted average density and C content was calculated for petroleum waxes, assuming that wax consumption is 80 percent paraffin wax and 20 percent microcrystalline wax. The weighted average C content is 85.30 percent, and the weighted average density is 6.75 pounds per gallon. EIA's standard heat content for waxes is 5.537 MMBtu per barrel. These inputs yield a C content coefficient for petroleum waxes of 19.80 Tg C/QBtu.

Data Sources

Density of paraffin wax was taken from ASTM (1985). Density of microcrystalline waxes was derived from 10 samples found in Guthrie (1960). A standard heat content for petroleum waxes was adopted from EIA (2009a).

Uncertainty

Although there is considerable qualitative uncertainty associated with the allocation of petroleum waxes and microcrystalline waxes, the quantitative variation in the C contents for all waxes is limited to ± 1 percent because of the nearly uniform relationship between C and other elements in petroleum waxes broadly defined.

Crude Oil, Unfinished Oils, and Miscellaneous Products

U.S. energy statistics include several categories of petroleum products designed to ensure that reported refinery accounts "balance" and cover any "loopholes" in the taxonomy of petroleum products. These categories include crude oil,

unfinished oils, and miscellaneous products. Crude oil is rarely consumed directly, miscellaneous products account for less than one percent of oil consumption, and unfinished oils are a balancing item that may show negative consumption. For C accounting purposes, it was assumed that all these products have the same C content as crude oil.

<u>Methodology</u>

EIA reports on the average density and sulfur content of U.S. crude oil purchased by refineries. To develop a method of estimating C content based on this information, results of ultimate analyses of 182 crude oil samples were collected. Within the sample set, C content ranged from 82 to 88 percent C, but almost all samples fell between 84 percent and 86 percent C. The density and sulfur content of the crude oil data were regressed on the C content, producing the following equation:

$$\text{Percent C} = 76.99 + (10.19 \times \text{Specific Gravity}) + (-0.76 \times \text{Sulfur Content})$$

Absent the term representing sulfur content, the equation had an R-squared of only 0.35.[21] When C content was adjusted to exclude sulfur, the R-squared value rose to 0.65. While sulfur is the most important non-hydrocarbon impurity, nitrogen and oxygen can also be significant, but they do not seem to be correlated with either density or sulfur content. Restating these results, density accounts for about 35 percent of the variation in C content, impurities account for about 30 percent of the variation, and the remaining 35 percent is accounted for by other factors, including (presumably) the degree to which aromatics and polynuclear aromatics are present in the crude oil. Applying this equation to the 2008 crude oil quality data (30.21 degrees API and 1.47 percent sulfur) produces an estimated C content of 84.79 percent. Applying the density and C content to the EIA standard energy content for crude oil of 5.800 MMBtu per barrel produced an emissions coefficient of 20.31 Tg C/QBtu.

<u>Data Sources</u>

C content was derived from 182 crude oil samples, including 150 samples from U.S. National Research Council (1927). A standard heat content for crude oil was adopted from EIA (2009a).

<u>Uncertainty</u>

The uncertainty of the estimated C content for crude oil centers on the 35 percent of variation that cannot be explained by density and sulfur content. This variation is likely to alter the C content coefficient by ±3 percent. Since unfinished oils and miscellaneous products are impossible to define, the uncertainty of applying a crude oil C content is likely to be bounded by the range of petroleum products described in this chapter at ±10 percent.

Chronology and Explanation of Changes in Individual Carbon Content Coefficients of Fossil Fuels

Coal

<u>Original 1994 Analysis</u>

A set of 5,426 coal samples from the EIA coal analysis file were used to develop carbon content estimates. The results from that sample set appear below in Table A-50. The EIA Coal Analysis File was originally developed by the U.S. Bureau of Mines and contained over 60,000 coal samples obtained through numerous coal seams throughout the United States. Many of the samples were collected starting in the 1940s and 1950s through the 1980s and analyzed in U.S. government laboratories.

Table A-50: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank, 1990 – 2000 (Tg C/QBtu)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Consuming Sector											
Electric Power	25.68	25.69	25.69	26.71	25.72	25.74	25.74	25.76	25.76	25.76	25.76
Industrial Coking	25.51	25.51	25.51	25.51	25.52	25.53	25.55	25.56	25.56	25.56	25.56
Other Industrial	25.58	25.59	25.62	25.61	25.63	25.63	25.61	25.63	25.63	25.63	25.63
Residential/Commercial	25.92	26.00	26.13	25.97	25.95	26.00	25.92	26.00	26.00	26.00	26.00
Coal Rank											
Anthracite	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13

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[21] R-squared represents the percentage of variation in the dependent variable (in this case carbon content) explained by variation in the independent variables.

Bituminous	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37
Subbituminous	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24
Lignite	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62

Sources: Emission factors be consuming sector from B.D. Hong and E.R. Slatnick, "Carbon Dioxide Emission Factors for Coal, " U.S. Energy Information Administration, *Quarterly Coal Report*, January-March 1994. (Washington, DC, 1994) and Emission factors by rank from Science Applications International Corporation, "Analysis of the Relationship Between Heat and Carbon Content of U.S. Fuels: Final Task Report," Prepared for the U.S. Energy Information Administration, Office of Coal, Nuclear, Electric and Alternative Fuels (Washington, DC 1992).

<u>2002 Update</u>

The methodology employed for these estimates was unchanged from previous years; however, the underlying coal data sample set was updated. A new database, CoalQual 2.0 (1998), compiled by the U.S. Geological Survey was adopted for the updated analysis. The updated sample set included 6,588 coal samples collected by the USGS and its state affiliates between 1973 and 1989. The decision to switch to the sample data contained in the USGS CoalQual database from the EIA database was made because the samples contained in the USGS database were collected and analyzed more recently than those obtained by EIA from the Bureau of Mines. The new coefficients developed in the 2002 revision were in use through the 1990-2007 Inventory and are provided in Table A-51, below.

Table A-51: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank, 1990 – 2000 (Tg C/QBtu)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Consuming Sector											
Electric Power	25.68	25.69	25.69	25.71	25.72	25.74	25.74	25.76	25.76	25.76	25.76
Industrial Coking	25.51	25.51	25.51	25.51	25.52	25.53	25.55	25.56	25.56	25.56	25.56
Other Industrial	25.58	25.60	25.62	25.61	25.63	25.63	25.61	25.63	25.63	25.63	25.63
Residential/Commercial	25.92	26.00	26.13	25.97	25.95	26.00	25.92	26.00	26.00	26.00	26.00
Coal Rank											
Anthracite	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26
Bituminous	25.43	25.45	25.44	25.45	25.46	25.47	25.47	25.48	25.47	25.48	25.49
Sub-bituminous	26.50	26.49	26.49	26.48	26.49	26.49	26.49	26.49	26.49	26.49	26.48
Lignite	26.19	26.21	26.22	26.21	26.24	26.22	26.17	26.20	26.23	26.26	26.30

Sources: Data from USGS, U.S. Coal Quality Database Version 2.0 (1998) and analysis prepared by SAIC, 2007.

<u>2007 Update</u>

The analysis of the USGS Coal Qual data was updated in 2007 to make a technical correction that affected the value for lignite and those sectors which consume lignite Table A-52 contains the annual coefficients that resulted from the 2007 analysis.

Table A-52: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank, 1990-2007 [Tg C/QBtu)

	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Consuming Sector														
Electric Power	25.68	25.74	25.74	25.76	25.76	25.76	25.76	25.76	25.76	25.76	25.76	25.76	25.76	25.76
Industrial Coking	25.51	25.53	25.55	25.56	25.56	25.56	25.56	25.56	25.56	25.56	25.56	25.56	25.56	25.56
Other Industrial	25.58	25.63	25.61	25.63	25.63	25.63	25.63	25.63	25.63	25.63	25.63	25.63	25.63	25.63
Residential/Commercial	25.92	26.00	25.92	26.00	26.00	26.00	26.00	26.00	26.00	26.00	26.00	26.00	26.00	26.00
Coal Rank														
Anthracite	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26	28.26
Bituminous	25.43	25.47	25.47	25.48	25.47	25.48	25.49	25.49	25.49	25.49	25.49	25.49	25.49	25.49
Sub-bituminous	26.50	26.49	26.49	26.49	26.49	26.49	26.48	26.48	26.48	26.48	26.48	26.48	26.48	26.48
Lignite	26.19	26.22	26.17	26.20	26.23	26.26	26.30	26.30	26.30	26.30	26.30	26.30	26.30	26.57

Sources: Data from USGS, U.S. Coal Quality Database Version 2.0 (1998) and analysis prepared by (SAIC 2007).

2010 Update

The estimated annual C content coefficients for coal by rank and sector of consumption were updated again in 2010. Sample data from the Energy Institute at Pennsylvania State University (504 samples) were added to the 6,588 USGS samples to create a new database of 7,092 samples. The same analytical method used in the 2002 update was applied using these additional samples to calculate revised state-level carbon contents for each coal rank and then for national average consumption by end-use sector and by rank.

Natural Gas

A revised analytical methodology underlies the natural gas coefficients used in this report. Prior to the current Inventory, descriptive statistics were used to stratify 6,743 samples of pipeline quality natural gas by heat content and then to determine the average C content of natural gas at the national average heat content (EIA 1994). The same coefficient was applied to all pipeline natural gas consumption for all years, because U.S. energy statistics showed a range of national average heat contents of pipeline gas of only 1,025 to 1,031 Btu per cubic foot (1 percent) from 1990 through 1994. A separate factor was developed in the same manner for all flared gas. In the previous Inventory, a weighted national average C content was calculated using the average C contents for each sub-sample of gas that conformed with an individual state's typical cubic foot of natural gas since there is regional variation in energy content. The result was a weighted national average of 14.47 Tg C/QBtu.

The current Inventory is revised to make use of the same set of samples, but utilizes a regression equation, as described above, of sample-based heat content and carbon content data in order to calculate annually-variable national average C content coefficients based on annual national average heat contents for pipeline natural gas and for flare gas. In addition, the revised analysis calculates an average C content from all samples with less than 1.5 percent CO_2 and less than 1,050 Btu/cf (samples most closely approximating the makeup of pipeline quality natural gas). The result was identical to the previous weighted national average of 14.47 Tg C/QBtu. The average C contents from the 1994 calculations are presented in Table A-53 below for comparison.

Table A-53: Carbon Content of Pipeline-Quality Natural Gas by Energy Content (Tg C/QBtu)

Sample	Average Carbon Content
GRI Full Sample	14.51
Greater than 1,000 Btu	14.47
1,025 to 1,035 Btu	14.45
975 to 1,000 Btu	14.73
1,000 to 1,025 Btu	14.43
1,025 to 1,050 Btu	14.47
1,050 to 1,075 Btu	14.58
1,075 to 1,100 Btu	14.65
Greater than 1,100 Btu	14.92
Weighted National Average	14.47

Source: EIA (1994).

Petroleum Products

All of the petroleum product carbon coefficients except that for Aviation Gasoline Blending Components have been updated for the current Inventory. EPA is updating these factors to better align the fuel properties data that underlie the Inventory factors with those published in the Mandatory Reporting of Greenhouse Gases Rule (EPA 2009b), Suppliers of Petroleum Products (MM) and Stationary Combustion (C) subparts. The coefficients that were applied in the previous report are provided in Table A-49 below. Specifically, each of the coefficients used in this report have been calculated from updated density and C share data, largely adopted from analyses undertaken for the Rule (EPA 2009b). In some cases, the heat content applied to the conversion to a carbon-per-unit-energy basis has also been updated. Additionally, the category Misc. Products (Territories), which is based upon the coefficients calculated for crude oil, has been allowed to vary annually with the crude oil coefficient. The petrochemical feedstock category has been eliminated for this report because the constituent products – naphthas and other oils – are estimated independently. Further, although the level of aggregation of U.S. energy statistics currently limits the application of coefficients for residual and distillate fuels to these two generic classifications, individual coefficients for the five major types of fuel oil (Nos. 1, 2, 4, 5 and 6) have been estimated for the current report and are presented in Table A-43 above. Each of the C coefficients applied in the previous Inventory is provided below for comparison (Table A-54).

Table A-54: Carbon Content Coefficients and Underlying Data for Petroleum Products

Fuel	2007 Carbon Content (Tg C/QBtu)	Gross Heat of Combustion (MMBtu/Barrel)	Density (API Gravity)	Percent Carbon
Motor Gasoline	19.33	5.219	59.1	86.60
LPG(total)	16.99	a	a	a
LPG (energy use)	17.18	a	a	a
LPG (non-energy use)	16.76	a	a	a
Jet Fuel	19.33	5.670	42.0	86.30
Distillate Fuel	19.95	5.825	35.5	86.34
Residual Fuel	21.49	6.287	11.0	85.68
Asphalt and Road Oil	20.62	6.636	5.6	83.47
Lubricants	20.24	6.065	25.6	85.80
Petrochemical Feedstocks	19.37	5.248 [b]	67.1 [b]	84.11 [b]
Aviation Gas	18.87	5.048	69.0	85.00
Kerosene	19.72	5.670	41.4	86.01
Petroleum Coke	27.85	6.024	-	92.28
Special Naphtha	19.86	5.248	51.2	84.76
Petroleum Waxes	19.81	5.537	43.3	85.29
Still Gas	17.51	6.000	-	-
Crude Oil	20.33	5.800	30.5	85.49
Unfinished Oils	20.33	5.825	30.5	85.49
Miscellaneous Products	20.33	5.796	30.5	85.49
Pentanes Plus	18.24	4.620	81.7	83.70
Natural Gasoline	14.47	4.620	81.7	83.70

[a] LPG is a blend of multiple paraffinic hydrocarbons: ethane, propane, isobutane, and normal butane, each with their own heat content, density and C content, see Table A-46.
[b] Parameters presented are for naphthas with a boiling temperature less than 400 degrees Fahrenheit. Petrochemical feedstocks with higher boiling points are assumed to have the same characteristics as distillate fuel.
- No sample data available
Sources: EIA (1994), EIA (2008a), and SAIC (2007).

Additional revisions to the inventory's carbon coefficients since 1990 are detailed below.

Jet Fuel

1995 Update

Between 1994 and 1995, the C content coefficient for kerosene-based jet fuel was revised downward from 19.71 Tg C/QBtu to 19.33 Tg C/QBtu. This downward revision was the result of a shift in the sample set used from one collected between 1959 and 1972 and reported on by Martel and Angello in 1977 to one collected by Boeing in 1989 and published by Hadaller and Momenthy in 1990. The downward revision was a result of a decrease in density, as well as slightly lower C shares than in the earlier samples. However, the assumed heat content is unchanged because it is based on an EIA standard and probably yields a downward bias in the revised C content coefficient.

2008 Inventory Update

The coefficient was revised again for the 2008 inventory, returning to Martel and Angello and NIPER as the source of the carbon share and density data, respectively, for kerosene-based fuels. This change was made in order to align the coefficients used for this report with the values used in the Mandatory Reporting of Greenhouse Gases Rule (EPA 2009b). The return to the use of the Martel and Angello and NIPER coefficients was deemed more appropriate for the Rule as it was considered a more conservative coefficient given the uncertainty and variability in coefficients across the types of jet fuel in use in the U.S. The factor will be revisited in future inventories in light of data received from reporting entities in response to the Rule.

Liquefied Petroleum Gases (LPG)

The C content coefficient of LPG is updated annually to reflect changes in the consumption mix of the underlying compounds: ethane; propane; isobutane; and normal butane. In 1994, EIA included pentanes plus— assumed to have the characteristics of hexane—in the mix of compounds broadly described as LPG. In 1995, EIA removed

pentanes plus from this fuel category. Because pentanes plus is relatively rich in C per unit of energy, its removal from the consumption mix lowered the C content coefficient for LPG from 17.26 Tg C/QBtu to 16.99 Tg C/QBtu. In 1998, EIA began separating LPG consumption into two categories: energy use and non-fuel use and providing individual coefficients for each. Because LPG for fuel use typically contains higher proportions of propane than LPG for non-fuel use, the C content coefficient for fuel use was 1.8 to 2.5 percent higher than the coefficient for non-fuel use in previous Inventories (see Table A-49).

However, for the current update of the LPG coefficients, the assumptions that underlie the selection of density and heat content data for each pure LPG compound have been updated, leading to a significant revision of the assumed properties of ethane. For this report, the physical characteristics of ethane, which constitutes over 90 percent of LPG consumption for non-fuel uses, have been updated to reflect ethane that is in (refrigerated) liquid form. Previously, the share of ethane was included using the density and energy content of gaseous ethane. Table A-55, below, compares the values applied for each of the compounds under the two sets of coefficient calculations. The carbon share of each pure compound was also updated by using more precise values for each compound's molecular weight.

Due in large part to the revised assumptions for ethane, the weighted C content for non-fuel use is now higher than that of the weighted coefficient for fuel use, which is dominated by the consumption of more dense propane. Under the revised assumptions, each annual weighted coefficient for non-fuel LPG consumption is 1.2 to 1.7 percent higher each year than is that for LPGs consumed for fuel (energy) uses.

Table A-55: Physical Characteristics of Liquefied Petroleum Gases

Compound	Chemical Formula	1990-2007 Density (bbl / MT)	Updated Density (bbl / MT)	1990-2007 Energy Content (MMBtu/bbl)	Updated Energy Content (MMBtu/bbl)	1990-2007 C Content Coefficient (Tg C/QBtu)	Updated C Content Coefficient (Tg C/QBtu)
Ethane	C_2H_6	16.88	11.55	2.916	3.082	16.25	17.16
Propane	C_3H_8	12.44	12.76	3.824	3.836	17.20	16.76
Isobutane	C_4H_{10}	11.20	11.42	4.162	3.974	17.75	17.77
n-butane	C_4H_{10}	10.79	10.98	4.328	4.326	17.72	17.75

Sources: Updated: Densities – CRC Handbook of Chemistry and Physics, 89th Ed. (2008/09); Energy Contents – EPA (2009b). All values are for the compound in liquid form. The density and energy content of ethane are for refrigerated ethane (-89 degrees C). Values for n-butane are for pressurized butane (-25 degrees C). Values in previous editions of this inventory: Gurthrie (1960).

Motor Gasoline

The C content coefficient for motor gasoline varies annually based on the density of and proportion of additives in a representative sample of motor gasoline examined each year. However, in 1997 EIA began incorporating the effects of the introduction of reformulated gasoline into its estimate of C content coefficients for motor gasoline. This change resulted in a downward step function in C content coefficients for gasoline of approximately 0.3 percent beginning in 1995. In 2005-2006 reformulated fuels containing ethers began to be phased out nationally. Ethanol was added to gasoline blends as a replacement oxygenate, leading to another shift in gasoline density (see Table A- 44), in the list and proportion of constituents that form the blend and in the blended C share based on those constituents.

Table A-56: Carbon Content Coefficients for Petroleum Products, 1990-2007 [Tg C/QBtu]

Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Petroleum														
Asphalt and Road Oil	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62
Aviation Gasoline	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
Distillate Fuel Oil	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95
Jet Fuel[a]	19.40	19.34	19.33	19.33	19.33	19.33	19.33	19.33	19.33	19.33	19.33	19.33	19.33	19.33
Kerosene	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72
LPG (energy use)[a]	17.21	17.20	17.20	17.18	17.23	17.25	17.20	17.21	17.20	17.21	17.20	17.19	17.19	17.18
LPG (non-energy use)[a]	16.83	16.87	16.86	16.88	16.88	16.84	16.81	16.83	16.82	16.84	16.81	16.81	16.78	16.76
Lubricants	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24
Motor Gasoline[a]	19.41	19.38	19.36	19.35	19.33	19.33	19.34	19.34	19.35	19.33	19.33	19.33	19.33	19.33
Residual Fuel	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49
Other Petroleum														
Av Gas Blend Comp.	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
Mo Gas Blend Comp[a]	19.41	19.38	19.36	19.35	19.33	19.33	19.34	19.34	19.35	19.33	19.33	19.33	19.33	19.33
Crude Oil[a]	20.16	20.23	20.25	20.24	20.24	20.19	20.23	20.29	20.30	20.28	20.33	20.33	20.33	20.33
Misc. Products[a]	20.16	20.23	20.25	20.24	20.24	20.19	20.23	20.29	20.30	20.28	20.33	20.33	20.33	20.33
Misc. Products (Terr.)	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Naphtha (<401 deg. F)	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14
Other oil (>401 deg. F)	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95
Pentanes Plus	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24
Petrochemical Feed.	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37
Petroleum Coke	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85
Still Gas	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51
Special Naphtha	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86
Unfinished Oils[a]	20.16	20.23	20.25	20.24	20.24	20.19	20.23	20.29	20.30	20.28	20.33	20.33	20.33	20.33
Waxes	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81
Other Wax and Misc.	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81

[a] C contents vary annually based on changes in fuel composition.

[b] C content for utility coal used in the electric power calculations. All coefficients based on higher heating value. Higher heating value (gross heating value) is the total amount of heat released when a fuel is burned. Coal, crude oil, and natural gas all include chemical compounds of carbon and hydrogen. When those fuels are burned, the carbon and hydrogen combine with oxygen in the air to produce CO_2 and water. Some of the energy released in burning goes into transforming the water into steam and is usually lost. The amount of heat spent in transforming the water into steam is counted as part of gross heat content. Lower heating value (net heating value), in contrast, does not include the heat spent in transforming the water into steam. Using a simplified methodology based on International Energy Agency defaults, higher heating value can be converted to lower heating value for coal and petroleum products by multiplying by 0.95 and for natural gas by multiplying by 0.90. Carbon content coefficients are presented in higher heating value because U.S. energy statistics are reported by higher heating value.

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2.3. Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels

Carbon (C) 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 C content) by a fuel-specific storage factor, as listed in Table A-57. The remaining C—i.e., that which is not stored—is emitted. This sub-annex explains the methods and data sources employed in developing the storage factors for petrochemical feedstocks (industrial other coal, natural gas for non-fertilizer uses, LPG, pentanes plus, naphthas, other oils, still gas, special naphtha), asphalt and road oil, lubricants, waxes, and miscellaneous products. The storage factors[22] for the remaining non-energy fuel uses are either based on values recommended for use by IPCC (2006), or when these were not available, assumptions based on the potential fate of C in the respective NEU products.

Table A-57: Fuel Types and Percent of C Stored for Non-Energy Uses

Sector/Fuel Type	Storage Factor (%)
Industry	-
Industrial Coking Coal[a]	10
Industrial Other Coal [b]	58
Natural Gas to Chemical Plants [b]	58
Asphalt & Road Oil	100
LPG [b]	58
Lubricants	9
Pentanes Plus [b]	58
Naphtha (<401 deg. F) [b]	58
Other Oil (>401 deg. F) [b]	58
Still Gas [b]	58
Petroleum Coke[c]	30
Special Naphtha [b]	58
Distillate Fuel Oil	50
Waxes	58
Miscellaneous Products	0
Transportation	-
Lubricants	9
U.S. Territories	-
Lubricants	9
Other Petroleum (Misc. Prod.)	10

- 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] The storage factor listed is the value for 2009. As described in this annex, the factor varies over time.
[c] Assumes petroleum coke consumption is for pigments. Consumption of petroleum coke for production of primary aluminum anodes, electric arc furnace anodes, titanium dioxide, ammonia, urea, and ferroalloys is covered in the Industrial Processes chapter.

The following sections describe the 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 are used in organic chemical synthesis and in other manufacturing processes, and are referred to collectively as "petrochemical feedstocks." 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, lubricants, waxes, and miscellaneous products follow.

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[22] Throughout this section, references to "storage factors" represent the proportion of carbon stored.

Petrochemical Feedstocks

Petrochemical feedstocks—industrial other coal, natural gas for non-fertilizer uses, LPG, pentanes plus, naphthas, other oils, still gas, special naphtha—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 fuel types. Chemically speaking, these fuels are diverse, ranging from simple natural gas (i.e., predominantly CH_4) to heavier, more complex naphthas and other oils.[23]

After adjustments for (1) use in industrial processes and (2) net exports, these eight fuel categories constituted approximately 189.1 Tg CO_2 Eq., or 62% percent, of the 306.1 Tg CO_2 Eq. of non-energy fuel consumption in 2009. For 2009 the storage factor for the eight fuel categories was 58 percent. In other words, of the net consumption, 58 percent was destined for long-term storage in products—including products subsequently combusted for waste disposal—while the remaining 42 percent 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. The derivation of the storage factor is described in the following sections.

Methodology and Data Sources

The petrochemical feedstocks storage factor is equal to the ratio of C stored in the final products to total C content for the non-energy fossil fuel feedstocks used in industrial processes, after adjusting for net exports of feedstocks. One aggregate storage factor was calculated to represent all eight 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) for the major categories of petrochemical feedstocks. EIA's *Petroleum Supply Annual* publication tracks imports and exports of petrochemical feedstocks, 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), which are derived from the primary chemicals produced by the refineries. These products represent very large flows of C derived from fossil fuels (i.e., fossil C), so estimates of net flows not already considered in EIA's dataset were developed for the entire time series from 1990 to 2009.

The approach to estimate imports and exports involves three steps, listed here and then described in more detail below:

Step 1. Identify commodities derived from petrochemical feedstocks, and calculate net import/export for each.

Step 2. Estimate the C content for each commodity.

Step 3. Sum the net C imports/exports across all commodities.

Step 1 relies heavily on information provided by the National Petrochemical and Refiners Association (NPRA) and U.S. Bureau of the Census (BoC) trade statistics published by the U.S. International Trade Commission (USITC). NPRA provided a spreadsheet of the ten-digit BoC Harmonized Tariff Schedule (HTS) Commodity Codes used to compile import-export data for periodic reports issued to NPRA's membership on trade issues. Additional feedstock commodities were identified by HTS code in the BoC data system and included in the net import/export analysis.

One of the difficulties in analyzing trade data is that a large portion of the outputs from the refining industry are fuels and fuel components, and it was difficult to segregate these from the outputs used for non-energy uses. The NPRA-supplied codes identify fuels and fuel components, thus providing a sound basis for isolating net imports/exports of petrochemical feedstocks. Although MTBE and related ether imports are included in the published NPRA data, these commodities are not included in the total net imports/exports calculated here, because it is assumed that they are fuel additives and do not contribute to domestic petrochemical feedstocks. Net exports of MTBE and related ethers are also not included in the totals, as these commodities are considered to be refinery products that are already accounted for in the

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[23] 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.

EIA data. Imports and exports of commodities for which production and consumption data are provided by EIA (e.g., butane, ethylene, and liquefied petroleum gases) are also not included in the totals, to avoid double-counting.

Another difficulty is that one must be careful to assure that there is not double-counting of imports and exports in the data set. Other parts of the mass balance (described later) provide information on C flows, in some cases based on production data and in other cases based on consumption data. Production data relates only to production within the country; consumption data incorporates information on imports and exports as well as production. Because many commodities are emissive in their use, but not necessarily their production, consumption data is appropriately used in calculations for emissive fates. For purposes of developing an overall mass balance on U.S. non-energy uses of C, for those materials that are non-emissive (e.g., plastics), production data is most applicable. And for purposes of adjusting the mass balance to incorporate C flows associated with imports and exports, it was necessary to carefully review whether or not the mass balance already incorporated cross-boundary flows (through the use of consumption data), and to adjust the import/export balance accordingly.

The BoC trade statistics are publicly available[24] and cover a complete time series from 1990 to 2009. These statistics include information on imports and exports of thousands of commodities. After collecting information on annual flows of the more than 100 commodities identified by NPRA, Step 2 involves calculating the C content for each commodity from its chemical formula. In cases where the imports and exports were expressed in units of volume, rather than mass, they were converted to mass based on the commodities' densities.

Step 3 involves summing the net C imports/exports across all commodities. The results of this step are shown in Table A-58. As shown in the table, the United States has been a net exporter of chemical intermediates and products throughout the 1990 to 2009 period.

Table A-58: Net Exports of Petrochemical Feedstocks, 1990 – 2009 (Tg CO_2 Eq.)

	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Net Exports	12.0	11.1	8.3	1.8	7.3	14.8	20.2	6.5	4.1	8.4	4.5	9.0

After adjusting for imports and exports, the C budget is adjusted for the quantity of C that is used in the Industrial Processes sector of the Inventory. Fossil fuels used for non-energy purposes in industrial processes—and for which C emissions and storage have been characterized through mass balance calculations and/or emission factors that directly link the non-energy use fossil fuel raw material and the industrial process product—are not included in the non-energy use sector. These industrial processes (and their non-energy use fossil fuel raw materials) include iron and steel (coal coke), primary aluminum (petroleum coke), titanium oxide (petroleum coke), ferroalloys (petroleum coke), and ammonia and urea (petroleum coke and natural gas).

For each year of the Inventory, the total C content of non-energy uses was calculated by starting with the EIA estimate of non-energy use, and reducing it by the adjustment factor for net exports (see Table A-58) to yield net domestic fuel consumption for non-energy. The balance was apportioned to either stored C or emissive C, based on a storage factor.

The overall storage factor for the feedstocks was determined by developing a mass balance on the C in feedstocks, and characterizing products, uses, and environmental releases as resulting in either storage or emissions. The total C in the system was estimated by multiplying net domestic consumption for non-energy by the C content of each of the feedstocks (i.e., industrial other coal, natural gas for non-fertilizer uses, LPG, pentanes plus, naphthas, other oils, still gas, special naphtha). C content values for the fuel feedstocks are discussed in the Estimating Emissions from Fossil Fuel Combustion and Estimating the Carbon Content from Fossil Fuel Combustion Annexes.

Next, C pools and releases in a variety of industrial releases, energy recovery processes, and products were characterized. The C fate categories are plastics, energy recovery, synthetic rubber, synthetic fibers, organic solvents, C black, detergents and personal cleansers, industrial non-methane volatile organic compound (NMVOC) emissions, hazardous waste incineration, industrial toxic chemical (i.e., TRI) releases, pesticides, food additives, antifreeze and deicers (glycols), and silicones.[25]

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[24] See the U.S International Trade Commission (USITC) Trade Dataweb at <http://dataweb.usitc.gov/>.

[25] 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.

The C in each product or waste produced was categorized as either stored or emitted. The aggregate storage factor is the C-weighted average of storage across fuel types. As discussed later in the section on uncertainty, the sum of stored C and emitted C (i.e., the outputs of the system) exceeded total C consumption (i.e., the inputs to the system) for some years in the time series.[26] To address this mass imbalance, the storage factor was calculated as C storage divided by total C outputs (rather than C storage divided by C inputs).

Note that the system boundaries for the storage factor do not encompass the entire life-cycle of fossil-based C consumed in the United States insofar as emissions of CO_2 from waste combustion are accounted for separately in the Inventory and are discussed in the Incineration of Waste section of the Energy chapter.

The following sections provide details on the calculation steps, assumptions, and data sources employed in estimating and classifying the C in each product and waste shown in Table A-59. Summing the C stored and dividing it by total C outputs yields the overall storage factor, as shown in the following equation for 2009:

$$\text{Overall Storage Factor} = \text{C Stored} / (\text{C Stored} + \text{C Emitted}) =$$

$$129.3 \text{ Tg CO}_2 \text{ Eq.} / (129.3 + 93.4) \text{ Tg CO}_2 \text{ Eq.} = 58\%$$

Table A-59: C Stored and Emitted by Products from Feedstocks in 2009 (Tg CO₂ Eq.)

Product/Waste Type	C Stored (Tg CO$_2$ Eq.)	C Emitted (Tg CO$_2$ Eq.)
Industrial Releases	**0.1**	**4.4**
TRI Releases	0.1	1.0
Industrial VOCs		2.3
Non-combustion CO		0.7
Hazardous Waste Incin.		0.4
Energy Recovery		**74.8**
Products	**129.2**	**14.2**
Plastics	111.1	
Synthetic Rubber	10.7	
Antifreeze and deicers		0.9
Abraded tire rubber		0.3
Food additives		0.8
Silicones	0.5	
Synthetic Fiber	6.7	
Pesticides	0.3	0.2
Soaps, shampoos, detergents		6.7
Solvent VOCs		5.3
Total	**129.3**	**93.4**

- Not applicable
Note: Totals may not sum due to independent rounding.

The three categories of C accounted for in the table are industrial releases, energy recovery, and products. Each is discussed below.

Industrial Releases

Industrial releases include toxic chemicals reported through the Toxics Release Inventory, industrial emissions of volatile organic compounds (VOCs), CO emissions (other than those related to fuel combustion), and emissions from hazardous waste incineration.

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[26] Overall, there was fairly close agreement between inputs and outputs: for the entire 1990 through 2009 time series, inputs exceeded outputs by a time-weighted average of 0.2 percent. During the period 1990 through 2000, carbon inputs exceeded carbon outputs (i.e., the sum of carbon stored and carbon emitted) by a time-weighted average of 10 percent. For those years, the assumption was made that the "missing" carbon was lost through fates leading to emissions. This discrepancy shifted during the period from 2001 through 2009, in which carbon outputs exceeded carbon inputs by a time-weighted average of 12 percent.

TRI Releases

Fossil-derived C is found in many toxic substances released by industrial facilities. The Toxics Release Inventory (TRI), maintained by 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 C 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 C stored and emitted in the form of toxic releases can be estimated.

The TRI specifies releases by chemical, so C contents were assigned to each chemical based on molecular formula. 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."[27] The C released in each disposal location is provided in Table A-60.

Each on-site classification was assigned a storage factor. A 100 percent storage factor was applied to disposition of C 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 C-weighted average storage factor for the on-site C 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 C content value, based upon the top 35 chemicals' C 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.

Data on TRI releases for the full 1990 through 2009 time series were not readily available. Since this category is small (less than 1 Tg C emitted and stored), the 1998 value was applied for the entire time series.

Table A-60: 1998 TRI Releases by Disposal Location (Gg CO₂ Eq.)

Disposal Location	Carbon Stored (Gg CO$_2$ Eq.)	Carbon Emitted (Gg CO$_2$ Eq.)
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.

Volatile Organic Compound Emissions from Industrial Processes and Solvent Evaporation Emissions

Data on annual non-methane volatile organic compound (NMVOC) emissions were obtained from preliminary data (EPA 2010, EPA 2009b), and disaggregated based on EPA (2003b), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. The 1990-2009 Trends data include information on NMVOC emissions by end-use category; some of these fall into the heading of "industrial releases" in Table A-60 above, and others are related to "product use"; for ease of discussion, both are covered here. The end-use categories that represent "Industrial NMVOC Emissions" include some chemical and allied products, certain petroleum related industries, and other industrial processes. NMVOC emissions from solvent utilization (product use) were considered to be a result of non-energy use of petrochemical feedstocks. These categories were used to distinguish non-energy uses from energy uses; 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 C content of the NMVOCs for each category of emissions. The assumptions for calculating the C fraction of industrial and solvent utilization emissions were made separately and differ significantly. For industrial NMVOC emissions, a C content of 85 percent was assumed. This value was chosen to reflect

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[27] 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 C 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 (C contents ranging from 80 to 85 percent based upon C number), alkenes (C contents approximately 85 percent), and some aromatics (C contents approximately 90 percent, depending upon substitution).

An EPA solvent evaporation emissions dataset (Tooly 2001) was used to estimate the C content of solvent emissions. The dataset identifies 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 C of each compound identified in the dataset was calculated based on the molecular formula of the individual compound (e.g., the C content of methylene chloride is 14 percent; the C content of toluene is 91 percent). For solvent emissions that are identified in the EPA dataset only by chemical category (e.g., butanediol derivatives) a single individual compound was selected to represent each category, and the C content of the category was estimated based on the C content of the representative compound. The overall C content of the solvent evaporation emissions for 1998, estimated to be 56 percent, is assumed to be constant across the entire time series.

The results of the industrial and solvent NMVOC emissions analysis are provided in Table A-61 for 1990 through 2009. Solvent evaporation emissions in 2009 were 5.3 Tg CO_2 Eq., and industrial NMVOC emissions in 2009 were 2.3 Tg CO_2 Eq.

Table A-61: Industrial and Solvent NMVOC Emissions

	1990	1995	2000	2005	2006	2007	2008	2009
Industrial NMVOCs[a]								
NMVOCs ('000 Short Tons)	1,279	1,358	803	824	806	788	769	829
Carbon Content (%)	85%	85%	85%	85%	85%	85%	85%	85%
Carbon Emitted (Tg CO_2 Eq.)	3.6	3.8	2.3	2.3	2.3	2.2	2.2	2.3
Solvent Evaporation[b]								
Solvents ('000 Short Tons)	5,750	6,183	4,832	4,245	4,239	4,232	4,226	2,847
Carbon Content (%)	56%	56%	56%	56%	56%	56%	56%	56%
Carbon Emitted (Tg CO_2 Eq.)	10.8	11.6	9.0	7.9	7.9	7.9	7.9	5.3

[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.

Non-Combustion Carbon Monoxide Emissions

Carbon monoxide (CO) emissions data were also obtained from the NEI preliminary data (EPA 2010, EPA 2009b), and disaggregated based on EPA (2003b).. There are three categories of CO emissions in the report that are classified as process-related emissions not related to fuel combustion. These include chemical and allied products manufacturing, metals processing, 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. These include total C emissions from the primary aluminum, titanium dioxide, iron and steel, and ferroalloys production processes. The total C (CO and CO_2) emissions from oil and gas production, petroleum refining, and asphalt manufacturing are also accounted for elsewhere in this Inventory. Biogenic emissions (e.g., pulp and paper process emissions) are accounted for in the Land Use, Land-Use Change and Forestry chapter and 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 thus included in the calculation of the petrochemical feedstocks storage factor. Table A-62 lists the CO emissions that remain after taking into account the exclusions listed above.

Table A-62: Non-Combustion Carbon Monoxide Emissions[a]

	1990	1995	2000	2005	2006	2007	2008	2009
Thousand short tons CO	489	481	623	461	469	477	484	461
Carbon Emitted (Tg CO2 Eq.)	0.7	0.7	0.9	0.7	0.7	0.7	0.7	0.7

Includes emissions from chemical and allied products, petroleum and related industries, metals processing, and other industrial processes categories.

Hazardous Waste Incineration

Hazardous wastes are defined by the EPA under the Resource Conservation and Recovery Act (RCRA).[28] 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 United States is burned in BIFs; because these processes are included in the energy recovery calculations described below, they are not included as part of hazardous waste incineration.

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. EPA stores this information in its Biennial Reporting System (BRS) database (EPA 2000a, 2007a). 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 C 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 C content factors (discussed in the Estimating the Carbon Content from Fossil Fuel Combustion Annex) yields tons of C emitted. Implied C content is calculated by dividing the tons of C emitted by the associated tons of waste incinerated.

Waste quantity data for hazardous wastes were obtained from EPA's BRS database for reporting years 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, and 2007 (EPA 2000a, 2007a). Values for 2008 and 2009 were held constant at the 2007 level. 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 A-63). Regulations require incinerators to achieve at least 99.99 percent destruction of organics; this formed the basis for assuming the fraction of C oxidized. Emissions from hazardous waste incineration in 2007 were 0.4 Tg CO_2 Eq. Table A-64 lists the CO_2 emissions from hazardous waste incineration.

Table A-63: 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

Table A-64: CO_2 Emitted from Hazardous Waste Incineration (Tg CO_2 Eq.)

	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
CO_2 Emissions	1.1	1.7	1.0	0.6	0.6	0.6	0.6	0.6	0.5	0.4	0.4	0.4

Energy Recovery

The amount of feedstocks combusted for energy recovery was estimated from data included in EIA's Manufacturers Energy Consumption Survey (MECS) for 1991, 1994, 1998, 2002, and 2006 (EIA 1994, 1997, 2001, 2005, 2010a). Some fraction of the fossil C exiting refineries and designated for use for feedstock purposes actually ends up being combusted for energy recovery (despite the designation of feedstocks as a "non-energy" use) because the chemical reactions in which fuel feedstocks are used are not 100 percent efficient. These chemical reactions may generate

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[28] [42 U.S.C. §6924, SDWA §3004]

unreacted raw material feedstocks or generate byproducts that have a high energy content. The chemical industry and many downstream industries are energy-intensive and often have boilers or other energy recovery units on-site, and thus these unreacted feedstocks or byproducts are often combusted for energy recovery. Also, as noted above in the section on hazardous waste incineration, regulations provide a strong incentive—and in some cases require—burning of organic wastes generated from chemical production processes.

Information available from the MECS 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; scrap tires; 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 in the refinery sector is also included separately in the fuel use data from EIA. The combustion of scrap tires in cement kilns, lime kilns, and electric arc furnaces is accounted for in the Waste Incineration chapter; data from the Rubber Manufacturers Association (RMA 2009a) were used to difference out energy recovery from scrap tires in these industries. Consumption of net steam, assumed to be generated from fossil fuel combustion, 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 analysis. The remaining categories of fuels, including waste gas; waste oils, tars, and related materials; and other uncharacterized fuels are assumed to be petrochemical feedstocks burned for energy recovery (see Table A-65). The conversion factors listed in the Estimating Emissions from Fossil Fuel Combustion Annex were used to convert the Btu values for each fuel feedstock to Tg CO_2. Petrochemical feedstocks combusted for energy recovery corresponded to 42.5 Tg CO_2 Eq. in 1991, 35.1 Tg CO_2 Eq. in 1994, 58.0 Tg CO_2 Eq. in 1998, 70.6 Tg CO_2 in 2002, and 74.8 in 2006. Values for petrochemical feedstocks burned for energy recovery for years between 1991 and 1994, between 1994 and 1998, between 1998 and 2002, and between 2002 and 2006 have been estimated by linear interpolation. The value for 1990 is assumed to be the same as the value for 1991, and values for years subsequent to 2006 are assumed to be the same as the value for 2006 (Table A-66).

Table A-65: Summary of 2006 MECS Data for Other Fuels Used in Manufacturing/Energy Recovery (Trillion Btu)

Subsector and Industry	NAICS CODE	Waste Gas[a]	Waste Oils/Tars[b]	Refinery Still Gas[c]	Net Steam[d]	Other Fuels[e]
Printing and Related Support	323	0	0	0	0	0
Petroleum and Coal Products	324	0	7	1,482	110	90
Chemicals	325	459	15	0	168	435
Plastics and Rubber Products	326	0	0	0	0	0
Nonmetallic Mineral Products	327	1	20	0	1	14
Primary Metals	331	1	0	0	17	20
Fabricated Metal Products	332	0	0	0	0	0
Machinery	333	0	0	0	1	1
Computer and Electronic Products	334	0	0	0	0	1
Electrical Equip., Appliances, Components	335	0	0	0	0	0
Transportation Equipment	336	5	0	0	0	11
Furniture and Related Products	337	0	0	0	0	0
Miscellaneous	339	0	0	0	0	0
Total (Trillion Btu)		466	42	1482	297	572
Average C Content (Tg/QBtu)		18.14	20.62	17.51	0	19.37
Fraction Oxidized		1	1	1	0	1
Total C (Tg)		8.45	0.87	25.95	0.00	11.08
Total C (Tg) (ex. still gas from refining)		8.45	0.87	-	-	11.08

[a] C content: Waste Gas is assumed to be same as naphtha <401 deg. F
[b] C content: Waste Oils/Tars is assumed to be same as asphalt/road oil
[c] Refinery "still gas" fuel consumption is reported elsewhere in the Inventory and is excluded from the total C content estimate
[d] Net steam fuel consumption is reported elsewhere in the Inventory and is excluded from the total C content estimate
[e] C content: "Other" is assumed to be the same as petrochemical feedstocks

Table A-66: Carbon Emitted from Fuels Burned for Energy Recovery (Tg CO₂ Eq.)

	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
C Emissions	42.5	40.8	64.3	67.4	70.6	71.6	72.7	73.7	74.8	74.8	74.8	74.8

Products

More C is found in products than in industrial releases or energy recovery. The principal types of products are plastics; synthetic rubber; synthetic fiber; C black; pesticides; soaps, detergents, and cleansers; food additives; antifreeze and deicers (glycols); silicones; and solvents. Solvent evaporation was discussed previously along with industrial releases of NMVOCs; the other product types are discussed below.

Plastics

Data on annual production of plastics through 2005 were taken from the American Plastics Council (APC), as published in *Chemical & Engineering News* and on the APC and Society of Plastics Industry (SPI) websites, and through direct communication with the APC (APC 2000, 2001, 2003 through 2006; SPI 2000; Eldredge-Roebuck 2000). Data for 2006 and subsequent years were taken from the American Chemistry Council (ACC 2007 through 2009 supplemented by Vallianos 2011). Production was organized by resin type (see Table A-67) and by year. Several of the resin categories included production from Canada and/or Mexico, in addition to the U.S. values for part of the time series. The production data for the affected resins and years were corrected using an economic adjustment factor, based on the percent of North American production value in this industry sector accounted for by the United States. A C content was then assigned for each resin. These C contents were based on molecular formulae and are listed in Table A-68 and Table A-69. 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 other resins, a weighted C content of 68 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 C was considered stored in products. As noted in the chapter, an estimate of emissions related to the combustion of these plastics in the municipal solid waste stream can be found in the Incineration of Waste section of the Energy chapter; those emissions are not incorporated in the mass balance for feedstocks (described in this annex) to avoid double-counting.

Table A-67: 2009 Plastic Resin Production (Tg dry weight) and C Stored (Tg CO₂ Eq.)

Resin Type	2009 Production[a] (Tg dry weight)	Carbon Stored (Tg CO_2 Eq.)
Epoxy	0.24	0.7
Urea	0.47	0.6
Melamine	0.47	0.5
Phenolic	1.44	4.0
Low-Density Polyethylene (LDPE)	2.74	8.6
Linear Low-Density Polyethylene (LLDPE)	5.39	17.0
High Density Polyethylene (HDPE)	6.97	21.9
Polypropylene (PP)	6.65	20.9
Acrylonitrile-butadiene-styrene (ABS)	0.37	1.2
Other Styrenics[c]	0.48	1.6
Polystyrene (PS)	2.00	6.8
Nylon	0.38	0.9
Polyvinyl chloride (PVC)[b]	5.24	7.4
Thermoplastic Polyester	3.24	7.4
All Other (including Polyester (unsaturated))	4.61	11.6
Total	**40.70**	**111.1**

[a] Production estimates provided by the American Chemistry Council include Canadian production for Urea, Melamine, Phenolic, LDPE, LLDPE, HDPE, PP, ABS, SAN, Other Styrenics, PS, Nylon, PVC, and Thermoplastic Polyester, and Mexican production for PP, ABS, SAN, Other Styrenics, Nylon, and Thermoplastic Polyester. Values have been adjusted to account just for U.S. production.
[b] Includes copolymers
[c] Includes Styrene-acrylonitrile (SAN)
Note: Totals may not sum due to independent rounding.

Table A-68: Assigned C Contents of Plastic Resins (% by weight)

Resin Type	C Content	Source of C Content Assumption
Epoxy	76%	Typical epoxy resin made from epichlorhydrin and bisphenol A
Polyester (Unsaturated)	63%	Poly (ethylene terephthalate) (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 A-69)
Polyvinyl Chloride (PVC)	38%	Polyvinyl chloride
Thermoplastic Polyester	63%	Polyethylene terephthalate
All Other	69%	Weighted average of other resin production

*Does not include alcoholic hydrogens.

Table A-69: Major Nylon Resins and their C Contents (% by weight)

Resin	C 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 synthetic rubber in tires were derived from data on the scrap tire market and the composition of scrap tires from the Rubber Manufacturers' Association (RMA). The market information is presented in the report *Scrap Tire Markets in the United States 2007 Edition* (RMA 2009a), while the tire composition information is from the "Scrap Tires, Facts and Figures" section of the organization's website (RMA 2009b). Data on synthetic rubber in other products (durable goods, nondurable goods, and containers and packaging) were obtained from EPA's *Municipal Solid Waste in the United States* reports (1996 through 2003a, 2005, 2007b, and 2008, 2009a, 2011) and detailed unpublished backup data for some years not shown in the *Characterization of Municipal Solid Waste in the United States* reports (Schneider 2007). The abraded rubber from scrap passenger tires was assumed to be 2.5 lbs per scrap tire, while the abraded rubber from scrap commercial tires was assumed to be 10 lbs per scrap tire. Data on abraded rubber weight were obtained by calculating the average weight difference between new and scrap tires (RMA 2009b).

A C content for synthetic rubber (90 percent for tire synthetic rubber and 85 percent for non-tire synthetic rubber) was assigned based on the weighted average of C contents (based on molecular formula) by elastomer type consumed in 1998, 2001, and 2002 (see Table A-70). The 1998 consumption data 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). The 2001 and 2002 consumption data were obtained from the IISRP press release, "IISRP Forecasts Moderate Growth in North America to 2007" (IISRP 2003).

The rubber in tires that is abraded during use (the difference between new tire and scrap tire rubber weight) was considered to be 100 percent emitted. Other than abraded rubber, there were no emissive uses of scrap tire and non-tire rubber identified, so 100 percent of the non-abraded amount was assumed stored. Emissions related to the combustion of rubber in scrap tires and consumer goods can be found in the Incineration of Waste section of the Energy chapter.

Table A-70: 2002 Rubber Consumption (Gg) and C Content (%)

Elastomer Type	2002 Consumption (Gg)*	C Content
SBR Solid	768	91%
Polybutadiene	583	89%
Ethylene Propylene	301	86%
Polychloroprene	54	59%
NBR Solid	84	77%
Polyisoprene	58	88%
Others	367	88%
Weighted Average	**-**	**90%**
Total	**2,215**	**-**

* 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* (FEB 2001, 2003, 2005, 2007, 2009, 2010). These data are organized by year and fiber type. For each fiber, a C content was assigned based on molecular formula (see Table A-71). For polyester, the C content for poly (ethylene terephthalate) (PET) was used as a representative compound. For nylon, the average C 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' C accounting displayed here because much of their C is of biogenic origin and carbon fluxes from biogenic compounds are accounted for in the Land Use, Land-Use Change and Forestry chapter. 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 C was considered stored. Note that emissions related to the combustion of textiles in municipal solid waste are accounted for under the Incineration of Waste section of the Energy chapter.

Table A-71: 2009 Fiber Production (Tg), C Content (%), and C Stored (Tg CO$_2$ Eq.)

Fiber Type	Production (Tg)	C Content	C Stored (Tg CO$_2$ Eq.)
Polyester	0.9	63%	2.14
Nylon	0.6	64%	1.46
Olefin	1.0	86%	3.00
Acrylic	+	68%	0.07
Total	**2.5**	**-**	**6.68**

+ Less than 0.05 Tg
- Not applicable
Note: Totals may not sum due to independent rounding

Pesticides

Pesticide consumption data were obtained from the *1994/1995, 1996/1997, 1998/1999, and 2000/2001 Pesticides Industry Sales and Usage Market Estimates* (EPA 1998, 1999, 2002, 2004) reports. The most recent data available were for 2001, so it was assumed that the 2002 through 2009 consumption was equal to that of 2001. Active ingredient compound names and consumption weights were available for the top 25 agriculturally-used pesticides and top 10 pesticides used in the home and garden and the industry/commercial/government categories. 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 C content value based on molecular formula. If the compound contained aromatic rings substituted with chlorine or other halogens, then the compound was considered persistent and the C in the compound was assumed to be stored. All other pesticides were assumed to release their C to the atmosphere. Over one-third of 2001 total pesticide active ingredient consumption was not specified by chemical type in the *Sales and Usage* report (EPA 2004). This unspecified portion of the active ingredient consumption was treated as a single chemical and assigned a C content and a storage factor based on the weighted average of the known chemicals' values.

Table A-72: Active Ingredient Consumption in Pesticides (Million lbs.) and C Emitted and Stored (Tg CO$_2$ Eq.) in 2001

Pesticide Use*	Active Ingredient (Million lbs.)	C Emitted (Tg CO$_2$ Eq.)	C Stored (Tg CO$_2$ Eq.)
Agricultural Uses	458.5	0.1	0.2
Non-Agricultural Uses	84.5	+	+
Home & Garden	38.5	+	+
Industry/Gov't/Commercial	46.0	+	+
Other	345.0	0.1	0.1
Total	**888.0**	**0.2**	**0.3**

+ Less than 0.05 Tg CO$_2$ Eq.
*2001 estimates (EPA 2004b).
Note: Totals may not sum due to independent rounding.

Soaps, Shampoos, and Detergents

Cleansers—soaps, shampoos, and detergents—are among the major consumer products that may contain fossil C. All of the C in cleansers was assumed to be fossil-derived, and, as cleansers eventually biodegrade, all of the C was assumed to be emitted. The first step in estimating C flows was to characterize the "ingredients" in a sample of cleansers. For this analysis, cleansers were limited to the following personal household cleaning products: bar soap, shampoo, laundry detergent (liquid and granular), dishwasher detergent, and dishwashing liquid. Data on the annual consumption of household personal cleansers were obtained from the U.S. Census Bureau 1992, 1997, 2002, and 2007 Economic Census (U.S. Bureau of the Census 1994, 1999, 2004, 2009). Consumption values for 1990 and 1991 were assumed to be the same as the 1992 value; consumption was interpolated between 1992 and 1997, 1997 and 2002, and 2002 and 2007; consumption for 2008 and 2009 was assumed to equal the 2007 value. Cleanser consumption values were adjusted by import and export data to develop US consumption estimates.

Chemical formulae were used to determine C contents (as percentages) of the ingredients in the cleansers. Each product's overall C content was then derived from the composition and contents of its ingredients. From these values the mean C content for cleansers was calculated to be 21.9 percent.

The Census Bureau presents consumption data in terms of quantity (in units of million gallons or million pounds) and/or terms of value (thousands of dollars) for eight specific categories, such as "household liquid laundry detergents, heavy duty" and "household dry alkaline automatic dishwashing detergents." Additionally, the report provides dollar values for the total consumption of "soaps, detergents, etc.—dry" and "soaps, detergents, etc.—liquid." The categories for which both quantity and value data are available is a subset of total production. Those categories that presented both quantity and value data were used to derive pounds per dollar and gallons per dollar conversion rates, and they were extrapolated (based on the Census Bureau estimate of total value) to estimate the total quantity of dry and liquid[29] cleanser categories, respectively.

Next, the total tonnage of cleansers was calculated (wet and dry combined) for 1997. Multiplying the mean C content (21.9 percent) by this value yielded an estimate of 4.6 Tg CO_2 Eq. in cleansers for 1997. For all subsequent years, it was assumed that the ratio of value of shipments to total carbon content remained constant. For 1998 through 2009, value of shipments was adjusted to 1997 dollars using the producer price index for soap and other detergent manufacturing (Bureau of Labor Statistics 2009). The ratio of value of shipments to carbon content was then applied to arrive at total carbon content of cleansers. For 1992, 2002, and 2007 the estimates are 3.6 Tg CO_2 Eq., 5.1 Tg CO_2 Eq., 7.6 Tg CO_2 Eq., respectively. Estimates for other years are based on these values as described above, and are shown in Table A-73.

Table A-73: C Emitted from Utilization of Soaps, Shampoos, and Detergents (Tg CO_2 Eq.)

	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
C Emissions	3.6	4.2	4.5	4.8	5.1	5.7	6.2	6.7	7.0	7.6	7.1	6.7

Antifreeze and Deicers

Glycol compounds, including ethylene glycol, propylene glycol, diethylene glycol, and triethylene glycol, are used as antifreeze in motor vehicles, deicing fluids for commercial aircraft, and other similar uses. These glycol compounds are assumed to ultimately enter wastewater treatment plants where they are degraded by the wastewater treatment process to CO_2 or to otherwise biodegrade to CO_2. Glycols are water soluble and degrade rapidly in the environment (Howard 1993).

Annual production data for each glycol compound used as antifreeze and deicers were obtained from the Guide to the Business of Chemistry (ACC 2010). Import and export data were used to adjust annual production data to annual consumption data. The percentage of the annual consumption of each glycol compound used for antifreeze and deicing applications was estimated from Chemical Profiles data published on The Innovation Group website and from similar data published in the Chemical Market Reporter, which became ICIS Chemical Business in 2005. Production data for propylene glycol, diethylene glycol, and triethylene glycol are no longer reported in the Guide to the Business of Chemistry, so data from ICIS Chemical Business on total demand was used with import and export data to estimate production of these chemicals.

The glycol compounds consumed in antifreeze and deicing applications is assumed to be 100 percent emitted as CO_2. Emissions of CO_2 from utilization of antifreeze and deicers are summarized in Table A-74.

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[29] A density of 1.05 g/mL—slightly denser than water—was assumed for liquid cleansers.

Table A-74: C Emitted from Utilization of Antifreeze and Deicers (Tg CO₂ Eq.)

	1990		1995		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
C Emissions	1.2		1.3		1.5	1.2	1.3	1.2	1.4	1.2	1.3	1.2	1.0	0.9

Food Additives

Petrochemical feedstocks are used to manufacture synthetic food additives, including preservatives, flavoring agents, and processing agents. These compounds include glycerin, propylene glycol, benzoic acid, and other compounds. These compounds are incorporated into food products, and are assumed to ultimately enter wastewater treatment plants where they are degraded by the wastewater treatment processes to CO_2 or to otherwise biodegrade to CO_2. Certain food additives, e.g., glycerin, are manufactured both from petrochemical feedstocks and from biogenic feedstocks. Food additives that are derived from biogenic feedstocks are accounted for in the Land Use, Land-Use Change and Forestry chapter.

Annual production data for food additive compounds were obtained from the Guide to the Business of Chemistry (ACC 2010). Import and export data were used to adjust annual production data to annual consumption data. The percentage of the annual consumption of food additive compounds was estimated from Chemical Profiles data published on The Innovation Group website[30] and from similar data published in the Chemical Market Reporter, which became ICIS Chemical Business in 2005.[31] Production data for several food additive compounds are no longer reported in the Guide to the Business of Chemistry, so data from ICIS Chemical Business on total demand was used with import and export data to estimate production of these chemicals. The consumption of synthetic food additives is assumed to be 100 percent emitted as CO_2. Emissions of CO_2 from utilization of synthetic food additives are summarized in Table A-75.

Table A-75: C Emitted from Utilization of Food Additives (Tg CO₂ Eq.)

	1990		1995		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
C Emissions	0.6		0.7		0.7	0.6	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8

Silicones

Silicone compounds (e.g., polymethyl siloxane) are used as sealants and in manufactured products. Silicone compounds are manufactured from petrochemical feedstocks including methyl chloride. It is assumed that petrochemical feedstocks used to manufacture silicones are incorporated into the silicone products and not emitted as CO_2 in the manufacturing process. It is also assumed that the C contained in the silicone products is stored, and not emitted as CO_2.

Annual production data for each silicone manufacturing compound were obtained from the Guide to the Business of Chemistry (ACC 2010). Import and export data were used to adjust annual production data to annual consumption data. The percentage of the annual consumption of each silicone manufacturing compound was estimated from Chemical Profiles data published on The Innovation Group website and from similar data published in the Chemical Market Reporter, which became ICIS Chemical Business in 2005. The consumption of silicone manufacturing compounds is assumed to be 100 percent stored, and not emitted as CO_2. Storage of silicone manufacturing compounds is summarized in Table A-76.

Table A-76: C Stored in Silicone Products (Tg CO₂ Eq.)

	1990		1995		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
C Storage	0.3		0.4		0.4	0.4	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.5

Uncertainty

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of the feedstocks C storage factor and the quantity of C emitted from feedstocks in 2009. The Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the Inventory estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. Uncertainty estimates for production data (the majority of the variables) were assumed to exhibit a normal distribution with a relative error of ±20 percent in the underlying EIA estimates, plus an additional ±15 percent to account for uncertainty in the assignment of imports and

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[30] http://www.the-innovation-group.com/ChemProfiles
[31] http://www.icis.com/home/default.aspx

exports. An additional 10 percent (for a total of ±45 percent) was applied to the production of other oils (>401 deg. F) to reflect the additional uncertainty in the assignment of part of the production quantity to industrial processes. A relatively narrow uniform distribution ±1 percent to ±15 percent, depending on the fuel type) was applied to each C coefficient.

The Monte Carlo analysis produced a storage factor distribution that approximates a normal curve, with a mean of 58 percent, a standard deviation of 1 percent, and the 95 percent confidence interval of 56 percent and 60 percent. This compares to the calculated Inventory estimate of 58 percent. The analysis produced a C emission distribution approximating a normal curve with a mean of 78.8 Tg CO_2 Eq., standard deviation of 8.5 Tg CO_2 Eq., and 95 percent confidence limits of 63.4 and 96.1 Tg CO_2 Eq. This compares with a calculated Inventory estimate of 79.3 Tg CO_2 Eq.

The apparently tight confidence limits for the storage factor and C storage probably understate uncertainty, as a result of the way this initial analysis was structured. As discussed above, the storage factor for feedstocks is based on an analysis of six fates that result in long-term storage (e.g., plastics production), and eleven that result in emissions (e.g., volatile organic compound emissions). Rather than modeling the total uncertainty around all 17 of these fate processes, the current analysis addresses only the storage fates, and assumes that all C that is not stored is emitted. As the production statistics that drive the storage factors are relatively well-characterized, this approach yields a result that is probably biased toward understating uncertainty.

As far as specific sources of uncertainty, there are several cross-cutting factors that pervade the characterization of C flows for feedstocks. The aggregate storage factor for petrochemical feedstocks (industrial other coal, natural gas for non-fertilizer uses, LPG, pentanes plus, naphthas, other oils, still gas, special naphtha) is based on assuming that the ultimate fates of all of these fuel types —in terms of storage and emissions—are similar. In addition, there are uncertainties associated with the simplifying assumptions made for each end use category C estimate. Generally, the estimate for a product is subject to one or more of the following uncertainties:

- The value used for estimating the C content has been assumed or assigned based upon a representative compound.

- The split between C storage and emission has been assumed based on an examination of the environmental fate of the products in each end use category.

- Environmental fates leading to emissions are assumed to operate rapidly, i.e., emissions are assumed to occur within one year of when the fossil C enters the non-energy mass balance. Some of the pathways that lead to emissions as CO_2 may actually take place on a time-scale of several years or decades. By attributing the emissions to the year in which the C enters the mass balance (i.e., the year in which it leaves refineries as a non-energy fuel use and thus starts being tracked by EIA), this approach has the effect of "front-end loading" the emission profile.

Another cross-cutting source of uncertainty is that for several sources the amount of C stored or emitted was calculated based on data for only a single year. This specific year may not be representative of storage for the entire Inventory period. Sources of uncertainty associated with specific elements of the analysis are discussed below.

Import and export data for petrochemical feedstocks were obtained from EIA, the National Petroleum Refiners Association, and the U.S. BoC for the major categories of petrochemical feedstocks (EIA 2001a, NPRA 2001, and U.S. BoC 2006). The complexity of the organic chemical industry, with multiple feedstocks, intermediates, and subtle differences in nomenclature, makes it difficult to ensure that the adjustments to the EIA data for imports and exports is accurate and the approach used here may underestimate or overestimate net exports of C.

Oxidation factors have been applied to non-energy uses of petrochemical feedstocks in the same manner as for energy uses. However, for those fuels where IPCC storage factors are used, this "oxidation factor" may be inherent in the storage factor applied when calculating emissions from non-energy consumption, which would result in a double-counting of the unoxidized C. 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 C emissions from non-energy uses.

The major uncertainty in using the TRI data is the possibility of double counting 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 C 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.

The principal sources of uncertainty in estimating CO_2 emissions from solvent evaporation and industrial NMVOC emissions are in the estimates of (a) total emissions and (b) their C content. 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 C 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 C content for industrial emissions has more uncertainty, however, as it is calculated from the average C content of an average volatile organic compound based on the list of the most abundant measured NMVOCs provided in EPA (2002a).

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 C 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 very minor source of uncertainty. C emission estimates from hazardous waste should be considered central value estimates that are likely to be accurate to within ±50 percent.

The amount of feedstocks combusted for energy recovery was estimated from data included in the Manufacturers Energy Consumption Surveys (MECS) for 1991, 1994, 1998, 2002, and 2006 (EIA 1994, 1997, 2001, 2005, 2010a). MECS is a comprehensive survey that is conducted every four years and 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 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. Moreover, 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. Taken as a whole, the estimate of energy recovery emissions probably introduces more uncertainty than any other element of the non-energy analysis.

Uncertainty in the C storage estimate for plastics arises primarily from four factors. First, production of some plastic resins is not tracked directly and must be estimated based on other market data. Second, the raw data on production for several resins include Canadian and/or Mexican production and may overestimate the amount of plastic produced from U.S. fuel feedstocks; this analysis includes adjustments to "back out" the Canadian and Mexican values, but these adjustments are approximate. Third, the assumed C 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). Fourth, the assumption that all of the C 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.

The quantity of C stored in synthetic rubber only accounts for the C stored in scrap tire synthetic rubber. The value does not take into account the rubber stored in other durable goods, clothing, footwear, and other non-durable goods, or containers and packaging. This adds uncertainty to the total mass balance of C stored. There are also uncertainties as to the assignment of C 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 C content values is much narrower. Lastly, assuming that all of the C contained in rubber is stored ignores the possibility of volatilization or degradation during product lifetimes. However, the proportion of the total C that is released to the atmosphere during use is probably negligible.

A small degree of uncertainty arises from the assignment of C content values in textiles; 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.

For pesticides, the largest source of uncertainty involves the assumption that an active ingredient's C 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, application method, and harvesting practice. Another smaller source of uncertainty arises from the C content values applied to the unaccounted for portion of active ingredient. C 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. Additionally, pesticide consumption data were only available for 1987, 1993, 1995, 1997, 1999, and 2001; the majority of the time series data were interpolated or held constant at the latest (2001) value. Another source of uncertainty is that only the "active" ingredients of pesticides are considered in the calculations; the "inactive" ingredients may also be derived from petrochemical feedstocks.

It is important to note that development of this uncertainty analysis is a multi-year process. The current feedstocks analysis examines NEU fuels that end in storage fates Thus only C stored in pesticides, plastics, synthetic fibers, synthetic rubbers, silicones, and TRI releases to underground injection and Subtitle C landfills is accounted for in the uncertainty estimate above. In the future this analysis will be expanded to include the uncertainty surrounding emitted fates in addition to the storage fates. Estimates of variable uncertainty will also be refined where possible to include fewer assumptions. With these major changes in future Inventories, the uncertainty estimate is expected to change, and likely increase. An increase in the uncertainty estimate in the coming years will not indicate that the Inventory calculations have become less certain, but rather that the methods for estimating uncertainty have become more comprehensive; thus, potential future changes in the results of this analysis will reflect a change in the uncertainty analysis, not a change in the Inventory quality.

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. Though minor amounts of C are emitted during production, asphalt has an overall C storage factor of almost 100 percent, as discussed below.

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 2001), 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 C in asphalt roofing; it was assumed that it has the same fate as C in asphalt paving applications.

Methodology and Data Sources

A C storage factor was calculated for each type of asphalt paving. The fraction of C emitted by each asphalt type was multiplied by consumption data for asphalt paving (EPA 2001) to estimate a weighted average C storage factor for asphalt as a whole.

The fraction of C emitted by HMA was determined by first calculating the organic emissions (volatile organic compounds [VOCs], carbon monoxide [CO], polycyclic aromatic hydrocarbons [PAHs], hazardous air pollutants [HAPs], and phenol) from HMA paving, using emission factors reported in EPA (2001) and total HMA production.[32] The next step was to estimate the C content of the organic emissions. This calculation was based on the C content of CO and phenol, and an assumption of 85 percent C content for PAHs and HAPs. The C content of asphalt paving is a function of (1) the proportion of asphalt cement in asphalt paving, assumed to be 8 percent asphalt cement content based on EPA (2001), and (2) the proportion of C in asphalt cement. For the latter factor, all paving types were characterized as having a mass fraction of 85 percent C 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 C in asphalt cement was retained (i.e., stored), and less than 0.01 percent was emitted.

Cut-back asphalt is produced in three forms: rapid, medium, and slow cure. The production processes for all three forms emit C primarily from the volatile petroleum distillate used in the process as a diluent to thin the asphalt cement so that it can be applied more readily (EPA 2001).

A mass balance on C losses from asphalt was constructed by first estimating the amount of carbon emitted as VOCs. Values for medium cure asphalt are used to represent all cut-back asphalt. The average weight of distillates used in medium cure cut-back asphalt (35 percent) is multiplied by the loss rate (as emissions of VOCs) of 70 percent from the *Emissions Inventory Guidebook* to arrive at an estimate that 25 percent of the diluent is emitted (Environment Canada 2006). Next, the fraction of C in the asphalt/ diluent mix that is emitted was estimated, assuming 85 percent C content; this yields an overall storage factor of 93.5 percent for cut-back asphalt.

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[32] The emission factors are expressed as a function of asphalt paving tonnage (i.e., including the rock aggregate as well as the asphalt cement).

One caveat associated with this calculation is that it is possible that the carbon flows for asphalt and diluent (volatile petroleum distillate) are accounted for separately in the EIA statistics on fossil fuel flows, and thus the mass balance calculation may need to re-map the system boundaries to correctly account for carbon flows. EPA plans to re-evaluate this calculation in the future.

It was assumed that there was no loss of C 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 on asphalt and road oil consumption and C content factors were supplied by EIA. Hot mix asphalt production and emissions factors, and the asphalt cement content of HMA were obtained from "Hot Mix Asphalt Plants Emissions Assessment Report" from EPA's *AP-42* (EPA 2001) publication. 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 from paving processes (EIIP 2001). "Asphalt Paving Operation" *AP-42* (EPA 2001) provided the emissions source information used in the calculation of the C 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

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of the asphalt C storage factor and the quantity of C stored in asphalt in 2009. The Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the Inventory estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. Uncertainty estimates for asphalt production were assumed to be ±20 percent, while the asphalt property variables were assumed to have narrower distributions. A narrow uniform distribution, with maximum 5 percent uncertainty (± 5 percent) around the mean, was applied to the C content coefficient.

The Monte Carlo analysis produced a tight distribution of storage factor values, with the 95 percent confidence interval of 99.1 percent and 99.8 percent, with the mean value of 99.5 percent. This compares to the storage factor value used in the Inventory of 99.6 percent. The analysis produced a C emission distribution with a mean of 0.31 Tg CO_2 Eq., standard deviation of 0.13 and 95 percent confidence limits of 0.12 Tg CO_2 Eq. and 0.63 Tg CO_2 Eq. This compares with an Inventory calculated estimate of 0.29 Tg CO_2 Eq.

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 C 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 hot mix asphalt 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 C storage factor is minimal (on the order of 0.1 percent). Similarly, changes in the assumed C 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. This change in trend would indicate an overestimate of emissions from asphalt.

Future improvements to this uncertainty analysis, and to the overall estimation of a storage factor for asphalt, include characterizing the long-term fate of asphalt.

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 (2010b), the C content from U.S. production of lubricants in 2009 was approximately 5.3 Tg C. 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 C storage factor was estimated to be 9.2 percent; thus, emissions in 2009 were about 4.8 Tg C, or 17.7 Tg CO_2 Eq.

Methodology and Data Sources

For each lubricant category, a storage factor was derived by identifying disposal fates and applying assumptions as to the disposition of the C for each practice. An overall lubricant C 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 20 years.[33] The effect of these regulations and policies has been to restrict landfilling and dumping, and to encourage collection of used oil. The economics of the petroleum industry have generally not favored re-refining—instead, most of the used oil that has been collected has been combusted.

Table A-77 provides an estimated allocation of the fates of lubricant oils (Rinehart 2000), along with an estimate of the proportion of C 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 (EIIP 1999), with correspondingly little long-term storage of C 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 (based on the observation that land farming—application to soil—is one of the most frequently used methods for degrading refinery wastes). 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, based on analogy with the persistence of petroleum in native petroleum-bearing strata, which is also anaerobic. Re-refining adds a recycling loop to the fate of oil. 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), that is, it was assumed that about 97 percent of the C in re-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 C in oil lubricants goes into long-term storage.

Table A-77: Commercial and Environmental Fate of Oil Lubricants (Percent)

Fate of Oil	Portion of Total Oil	C Stored
Combusted During Use	**20%**	**0.2%**
Not Combusted During Use	**80%**	**2.7%**
Combusted as Used Oil *	64%	0.6%
Dumped on the ground or in storm sewers	6%	-
Landfilled	2%	1.8%
Re-refined into lube oil base stock and other products	8%	0.2%
Weighted Average		**2.9%**

* (e.g., in boilers or space heaters)
- Not applicable

Greases

Table A-78 provides analogous estimates for lubricant greases. Unlike oils, grease is generally not combusted during use, and combustion for energy recovery and re-refining is 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, and because greases contain longer chain paraffins, which are more persistent than oils, it was assumed that 90 percent and 50 percent of the C in landfilled and dumped grease, respectively, would be stored. The overall storage factor is 82 percent for grease.

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[33] 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.

Table A-78: Commercial and Environmental Fate of Grease Lubricants (Percent)

Fate of Grease	Portion of Total Grease	C Stored
Combusted During Use	**5%**	**0.1%**
Not Combusted During Use	**95%**	**81.7%**
Landfilled	86%	77.0%
Dumped on the ground or in storm sewers	10%	4.8%
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. These were retrieved from the relevant industry series summaries from the 1997 Economic Census (Census Bureau 1999). 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 9.2 percent.

Uncertainty

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of the lubricants weighted average C storage factor and the quantity of C emitted from lubricants in 2009. The Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the Inventory estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. Uncertainty estimates for oil and grease variables were assumed to have a moderate variance, in triangular or uniform distribution. Uncertainty estimates for lubricants production were assumed to be rather high (±20 percent). A narrow uniform distribution, with 6 percent uncertainty (± 6 percent) around the mean, was applied to the lubricant C content coefficient.

The Monte Carlo analysis produced a storage factor distribution with the 95 percent confidence interval of 4 percent and 17 percent around a mean value of 10 percent. This compares to the calculated Inventory estimate of 9 percent. The analysis produced a C emission distribution approximating a normal curve with a mean of 17.5 Tg CO_2 Eq., standard deviation of 1.5 and 95 percent confidence limits of 14.6 Tg CO_2 Eq. and 20.5 Tg CO_2 Eq.. This compares with an Inventory calculated estimate of 17.7 Tg CO_2 Eq..

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 C 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 have a large effect on the weighted storage factor.

Future improvements to the analysis of uncertainty surrounding the lubricants C storage factor and C stored include further refinement of the uncertainty estimates for the individual activity variables.

Waxes

Waxes are organic substances that are solid at ambient temperature, but whose viscosity decreases as temperature increases. Most commercial waxes are produced from petroleum refining, though "mineral" waxes derived from animals, plants, and lignite [coal] are also used. An analysis of wax end uses in the United States, and the fate of C in these uses, suggests that about 42 percent of C in waxes is emitted, and 58 percent is stored.

Methodology and Data Sources

The National Petroleum Refiners Association (NPRA) considers the exact amount of wax consumed each year by end use to be proprietary (Maguire 2004). In general, about thirty percent of the wax consumed each year is used in packaging materials, though this percentage has declined in recent years. The next highest wax end use, and fastest growing end use, is candles, followed by construction materials and firelogs. Table A-79 categorizes some of the wax end uses, which the NPRA generally classifies into cosmetics, plastics, tires and rubber, hot melt (adhesives), chemically modified wax substances, and other miscellaneous wax uses (NPRA 2002)

Table A-79: Emissive and Non-emissive (Storage) Fates of Waxes: Uses by Fate and Percent of Total Mass

Use	Emissive	Non-emissive
Packaging	**6%**	**24%**
Non-packaging	**36%**	**34%**
Candles	18%	2%
Construction Materials	4%	14%
Firelogs	7%	+
Cosmetics	1%	2%
Plastics	1%	2%
Tires/Rubber	1%	1%
Hot Melts	1%	1%
Chemically Modified	0%	1%
Other	2%	9%
Total	**42%**	**58%**

+ Does not exceed 0.5 percent

A C storage factor for each wax end use was estimated and then summed across all end uses to provide an overall C storage factor for wax. Because no specific data on C contents of wax used in each end use were available, all wax products are assumed to have the same C content. Table A-80 categorizes wax end uses identified by the NPRA, and lists each end use's estimated C storage factor.

Table A-80: Wax End-Uses by Fate, Percent of Total Mass, Percent C Stored, and Percent of Total C Mass Stored

Use	Percent of Total Wax Mass	Percent of C Stored	Percent of Total C Mass Stored
Packaging	30%	79%	24%
Non-Packaging			
Candles	20%	10%	2%
Construction Materials	18%	79%	14%
Firelogs	7%	1%	+
Cosmetics	3%	79%	2%
Plastics	3%	79%	2%
Tires/Rubber	3%	47%	1%
Hot Melts	3%	50%	1%
Chemically Modified	1%	79%	1%
Other	12%	79%	9%
Total	**100%**	**NA**	**58%**

+ Does not exceed 0.5 percent
Source, mass percentages: NPRA 2002. Estimates of percent stored are based on professional judgment, ICF Consulting.
Note: Totals may not sum due to independent rounding.

Emissive wax end-uses include candles, firelogs (synthetic fireplace logs), hotmelts (adhesives), matches, and explosives. At about 20 percent, candles consume the greatest portion of wax among emissive end uses. As candles combust during use, they release emissions to the atmosphere. For the purposes of the Inventory, it is assumed that 90 percent of C contained in candles is emitted as CO_2. In firelogs, petroleum wax is used as a binder and as a fuel, and is combusted during product use, likely resulting in the emission of nearly all C contained in the product. Similarly, C contained in hotmelts is assumed to be emitted as CO_2 as heat is applied to these products during use. It is estimated that 50 percent of the C contained in hot melts is stored. Together, candles, firelogs, and hotmelts constitute approximately 30 percent of annual wax production (NPRA 2002).

All of the wax utilized in the production of packaging, cosmetics, plastics, tires and rubber, and other products is assumed to remain in the product (i.e., it is assumed that there are no emissions of CO_2 from wax during the production of the product). Wax is used in many different packaging materials including wrappers, cartons, papers, paperboard, and

corrugated products (NPRA 2002). Davie (1993) and Davie et al. (1995) suggest that wax coatings in packaging products degrade rapidly in an aerobic environment, producing CO_2; however, because packaging products ultimately enter landfills typically having an anaerobic environment, most of the C from this end use is assumed to be stored in the landfill.

In construction materials, petroleum wax is used as a water repellent on wood-based composite boards, such as particle board (IGI 2002). Wax used for this end-use should follow the life-cycle of the harvested wood used in product, which is classified into one of 21 categories, evaluated by life-cycle, and ultimately assumed to either be disposed of in landfills or be combusted (EPA 2003).

The fate of wax used for packaging, in construction materials, and for most remaining end uses is ultimately to enter the municipal solid waste (MSW) stream, where it is either combusted or sent to landfill for disposal. Most of the C contained in these wax products will be stored. It is assumed that approximately 21 percent of the C contained in these products will be emitted through combustion or at landfill. With the exception of tires and rubber, these end-uses are assigned a C storage factor of 79 percent.

Waxes used in tires and rubber follow the life cycle of the tire and rubber products. Used tires are ultimately recycled, landfilled, or combusted. The life-cycle of tires is addressed elsewhere in this annex as part of the discussion of rubber products derived from petrochemical feedstocks. For the purposes of the estimation of the C storage factor for waxes, wax contained in tires and rubber products is assigned a C storage factor of 47 percent.

Uncertainty

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of the wax C storage factor and the quantity of C emitted from wax in 2009. A Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the Inventory estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. Uncertainty estimates for wax variables were assumed to have a moderate variance, in normal, uniform, or triangular distribution; uniform distributions were applied to total consumption of waxes and the C content coefficients.

The Monte Carlo analysis produced a storage factor distribution, whose 95 percent confidence interval values fell within the range of 49 percent and 71 percent, around the mean value of about 60 percent. This compares to the calculated Inventory estimate of 58 percent. The analysis produced an emission distribution, with the 95 percent confidence interval values of 0.3 Tg CO_2 Eq. and 0.7 Tg CO_2 Eq., with a mean value of 0.4 Tg CO_2 Eq. This compares with a calculated Inventory estimate of 0.4 Tg CO_2 Eq., which falls within the range of 95 percent confidence limits established by this quantitative uncertainty analysis. Uncertainty associated with the wax storage factor is considerable due to several assumptions pertaining to wax imports/exports, consumption, and fates.

Miscellaneous Products

Miscellaneous products are defined by the U.S. Energy Information Administration as: "all finished [petroleum] products not classified elsewhere, e.g., petrolatum; lube refining byproducts (e.g., aromatic extracts and tars); absorption oils; ram-jet fuel; petroleum rocket fuel; synthetic natural gas feedstocks; and specialty oils."

Methodology and Data Sources

Data are not available concerning the distribution of each of the above-listed subcategories within the "miscellaneous products" category. However, based on the anticipated disposition of the products in each subcategory, it is assumed that all of the C content of miscellaneous products is emitted rather than stored. Petrolatum and specialty oils (which include greases) are likely to end up in solid waste or wastewater streams rather than in durable products, and would be emitted through waste treatment. Absorption oil is used in natural gas processing and is not a feedstock for manufacture of durable products Jet fuel and rocket fuel are assumed to be combusted in use, and synthetic natural gas feedstocks are assumed to be converted to synthetic natural gas that is also combusted in use. Lube refining byproducts could potentially be used as feedstocks for manufacture of durable goods, but such byproducts are more likely to be used in emissive uses. Lube refining byproducts and absorption oils are liquids and are precluded from disposal in landfills. Because no sequestering end uses of any of the miscellaneous products subcategories have been identified, a zero percent storage factor is assigned to miscellaneous products. According to EIA (2010b), the C content of miscellaneous petroleum

products in 2009 was approximately 20.3 Tg C/QBtu. One hundred percent of the C content is assumed to be emitted to the atmosphere, where it is oxidized to CO_2.

Uncertainty

A separate uncertainty analysis was not conducted for miscellaneous products, though this category was included in the uncertainty analysis of other non-energy uses discussed in the following section.

Other Non-Energy Uses

The remaining fuel types use storage factors that are not based on U.S.-specific analysis. For industrial coking coal and distillate fuel oil, storage factors were taken from IPCC (2006), which in turn draws from Marland and Rotty (1984). These factors are 0.1 and 0.5, respectively.

IPCC does not provide guidance on storage factors for the remaining fuel types (petroleum coke, miscellaneous products, and other petroleum), and assumptions were made based on the potential fate of C in the respective NEUs. Specifically, the storage factor for petroleum coke is 0.3, based on information from Huurman (2006) indicating that petroleum coke is used in the Netherlands for production of pigments, with 30% being stored long-term. EIA defines "miscellaneous products" as "all finished products not classified elsewhere (e.g., petrolatum, lube refining byproducts (aromatic extracts and tars), absorption oils, ram-jet fuel, petroleum rocket fuels, synthetic natural gas feedstocks, and specialty oils)." All of these uses are emissive, and therefore the storage factor for miscellaneous products is set at zero (EIA 20010b). The "other petroleum" category is reported by U.S. territories and accounts mostly for the same products as miscellaneous products, but probably also includes some asphalt, known to be non-emissive. The exact amount of asphalt or any of the other miscellaneous products is confidential business information, but based on judgment the storage factor for this category was estimated at 0.1.

For all these fuel types, the overall methodology simply involves multiplying C content by a storage factor, yielding an estimate of the mass of C stored. To provide a complete analysis of uncertainty for the entire NEU subcategory, the uncertainty around the estimate of "other" NEUs was characterized, as discussed below.

Uncertainty

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the weighted average of the remaining fuels' C storage factors and the total quantity of C emitted from these other fuels in 2009. A Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the Inventory estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for some of the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. A uniform distribution was applied to coking coal consumption, while the remaining consumption inputs were assumed to be normally distributed. The C content coefficients were assumed to have a uniform distribution; the greatest uncertainty range of 10 percent (±10%) around the inventory value, was applied to coking coal and miscellaneous products. C coefficients for distillate fuel oil ranged from 18.5 to 21.1 Tg C/QBtu. The fuel-specific storage factors were assigned wide triangular distributions indicating greater uncertainty.

The Monte Carlo analysis produced a storage factor distribution with 95 percent confidence limits of 16 percent and 66 percent, with a mean of 39 percent. This compares to the Inventory calculation of weighted average (across the various fuels) storage factor of about 17 percent. The analysis produced an emission distribution, with the 95 percent confidence limit of 10.3 Tg CO_2 Eq. and 27.0 Tg CO_2 Eq., and a mean of 18.9 Tg CO_2 Eq.. This compares with the Inventory estimate of 25.7 Tg CO_2 Eq., which falls closer to the upper boundary of the 95 percent confidence limit. The uncertainty analysis results are driven primarily by the very broad uncertainty inputs for the storage factors.

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U.S. International Trade Commission (1990-2011) "Interactive Tariff and Trade DataWeb: Quick Query." Available online at: http://dataweb.usitc.gov/ Accessed January 2011.

Vallianos, Jean (2011) Personal communication between Joe Indvik of ICF International and Jean Vallianos of the American Chemistry Council, 4 January 2011.

Figure A-1: Carbon Content for Samples of Pipeline-Quality Natural Gas Included in the Gas Technology Institute Database
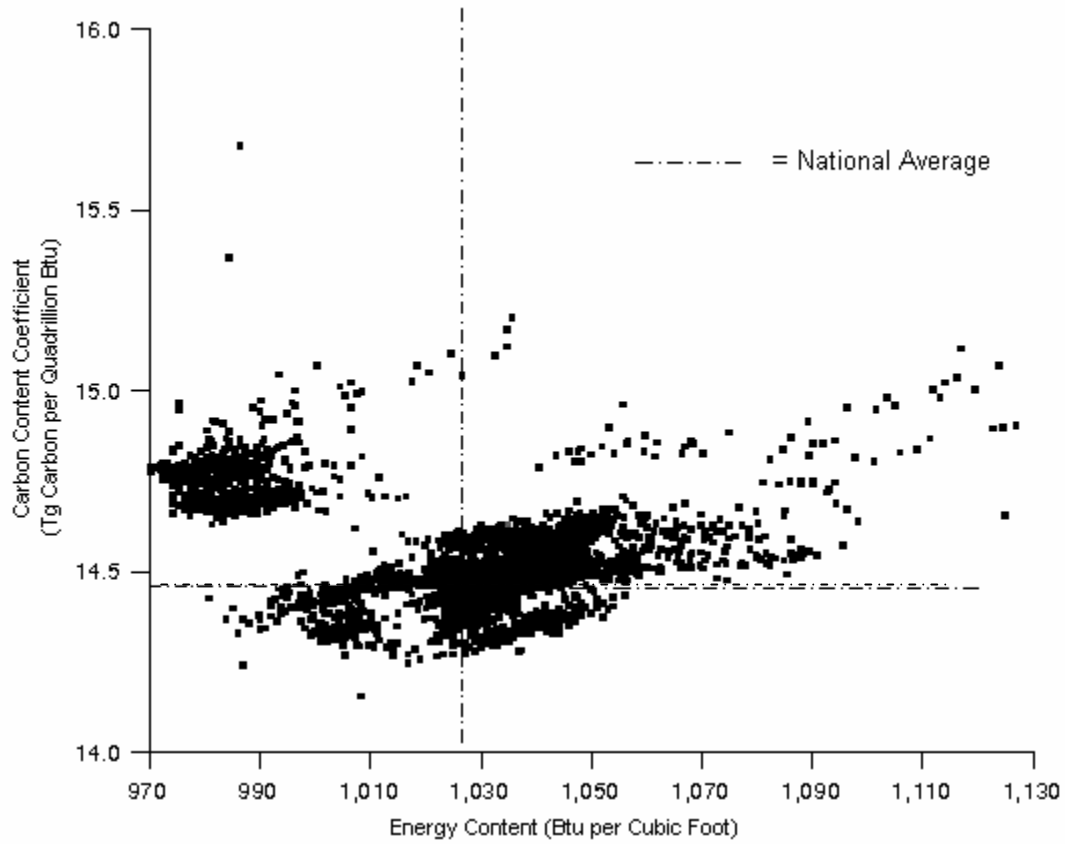
Source: EIA (1994) Energy Information Administration, Emissions of Greenhouse Gases in the United States 1987-1992, U.S. Department of Energy, Washington, DC, November, 1994, DOE/EIA 0573, Appendix A.

Figure A-2: Estimated and Actual Relationships Between Petroleum Carbon Content Coefficients and Hydrocarbon Density
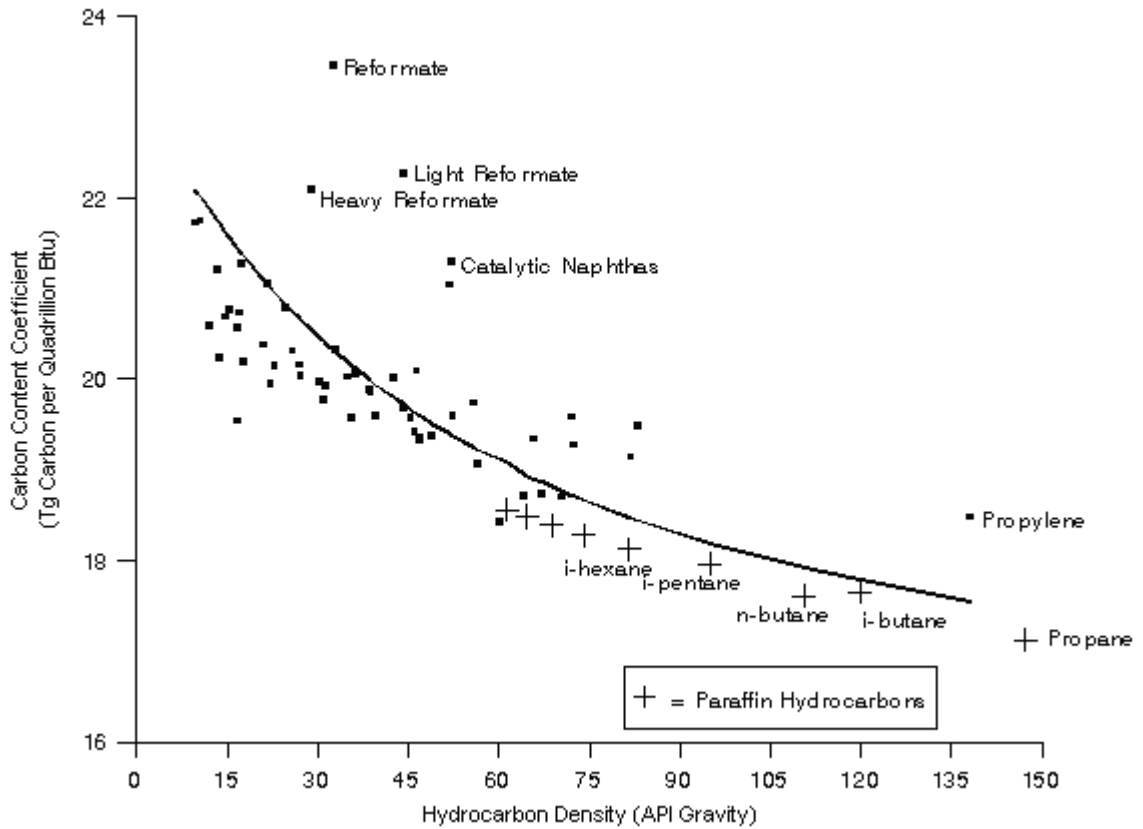
Source: Carbon content factors for paraffins are calculated based on the properties of hydrocarbons in V. Guthrie (ed.), *Petroleum Products Handbook* (New York: McGraw Hill, 1960) p. 33. Carbon content factors from other petroleum products are drawn from sources described below. Relationship between density and emission factors based on the relationship between density and energy content in U.S. Department of Commerce, National Bureau of Standards, *Thermal Properties of Petroleum Products*, Miscellaneous Publication, No. 97 (Washington, D.C., 1929), pp.16-21, and relationship between energy content and fuel composition in S. Ringen, J. Lanum, and F.P. Miknis, "Calculating Heating Values from the Elemental Composition of Fossil Fuels,' *Fuel,* Vol. 58 (January 1979), p.69.

Figure A-3: Carbon Content of Pure Hydrocarbons as a Function of Carbon Number
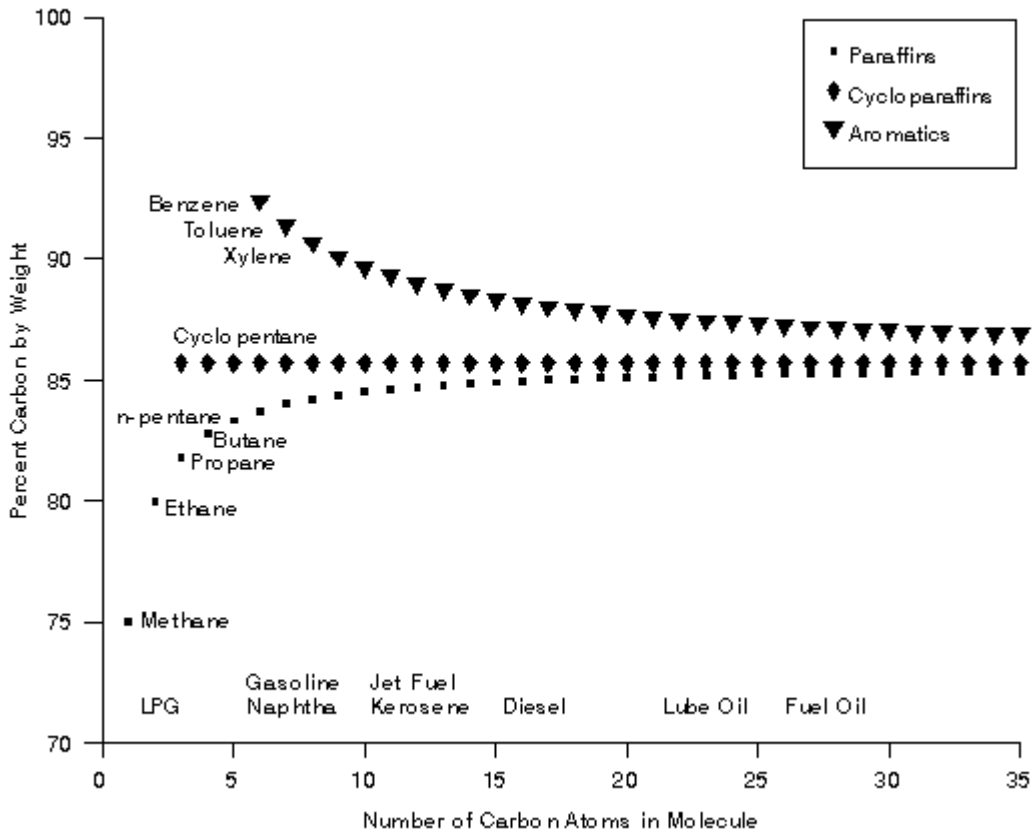
Source: J.M. Hunt, *Petroleum Geochemistry and Geology* (San Francisco, CA, W.H. Freeman and Company, 1979), pp. 31-37.

ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories

3.1. Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Stationary Combustion

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 A-81 through Table A-85.

Step 1: Determine Energy Consumption by Sector and Fuel Type

Energy consumption from stationary combustion activities was grouped by sector: industrial, commercial, residential, electric power, and U.S. territories. For CH_4 and N_2O, estimates were based upon consumption of coal, gas, oil, and wood. Energy consumption data for the United States were obtained from EIA's *Monthly Energy Review, January 2010* and Published Supplemental Tables on Petroleum Product detail (EIA 2011). Wood consumption data for the United States was obtained from EIA's *Annual Energy Review* (EIA 2010). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were collected separately from the EIA from Jacobs (2010).[34] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[35] Construction and agricultural fuel use was obtained from EPA (2010). The energy consumption data by sector were then adjusted from higher to lower heating values by multiplying by 0.9 for natural gas and wood and by 0.95 for coal and petroleum fuel. This is a simplified convention used by the International Energy Agency. Table A-81 provides annual energy consumption data for the years 1990 through 2009.

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 emission estimates. Emission factors for the residential, commercial, industrial, and electric power sectors were taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). These N_2O emission factors by fuel type (consistent across sectors) were also assumed for U.S. territories. The CH_4 emission factors by fuel type for U.S. territories were estimated based on the emission factor for the primary sector in which each fuel was combusted. Table A-82 provides emission factors used for each sector and fuel type.

Estimates of NO_x, CO, and NMVOC Emissions

Emissions estimates for NO_x, CO, and NMVOCs were obtained from preliminary data (EPA 2010b, EPA 2009) and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site.

For indirect greenhouse gases, the major source categories included 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 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. The national activity data used to calculate the individual categories were obtained from various sources. Depending upon the category, these activity data may include

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[34] U.S. territories data also include combustion from mobile activities because data to allocate territories' energy use were unavailable. For this reason, CH_4 and N_2O emissions from combustion by U.S. Territories are only included in the stationary combustion totals.

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

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 A-83 through Table A-85 present indirect greenhouse gas emission estimates for 1990 through 2008.

The basic calculation procedure for most source categories presented in EPA (2003) and EPA (2009) 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 A-81: Fuel Consumption by Stationary Combustion for Calculating CH$_4$ and N$_2$O Emissions (TBtu)

Fuel/End-Use Sector	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Coal	**18,064**	**19,138**	**20,032**	**20,517**	**20,802**	**20,779**	**21,682**	**21,085**	**21,139**	**21,562**	**21,713**	**22,095**	**21,758**	**22,062**	**21,709**	**19,283**
Residential	31	17	17	16	12	14	11	12	12	12	11	8	6	8	8	7
Commercial	124	117	122	129	93	103	92	97	90	82	103	97	65	70	69	61
Industrial	1,640	1,527	1,455	1,457	1,471	1,373	1,349	1,358	1,244	1,249	1,262	1,219	1,188	1,130	1,083	881
Electric Power	16,261	17,466	18,429	18,905	19,216	19,279	20,220	19,614	19,783	20,185	20,305	20,737	20,462	20,808	20,513	18,296
U.S. Territories	7	10	10	10	11	10	10	4	11	34	32	33	37	47	36	38
Petroleum	**6,749**	**5,425**	**5,933**	**5,879**	**5,697**	**5,844**	**6,047**	**6,657**	**5,978**	**6,630**	**6,881**	**6,812**	**6,413**	**6,217**	**5,439**	**4,994**
Residential	1,375	1,261	1,397	1,334	1,207	1,342	1,427	1,463	1,359	1,466	1,475	1,369	1,205	1,225	1,215	1,197
Commercial	891	694	718	655	609	614	694	719	645	762	767	716	678	681	669	708
Industrial	2,818	2,254	2,566	2,519	2,129	2,216	2,310	2,567	2,456	2,576	2,774	2,869	3,261	3,103	2,609	2,195
Electric Power	1,289	755	817	927	1,306	1,211	1,144	1,277	961	1,205	1,212	1,235	648	657	468	390
U.S. Territories	375	462	435	445	445	461	472	632	557	622	654	623	621	552	479	504
Natural Gas	**18,202**	**21,088**	**21,492**	**21,556**	**21,230**	**21,254**	**22,281**	**21,400**	**22,129**	**21,550**	**21,604**	**21,243**	**20,904**	**22,315**	**22,436**	**21,974**
Residential	4,491	4,954	5,354	5,093	4,646	4,835	5,105	4,889	5,014	5,209	4,981	4,946	4,476	4,850	4,989	4,852
Commercial	2,682	3,096	3,226	3,285	3,083	3,115	3,252	3,097	3,225	3,261	3,201	3,073	2,902	3,094	3,211	3,168
Industrial	7,721	8,736	9,049	9,052	8,827	8,402	8,619	7,933	8,100	7,806	7,802	7,185	7,125	7,340	7,378	6,887
Electric Power	3,309	4,302	3,862	4,126	4,675	4,902	5,293	5,458	5,767	5,246	5,595	6,015	6,375	7,005	6,829	7,038
U.S. Territories	0	0	0	0	0	0	13	23	23	27	25	24	26	27	29	27
Wood	**2,216**	**2,370**	**2,437**	**2,371**	**2,184**	**2,214**	**2,262**	**2,006**	**1,995**	**2,002**	**2,121**	**2,136**	**2,109**	**2,098**	**2,044**	**1,891**
Residential	580	520	540	430	380	390	420	370	380	400	410	430	390	430	450	430
Commercial	66	72	76	73	64	67	71	67	69	71	70	70	65	69	73	72
Industrial	1,442	1,652	1,683	1,731	1,603	1,620	1,636	1,443	1,396	1,363	1,476	1,452	1,472	1,413	1,344	1,217
Electric Power	129	125	138	137	137	138	134	126	150	167	165	185	182	186	177	173
U.S. Territories	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Table A-82: CH₄ and N₂O Emission Factors by Fuel Type and Sector (g/GJ) [36]

Fuel/End-Use Sector	CH₄	N₂O
Coal		
Residential	300	1.5
Commercial	10	1.5
Industrial	10	1.5
Electric Power	1	1.5
U.S. Territories	1	1.5
Petroleum		
Residential	10	0.6
Commercial	10	0.6
Industrial	3	0.6
Electric Power	3	0.6
U.S. Territories	5	0.6
Natural Gas		
Residential	5	0.1
Commercial	5	0.1
Industrial	1	0.1
Electric Power	1	0.1
U.S. Territories	1	0.1
Wood		
Residential	300	4.0
Commercial	300	4.0
Industrial	30	4.0
Electric Power	30	4.0
U.S. Territories	NA	NA

NA (Not Applicable)

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[36] GJ (Gigajoule) = 10^9 joules. One joule = 9.486×10^{-4} Btu

Table A-83: NOx Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Electric Power	**6,045**	**5,792**	**5,581**	**5,683**	**5,637**	**5,183**	**4,829**	**4,453**	**4,265**	**3,988**	**3,711**	**3,434**	**3,121**	**3,007**	**2,722**	**1,766**
Coal	5,119	5,061	5,079	5,118	4,932	4,437	4,130	3,802	3,634	3,398	3,162	2,926	2,659	2,562	2,319	1,505
Fuel Oil	200	87	107	131	202	179	147	149	142	133	124	114	104	100	91	59
Natural gas	513	510	248	277	329	393	376	325	310	290	270	250	227	219	198	128
Wood	NA	NA	5	6	24	33	36	37	36	33	31	29	26	25	23	15
Other Fuels[a]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Internal Combustion	213	134	142	150	149	141	140	140	143	134	124	115	105	101	91	59
Industrial	**2,559**	**2,650**	**2,666**	**2,614**	**2,570**	**2,283**	**2,278**	**2,296**	**1,699**	**1,638**	**1,577**	**1,515**	**1,520**	**1,525**	**1,530**	**1,478**
Coal	530	541	490	487	475	475	484	518	384	370	356	342	343	344	345	334
Fuel Oil	240	224	203	196	190	190	166	153	114	110	105	101	102	102	102	99
Natural gas	877	999	900	880	869	706	710	711	526	507	488	469	471	472	474	458
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	119	111	109	103	104	100	109	116	86	82	79	76	77	77	77	74
Internal Combustion	792	774	965	948	932	813	809	798	591	569	548	527	528	530	532	514
Commercial	**671**	**607**	**734**	**539**	**510**	**483**	**507**	**428**	**438**	**456**	**473**	**490**	**486**	**483**	**479**	**501**
Coal	36	35	30	32	34	23	21	21	19	19	19	19	19	19	19	19
Fuel Oil	88	94	86	88	73	54	52	52	50	49	49	49	49	49	49	49
Natural gas	181	210	224	229	220	156	161	165	157	156	156	155	155	155	154	154
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	366	269	394	191	183	249	273	189	213	231	249	267	263	261	257	280
Residential	**749**	**813**	**726**	**699**	**651**	**441**	**439**	**446**	**423**	**421**	**420**	**418**	**417**	**417**	**416**	**414**
Coal[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel Oil[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	42	44	27	27	27	25	21	22	21	21	21	20	20	20	20	20
Other Fuels[a]	707	769	699	671	624	416	417	424	402	400	399	397	397	396	396	394
Total	**10,023**	**9,862**	**9,707**	**9,534**	**9,369**	**8,390**	**8,053**	**7,623**	**6,825**	**6,503**	**6,181**	**5,858**	**5,545**	**5,432**	**5,148**	**4,159**

NA (Not Applicable)

[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2003, 2009, 2010b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2003, 2009, 2010b).

Note: Totals may not sum due to independent rounding.

Table A-84: CO Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Electric Power	**329**	**337**	**369**	**385**	**410**	**450**	**439**	**439**	**595**	**590**	**586**	**582**	**598**	**616**	**633**	**631**
Coal	213	227	228	233	220	187	221	220	298	296	293	292	300	308	317	316
Fuel Oil	18	9	11	13	17	36	27	28	38	37	37	37	38	39	40	40
Natural gas	46	49	72	76	88	150	96	92	125	124	123	122	126	129	133	132
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	7	8	30	24	31	32	44	43	43	43	44	45	46	46
Internal Combustion	52	52	52	54	55	52	63	67	91	90	89	89	91	94	97	96
Industrial	**797**	**958**	**1,078**	**1,054**	**1,044**	**1,100**	**1,106**	**1,137**	**1,149**	**1,115**	**1,080**	**1,045**	**1,064**	**1,084**	**1,103**	**1,030**
Coal	95	88	100	99	96	114	118	125	127	123	119	115	117	119	121	113

	1990		1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Fuel Oil	67		64	49	47	46	54	48	45	46	44	43	42	42	43	44	41
Natural gas	205		313	307	307	305	350	355	366	370	359	347	336	342	349	355	331
Wood	NA		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	253		270	316	302	303	286	300	321	325	315	305	296	301	307	312	291
Internal Combustion	177		222	305	299	294	296	285	279	282	274	265	257	261	266	271	253
Commercial	**205**		**211**	**122**	**126**	**122**	**151**	**151**	**154**	**177**	**173**	**169**	**166**	**166**	**167**	**168**	**158**
Coal	13		14	13	13	14	16	14	13	15	15	15	14	15	15	15	14
Fuel Oil	16		17	17	18	15	17	17	17	20	19	19	19	19	19	19	18
Natural gas	40		49	58	59	57	81	83	84	97	95	93	91	91	92	92	87
Wood	NA		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	136		132	34	36	36	36	36	38	44	43	42	41	42	42	42	40
Residential	**3,668**		**3,877**	**2,364**	**2,361**	**2,352**	**3,323**	**2,644**	**2,648**	**3,044**	**2,981**	**2,919**	**2,856**	**2,867**	**2,878**	**2,889**	**2,725**
Coal[b]	NA		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel Oil[b]	NA		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	3,430		3,629	2,133	2,133	2,133	3,094	2,416	2,424	2,787	2,730	2,672	2,615	2,624	2,635	2,645	2,495
Other Fuels[a]	238		248	231	229	220	229	228	224	257	252	246	241	242	243	244	230
Total	**5,000**		**5,383**	**3,934**	**3,926**	**3,928**	**5,024**	**4,340**	**4,377**	**4,965**	**4,860**	**4,753**	**4,649**	**4,695**	**4,744**	**4,792**	**4,543**

NA (Not Applicable)

[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2003, 2009, 2010b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2003, 2009, 2010b).

Note: Totals may not sum due to independent rounding.

Table A-85: NMVOC Emissions from Stationary Combustion (Gg)

Sector/Fuel Type	1990		1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Electric Power	**43**		**40**	**44**	**47**	**51**	**49**	**56**	**55**	**44**	**44**	**44**	**44**	**44**	**45**	**45**	**46**
Coal	24		26	25	26	26	25	27	26	21	21	21	21	21	22	22	22
Fuel Oil	5		2	3	4	5	4	4	4	4	4	4	3	4	4	4	4
Natural gas	2		2	7	7	9	9	12	12	10	10	10	10	10	10	10	10
Wood	NA		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA		NA	+	+	1	2	2	2	1	1	1	1	1	1	1	1
Internal Combustion	11		9	9	10	10	10	11	11	8	8	8	8	8	9	9	9
Industrial	**165**		**187**	**163**	**160**	**159**	**156**	**157**	**160**	**138**	**132**	**126**	**121**	**120**	**119**	**118**	**110**
Coal	7		5	6	6	6	9	9	10	9	9	8	8	8	8	8	7
Fuel Oil	11		11	8	7	7	10	9	9	7	7	7	6	6	6	6	6
Natural gas	52		66	54	54	54	52	53	54	47	45	43	41	41	40	40	37
Wood	NA		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	46		45	33	31	31	26	27	29	25	24	23	22	22	22	22	20
Internal Combustion	49		60	63	62	61	60	58	57	49	47	45	43	43	42	42	39
Commercial	**18**		**21**	**22**	**22**	**21**	**25**	**28**	**29**	**61**	**53**	**45**	**33**	**36**	**38**	**40**	**23**
Coal	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	+
Fuel Oil	3		3	3	3	3	3	4	4	6	5	3	2	3	4	5	1

Natural gas	7		10	13	13	12	11	14	14	23	18	14	9	12	16	19	4
Wood	NA		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	8		8	5	5	5	10	9	10	31	29	27	22	19	17	15	18
Residential	**686**		**725**	**788**	**788**	**786**	**815**	**837**	**837**	**1,341**	**1,066**	**792**	**519**	**719**	**918**	**1,117**	**244**
Coal[b]	NA		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel Oil[b]	NA		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	651		688	756	757	756	794	809	809	1,298	1,032	767	502	695	888	1,081	236
Other Fuels[a]	35		37	33	32	30	21	27	27	43	35	26	17	23	30	36	8
Total	**912**		**973**	**1,018**	**1,017**	**1,016**	**1,045**	**1,077**	**1,081**	**1,585**	**1,296**	**1,008**	**716**	**918**	**1,120**	**1,321**	**424**

NA (Not Applicable)

+ Does not exceed 1 Gg.

[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2003, 2009, 2010b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2003, 2009, 2010b).

Note: Totals may not sum due to independent rounding.

3.2. Methodology for Estimating Emissions of CH₄, N₂O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related GHG Emissions

Estimating CO₂ Emissions by Transportation Mode

Transportation-related CO_2 emissions, as presented in the Carbon Dioxide Emissions from Fossil Fuel Combustion section of the Energy chapter, were calculated using the methodology described in Annex 2.1. This section provides additional information on the data sources and approach used for each transportation fuel type. As noted in Annex 2.1, CO_2 emissions estimates for the transportation sector were calculated directly for on-road diesel fuel and motor gasoline based on data sources for individual modes of transportation (considered a "bottom up" approach). For most other fuel and energy types (i.e., jet fuel, aviation gasoline, residual fuel oil, natural gas, LPG, and electricity), CO_2 emissions were calculated based on transportation sector-wide fuel consumption estimates from the Energy Information Administration (EIA 2007b and EIA 2007 through 2009) and apportioned to individual modes (considered a "top down" approach).

Based on interagency discussions between EPA, EIA, and FHWA beginning in 2005, it was agreed that use of "bottom up" data would be more accurate for diesel fuel and motor gasoline, based on the availability of reliable transportation-specific data sources. A "bottom up" diesel calculation was implemented in the 1990-2005 Inventory, and a bottom-up gasoline calculation was introduced in the 1990-2006 Inventory for the calculation of emissions from on-road vehicles. Motor gasoline and diesel consumption data for on-road vehicles come from FHWA's *Highway Statistics*, Table VM-1 (FHWA 1996 through 2009), and are based on federal and state fuel tax records. These fuel consumption estimates were then combined with estimates of fuel shares by vehicle type from DOE's Transportation Energy Data Book (DOE 1993 through 2009) to develop an estimate of fuel consumption for each vehicle type (i.e., passenger cars, light-duty trucks, buses, medium- and heavy-duty trucks, motorcycles). The on-road gas and diesel fuel consumption estimates by vehicle type were then adjusted for each year so that the sum of gasoline and diesel fuel consumption across all vehicle categories matched the fuel consumption estimates in *Highway Statistics'* Tables MF-21 and MF-27 (FHWA 1996 through 2010). Table MF-21 provided fuel consumption estimates for the most current Inventory year; Table MF-27 provided fuel consumption estimates for years 1990-2008. This resulted in a final estimate of motor gasoline and diesel fuel use by vehicle type, consistent with the FHWA total for on-road motor gasoline and diesel fuel use.

Estimates of diesel fuel consumption from rail were taken from the Association of American Railroads (AAR 2008 through 2010) for Class I railroads, the American Public Transportation Association (APTA 2007 through 2010 and APTA 2006) and Gaffney (2007) for commuter rail, the Upper Great Plains Transportation Institute (Benson 2002 through 2004) and Whorton (2006 through 2009) for Class II and III railroads, and DOE's *Transportation Energy Data Book* (DOE 1993 through 2010) for passenger rail. Estimates of diesel from ships and boats were taken from EIA's *Fuel Oil and Kerosene Sales* (1991 through 2011).

Since EIA's total fuel consumption estimate for each fuel type is considered to be accurate at the national level, adjustments needed to be made in the estimates for other sectors to equal the EIA total. In the case of motor gasoline, estimates of fuel use by recreational boats come from EPA's NONROAD Model (EPA 2010b), and these estimates along with those from other sectors (e.g., commercial sector, industrial sector) were adjusted. Similarly, to ensure consistency with EIA's total diesel estimate for all sectors, the diesel consumption totals for the residential, commercial, and industrial sectors were adjusted downward proportionately.

As noted above, for fuels other than motor gasoline and diesel, EIA's transportation sector total was apportioned to specific transportation sources. For jet fuel, estimates come from: DOT (1991 through 2010) and FAA (2011, 2006) for commercial aircraft, FAA (2009) for general aviation aircraft, and DESC (2008) for military aircraft. Estimates for biofuels, including ethanol and biodiesel were discussed separately and were not apportioned to specific transportation sources. Consumption estimates for biofuels were calculated based on data from the Energy Information Administration (EIA2010b).

Table A-86 displays estimated fuel consumption by fuel and vehicle type. Table A-87 displays estimated energy consumption by fuel and vehicle type. The values in both of these tables correspond to the figures used to calculate CO_2 emissions from transportation. Except as noted above, they are estimated based on EIA transportation sector energy estimates by fuel type, with activity data used to apportion consumption to the various modes of transport. For motor gasoline, the figures do not include ethanol blended with gasoline; although ethanol is included in FHWA's totals for reported motor gasoline use. Ethanol is a biofuel and in order to be in line with IPCC methodological guidance and

UNFCCC reporting obligations, net carbon fluxes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change and Forestry chapter, not in Energy chapter totals. Ethanol and biodiesel consumption estimates are shown separately in Table A-88.

Table A-86. Fuel Consumption by Fuel and Vehicle Type (million gallons unless otherwise specified)[a]

Fuel/Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009
Motor Gasoline[b]	**110,440.9**	**118,216.0**	**129,101.8**	**137,294.2**	**132,944.7**	**132,543.8**	**127,524.7**	**127,012.2**
Passenger Cars	69,762.4	67,948.0	72,859.7	76,059.6	71,645.8	70,548.0	67,022.7	66,945.0
Light-Duty Trucks	34,698.4	44,369.3	50,773.8	55,336.4	55,459.3	56,117.9	54,889.7	54,826.0
Motorcycles	194.0	200.3	209.8	183.4	212.2	230.9	241.5	241.2
Buses	38.9	41.7	43.6	41.9	41.7	43.6	42.8	38.9
Medium- and Heavy- Duty Trucks	4,349.8	4,071.6	4,095.5	3,960.1	4,008.3	4,046.5	3,803.7	3,454.2
Recreational Boats[c]	1,397.3	1,585.1	1,119.3	1,597.9	1,577.4	1,556.9	1,524.2	1,506.8
Distillate Fuel Oil (Diesel Fuel)	**25,631.2**	**31,604.6**	**39,241.4**	**44,659.2**	**45,847.6**	**46,432.3**	**43,236.5**	**39,243.4**
Passenger Cars	771.2	764.9	356.1	414.0	403.2	399.7	382.4	380.2
Light-Duty Trucks	1,118.5	1,452.0	1,960.6	2,518.4	2,609.9	2,658.5	2,618.5	2,603.2
Buses	781.0	851.1	996.6	1,030.1	1,048.5	1,048.5	1,007.3	910.4
Medium- and Heavy- Duty Trucks	18,574.2	23,240.7	30,179.9	35,160.0	36,078.5	36,665.4	34,706.1	31,368.6
Recreational Boats	190.4	228.1	265.6	305.4	313.4	321.4	87.8	337.5
Ships and Other Boats	735.3	1,204.3	1,376.8	785.3	729.5	799.8	218.4	118.8
Rail	3,460.6	3,863.5	4,105.9	4,446.1	4,664.5	4,538.9	4,216.0	3,524.8
Jet Fuel[d]	**18,349.7**	**17,850.3**	**20,491.9**	19,919.9	**17,386.1**	**17,305.8**	**15,906.2**	**14,239.3**
Commercial Aircraft	14,103.4	14,795.9	17,352.8	16,532.7	14,065.0	14,163.9	12,533.8	11,425.1
General Aviation Aircraft	662.9	559.8	972.0	1,526.7	1,642.6	1,485.6	1,705.7	1,364.3
Military Aircraft	3,583.4	2,494.6	2,167.1	1,860.5	1,678.5	1,656.3	1,666.8	1,449.9
Aviation Gasoline[d]	**374.2**	**329.3**	**301.9**	**294.2**	**278.3**	**262.8**	**235.3**	**221.0**
General Aviation Aircraft	374.2	329.3	301.9	294.2	278.3	262.8	235.3	221.0
Residual Fuel Oil[d, e]	**2,006.2**	**2,587.4**	**2,962.5**	1,713.1	**2,046.3**	**2,579.4**	**1,770.5**	**1,064.8**
Ships and Other Boats	2,006.2	2,587.4	2,962.5	1,713.1	2,046.3	2,579.4	1,770.5	1,064.8
Natural Gas[d] (million cubic feet)	**0.7**	**0.7**	**0.7**	**0.6**	**0.6**	**0.6**	**0.7**	**0.7**
Passenger Cars	-	+	-	-	-	-	-	-
Light-Duty Trucks	-	+	-	-	-	-	-	-
Buses	-	+	+	+	+	+	+	+
Pipelines	0.7	0.7	0.6	0.6	0.6	0.6	0.7	0.6
LPG[d]	**265.2**	**205.5**	**138.4**	**308.7**	**320.0**	**256.7**	**459.5**	**487.5**
Buses	-	1.6	1.5	1.0	1.0	-	-	-
Light-Duty Trucks	106.1	98.3	88.0	233.2	229.5	184.7	334.0	354.3
Medium- and Heavy- Duty Trucks	159.1	105.6	48.8	74.6	89.5	72.0	125.5	133.2
Electricity[d]	**4,751.2**	**4,974.5**	**5,381.9**	**7,506.4**	**7,357.6**	**8,172.6**	**7,699.6**	**7,688.5**
Rail	4,751.2	4,974.5	5,381.9	7,506.4	7,357.6	8,172.6	7,699.6	7,688.5

[a] FHWA data on vehicle miles traveled from the VM-1 table were not available for 2009 due to a delay caused by changes in data collection procedures. Based on data from FHWA's Traffic Volume Trends Program, the overall increase in VMT between 2008 and 2009 was estimated to be 0.2%. Total VMT was distributed among vehicle classes based on trends in fuel consumption by fuel type between 2008 and 2009, as described below.

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

[b] Figures do not include ethanol blended in motor gasoline. Net carbon fluxes associated with ethanol are accounted for in the Land Use, Land-Use Change and Forestry chapter.

[c] Fluctuations in recreational boat gasoline estimates reflect the use of this category to reconcile bottom-up values with EIA total gasoline estimates.

[d] Estimated based on EIA transportation sector energy estimates by fuel type, with bottom-up activity data used for apportionment to modes.

[e] Fluctuations in reported fuel consumption may reflect data collection problems.

\+ Less than 0.05 million gallons or 0.05 million cubic feet

\- Unreported or zero

Table A-87: Energy Consumption by Fuel and Vehicle Type (Tbtu)

Fuel/Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009

	1990	1995	2000	2005	2006	2007	2008	2009
Motor Gasoline[b]	**13,813.0**	**14,678.5**	**16,014.8**	**16,729.6**	**16,516.8**	**16,470.1**	**15,843.4**	**15,779.7**
Passenger Cars	8,725.3	8,436.9	9,038.1	9,268.0	8,901.1	8,766.4	8,326.8	8,317.1
Light-Duty Trucks	4,339.8	5,509.2	6,298.4	6,742.8	6,890.2	6,973.3	6,819.4	6,811.5
Motorcycles	24.3	24.9	26.0	22.8	26.4	28.7	30.0	30.0
Buses	4.9	5.2	5.4	5.1	5.2	5.4	5.3	4.8
Medium- and Heavy- Duty Trucks	544.0	505.6	508.0	492.2	498.0	502.8	472.6	429.1
Recreational Boats[c]	174.8	196.8	138.8	198.6	196.0	193.5	189.4	187.2
Distillate Fuel Oil (Diesel Fuel)	**3,554.8**	**4,383.3**	**5,442.4**	**6,193.8**	**6,358.6**	**6,439.7**	**5,996.5**	**5,442.7**
Passenger Cars	107.0	106.1	49.4	57.4	55.9	55.4	53.0	52.7
Light-Duty Trucks	155.1	201.4	271.9	349.3	362.0	368.7	363.2	361.0
Buses	108.3	118.0	138.2	142.9	145.4	145.4	139.7	126.3
Medium- and Heavy- Duty Trucks	2,576.1	3,223.3	4,185.7	4,876.4	5,003.7	5,085.1	4,813.4	4,350.5
Recreational Boats	26.4	31.6	36.8	42.4	43.5	44.6	12.2	46.8
Ships and Other Boats	102.0	167.0	190.9	108.9	101.2	110.9	30.3	16.5
Rail	480.0	535.8	569.4	616.6	646.9	629.5	584.7	488.9
Jet Fuel[c]	**2,477.2**	**2,409.8**	**2,766.4**	**2,689.2**	**2,347.1**	**2,336.3**	**2,147.3**	**1,922.3**
Commercial Aircraft	1,904.0	1,997.4	2,342.6	2,231.9	1,898.8	1,912.1	1,692.1	1,542.4
General Aviation Aircraft	89.5	75.6	131.2	206.1	221.8	200.6	230.3	184.2
Military Aircraft	483.8	336.8	292.6	251.2	226.6	223.6	225.0	195.7
Aviation Gasoline[d]	**45.0**	**39.6**	**36.3**	**35.4**	**33.4**	**31.6**	**28.3**	**26.6**
General Aviation Aircraft	45.0	39.6	36.3	35.4	33.4	31.6	28.3	26.6
Residual Fuel Oil[d, e]	**300.3**	**387.3**	**443.5**	**256.4**	**306.3**	**386.1**	**265.0**	**159.4**
Ships and Other Boats	300.3	387.3	443.5	256.4	306.3	386.1	265.0	159.4
Natural Gas[d]	**679.9**	**724.0**	**672.0**	**623.9**	**625.0**	**665.4**	**694.5**	**684.2**
Passenger Cars	-	1.9	-	-	-	-	-	-
Light-Duty Trucks	-	0.1	-	-	-	-	-	-
Buses	-	1.0	8.3	15.8	15.5	18.6	20.7	20.8
Pipelines	679.9	721.0	663.7	608.1	609.4	646.8	673.8	663.5
LPG[d]	**22.9**	**17.7**	**11.9**	**28.2**	**27.5**	**21.9**	**39.4**	**41.2**
Buses	-	0.1	0.1	0.1	0.1	-	-	-
Light-Duty Trucks	9.2	8.5	7.6	21.3	19.7	15.8	28.6	30.0
Medium- and Heavy- Duty Trucks	13.7	9.1	4.2	6.8	7.7	6.2	10.8	11.3
Electricity[d]	**16.2**	**17.0**	**18.4**	**25.6**	**25.1**	**27.9**	**26.1**	**26.1**
Rail	16.2	17.0	18.4	25.6	25.1	27.9	26.1	26.1
Total	**20,909.3**	**22,657.1**	**25,405.6**	**26,582.1**	**26,239.8**	**26,379.1**	**25,040.5**	**24,082.3**

[a] FHWA data on vehicle miles traveled from the VM-1 table were not available for 2009 due to a delay caused by changes in data collection procedures. Based on data from FHWA's Traffic Volume Trends Program, the overall increase in VMT between 2008 and 2009 was estimated to be 0.2%. Total VMT was distributed among vehicle classes based on trends in fuel consumption by fuel type between 2008 and 2009, as described below.

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

[b] Figures do not include ethanol blended in motor gasoline. Net carbon fluxes associated with ethanol are accounted for in the Land Use, Land-Use Change and Forestry chapter.

[c] Fluctuations in recreational boat gasoline estimates reflect the use of this category to reconcile bottom-up values with EIA total gasoline estimates.

[d] Estimated based on EIA transportation sector energy estimates, with bottom-up data used for apportionment to modes

[e] Fluctuations in reported fuel consumption may reflect data collection problems.

- Unreported or zero

Table A-88. Biofuel Consumption by Fuel Type (million gallons)

Fuel Type	1990	1995	2000	2005	2006	2007	2008	2009
Ethanol	717.5	1,335.8	1,601.7	3,888.0	5,245.0	6,611.6	9,331.5	10,432.2
Biodiesel	NA	NA	NA	137.5	394.6	542.3	484.9	514.0

Estimates of CH$_4$ and N$_2$O Emissions

Mobile source emissions of greenhouse gases other than CO$_2$ are reported by transport mode (e.g., road, rail, aviation, and waterborne), vehicle type, and fuel type. Emissions estimates of CH$_4$ and N$_2$O were derived 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 agencies and other publications. Depending on the category, these basic activity data included fuel consumption and vehicle miles traveled (VMT). These estimates were then multiplied by emission factors, expressed as grams per unit of fuel consumed or per vehicle mile.

Methodology for On-Road Gasoline and Diesel Vehicles

Step 1: Determine Vehicle Miles Traveled by Vehicle Type, Fuel Type, and Model Year

VMT by vehicle type (e.g., passenger cars, light-duty trucks, medium- and heavy-duty trucks,[37] buses, and motorcycles) were obtained from the Federal Highway Administration's (FHWA) *Highway Statistics* (FHWA 1996 through 2009). As these vehicle categories are not fuel-specific, VMT for each vehicle type was disaggregated by fuel type (gasoline, diesel) so that the appropriate emission factors could be applied. VMT from *Highway Statistics* Table VM-1 (FHWA 1996 through 2009) was allocated to fuel types (gasoline, diesel, other) using historical estimates of fuel shares reported in the Appendix to the *Transportation Energy Data Book* (DOE 1993 through 2010). These fuel shares are drawn from various sources, including the Vehicle Inventory and Use Survey, the National Vehicle Population Profile, and the American Public Transportation Association. The fuel shares were first adjusted proportionately so that the gasoline and diesel shares for each vehicle type summed to 100 percent in order to develop an interim estimate of VMT for each vehicle/fuel type category that summed to the total national VMT estimate. VMT for alternative fuel vehicles (AFVs) was calculated separately, and the methodology is explained in the following section on AFVs. Estimates of VMT from AFVs were then subtracted from the appropriate interim VMT estimates to develop the final VMT estimates by vehicle/fuel type category.[38] The resulting national VMT estimates for gasoline and diesel on-road vehicles are presented in Table A-89 and Table A-90, respectively.

Total VMT for each on-road category (i.e., gasoline passenger cars, light-duty gasoline trucks, heavy-duty gasoline vehicles, diesel passenger cars, light-duty diesel trucks, medium- and heavy-duty diesel vehicles, and motorcycles) were distributed across 31 model years shown for 2009 in Table A-93. Distributions for 1990-2007 are presented in the Inventory Docket. This distribution was derived by weighting the appropriate age distribution of the U.S. vehicle fleet according to vehicle registrations by the average annual age-specific vehicle mileage accumulation of U.S. vehicles. Age distribution values were obtained from EPA's MOBILE6 model for all years before 1999 (EPA 2000) and EPA's MOVES model for years 1999 forward (EPA 2010a).[39] Age-specific vehicle mileage accumulation was obtained from EPA's MOBILE6 model (EPA 2000).

Step 2: Allocate VMT Data to Control Technology Type

VMT by vehicle type for each model year was distributed across various control technologies as shown in Table A-97 through Table A-100. The categories "EPA Tier 0" and "EPA Tier 1" were used instead of the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the *Revised 1996 IPCC Guidelines*. EPA Tier 0, EPA Tier 1, EPA Tier 2, and LEV refer to U.S. emission regulations, rather than control technologies; however, each does correspond to particular combinations of control technologies and engine design. EPA Tier 2 and its predecessors EPA Tier 1 and Tier 0 apply to vehicles equipped with three-way catalysts. The introduction of "early three-way catalysts," and "advanced three-way catalysts," as described in the *Revised 1996 IPCC Guidelines*, roughly correspond to the introduction of EPA Tier 0 and EPA Tier 1 regulations (EPA 1998).[40] EPA Tier 2 regulations affect vehicles produced starting in 2004 and are responsible for a noticeable decrease in N$_2$O emissions compared EPA Tier 1 emissions technology (EPA 1999b).

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[37] Medium-duty trucks include vehicles with a gross vehicle weight rating (GVWR) of 8,500 to 14,000 lbs. while heavy-duty trucks include those with a GVWR of over 14,000 lbs.

[38] In Inventories through 2002, gasoline-electric hybrid vehicles were considered part of an "alternative fuel and advanced technology" category. However, vehicles are now only separated into gasoline, diesel, or alternative fuel categories, and gas-electric hybrids are now considered within the gasoline vehicle category.

[39] Age distributions were held constant for the period 1990-1998, and reflect a 25-year vehicle age span. EPA (2010) provides a variable age distribution and 31-year vehicle age span beginning in year 1999.

[40] For further description, see "Definitions of Emission Control Technologies and Standards" section of this annex.

Control technology assignments for light and heavy-duty conventional fuel vehicles for model years 1972 (when regulations began to take effect) through 1995 were estimated in EPA (1998). Assignments for 1998 through 2007 were determined using confidential engine family sales data submitted to EPA (EPA 2007b). Vehicle classes and emission standard tiers to which each engine family was certified were taken from annual certification test results and data (EPA 2007a). This information was used to determine the fraction of sales of each class of vehicle that met EPA Tier 0, EPA Tier 1, Tier 2, and LEV standards. Assignments for 1996 and 1997 were estimated based on the fact that EPA Tier 1 standards for light-duty vehicles were fully phased in by 1996. Tier 2 began initial phase-in by 2004.

Step 3: Determine CH$_4$ and N$_2$O Emission Factors by Vehicle, Fuel, and Control Technology Type

Emission factors for gasoline and diesel on-road vehicles were developed by ICF (2004). These factors were based on EPA and CARB laboratory test results of different vehicle and control technology types. The EPA and CARB tests were designed following the Federal Test Procedure (FTP), which covers three separate driving segments, since vehicles emit varying amounts of GHGs depending on the driving segment. These driving segments are: (1) a transient driving cycle that includes cold start and running emissions, (2) a cycle that represents running emissions only, and (3) a transient driving cycle that includes hot start and running emissions. For each test run, a bag was affixed to the tailpipe of the vehicle and the exhaust was collected; the content of this bag was later analyzed to determine quantities of gases present. The emission characteristics of segment 2 was used to define running emissions, and subtracted from the total FTP emissions to determine start emissions. These were then recombined based upon MOBILE6.2's ratio of start to running emissions for each vehicle class to approximate average driving characteristics.

Step 4: Determine the Amount of CH$_4$ and N$_2$O Emitted by Vehicle, Fuel, and Control Technology Type

Emissions of CH$_4$ and N$_2$O were then calculated by multiplying total VMT by vehicle, fuel, and control technology type by the emission factors developed in Step 3.

Methodology for Alternative Fuel Vehicles (AFVs)

Step 1: Determine Vehicle Miles Traveled by Vehicle and Fuel Type

VMT for alternative fuel and advanced technology vehicles were calculated from "VMT Projections for Alternative Fueled and Advanced Technology Vehicles through 2025" (Browning 2003). Alternative Fuels include Compressed Natural Gas (CNG), Liquid Natural Gas (LNG), Liquefied Petroleum Gas (LPG), Ethanol, Methanol, and Electric Vehicles (battery powered). Most of the vehicles that use these fuels run on an Internal Combustion Engine (ICE) powered by the alternative fuel, although many of the vehicles can run on either the alternative fuel or gasoline (or diesel), or some combination.[41] The data obtained include vehicle fuel use and total number of vehicles in use from 1992 through 2007. Because AFVs run on different fuel types, their fuel use characteristics are not directly comparable. Accordingly, fuel economy for each vehicle type is expressed in gasoline equivalent terms, i.e., how much gasoline contains the equivalent amount of energy as the alternative fuel. Energy economy ratios (the ratio of the gasoline equivalent fuel economy of a given technology to that of conventional gasoline or diesel vehicles) were taken from full fuel cycle studies done for the California Air Resources Board (Unnasch and Browning, Kassoy 2001). These ratios were used to estimate fuel economy in miles per gasoline gallon equivalent for each alternative fuel and vehicle type. Energy use per fuel type was then divided among the various weight categories and vehicle technologies that use that fuel. Total VMT per vehicle type for each calendar year was then determined by dividing the energy usage by the fuel economy. Note that for AFVs capable of running on both/either traditional and alternative fuels, the VMT given reflects only those miles driven that were powered by the alternative fuel, as explained in Browning (2003). VMT estimates for AFVs by vehicle category (passenger car, light-duty truck, heavy-duty vehicles) are shown in Table A- 91, while more detailed estimates of VMT by control technology are shown in Table A- 92.

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[41] Fuel types used in combination depend on the vehicle class. For light-duty vehicles, gasoline is generally blended with ethanol or methanol; some vehicles are also designed to run on gasoline or an alternative fuel – either natural gas or LPG – but not at the same time, while other vehicles are designed to run on E85 (85% ethanol) or gasoline, or any mixture of the two. Heavy-duty vehicles are more likely to run on a combination of diesel fuel and either natural gas, LPG, ethanol, or methanol.

Step 2: Determine CH$_4$ and N$_2$O Emission Factors by Vehicle and Alternative Fuel Type

CH$_4$ and N$_2$O emission factors for alternative fuel vehicles (AFVs) are calculated according to studies by Argonne National Laboratory (2006) and Lipman & Delucchi (2002), and are reported in ICF (2006a). In these studies, N$_2$O and CH$_4$ emissions for AFVs were expressed as a multiplier corresponding to conventional vehicle counterpart emissions. Emission estimates in these studies represent the current AFV fleet and were compared against Tier 1 emissions from light-duty gasoline vehicles to develop new multipliers. Alternative fuel heavy-duty vehicles were compared against gasoline heavy-duty vehicles as most alternative fuel heavy-duty vehicles use catalytic after treatment and perform more like gasoline vehicles than diesel vehicles. These emission factors are shown in Table A- 102.

Step 3: Determine the Amount of CH$_4$ and N$_2$O Emitted by Vehicle and Fuel Type

Emissions of CH$_4$ and N$_2$O were calculated by multiplying total VMT for each vehicle and fuel type (Step 1) by the appropriate emission factors (Step 2).

Methodology for Non-Road Mobile Sources

CH$_4$ and N$_2$O emissions from non-road mobile sources were estimated by applying emission factors to the amount of fuel consumed by mode and vehicle type.

Activity data for non-road vehicles include annual fuel consumption statistics by transportation mode and fuel type, as shown in Table A- 96. Consumption data for ships and other boats (i.e., vessel bunkering) were obtained from DHS (2008) and EIA (1991 through 2011) for distillate fuel, and DHS (2008) and EIA (2007b) for residual fuel; marine transport fuel consumption data for U.S. territories (EIA 2008b, EIA 1991 through 2011) were added to domestic consumption, and this total was reduced by the amount of fuel used for international bunkers.[42] Gasoline consumption by recreational boats was obtained from EPA's NONROAD model (EPA 2010). Annual diesel consumption for Class I rail was obtained from the Association of American Railroads (AAR) (2008), diesel consumption from commuter rail was obtained from APTA (2007 through 2010) and Gaffney (2007), and consumption by Class II and III rail was provided by Benson (2002 through 2004) and Whorton (2006 through 2009). Diesel consumption by commuter and intercity rail was obtained from DOE (1993 through 2010). Data on the consumption of jet fuel and aviation gasoline in aircraft were obtained from EIA (2007b), as described in Annex 2.1: Methodology for Estimating Emissions of CO$_2$ from Fossil Fuel Combustion, and were reduced by the amount allocated to international bunker fuels. Pipeline fuel consumption was obtained from EIA (2007 through 2010) (note: pipelines are a transportation source but are stationary, not mobile, sources). Data on fuel consumption by all non-transportation mobile sources[43] were obtained from EPA's NONROAD model (EPA 2010) and from FHWA (1996 through 2010) for gasoline consumption for trucks used off-road.

Emissions of CH$_4$ and N$_2$O from non-road mobile sources 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 source type (see Table A- 103).

Estimates of NO$_x$, CO, and NMVOC Emissions

The emission estimates of NO$_x$, CO, and NMVOCs from mobile combustion (transportation) were obtained from preliminary data (EPA 2010, EPA 2009), which, in final iteration, will be published on the EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends web site. This EPA report provides emission estimates for these gases by fuel type using a procedure whereby emissions were calculated using basic activity data, such as amount of fuel delivered or miles traveled, as indicators of emissions.

Table A- 104 through Table A- 106 provides complete emission estimates for 1990 through 2009.

Table A- 89: Vehicle Miles Traveled for Gasoline On-Road Vehicles (10^9 Miles)[a]

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles	Motorcycles
1990	1391.2	554.3	25.4	9.6
1991	1341.7	627.2	25.0	9.2
1992	1354.8	682.9	24.8	9.6

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[42] See International Bunker Fuels section of the Energy Chapter.

[43] "Non-transportation mobile sources" are defined as any vehicle or equipment not used on the traditional road system, but excluding aircraft, rail and watercraft. This category includes snowmobiles, golf carts, riding lawn mowers, agricultural equipment, and trucks used for off-road purposes, among others.

Year				
1993	1356.5	720.5	24.5	9.9
1994	1387.5	738.8	25.0	10.2
1995	1420.6	762.5	24.7	9.8
1996	1454.7	788.0	24.0	9.9
1997	1488.5	820.8	23.6	10.1
1998	1536.6	836.8	23.6	10.3
1999	1559.1	867.4	23.8	10.6
2000	1591.5	886.7	23.6	10.5
2001	1619.3	904.9	23.2	9.6
2002	1649.2	925.8	23.1	9.6
2003	1662.6	943.0	23.5	9.6
2004	1690.2	984.2	23.8	10.1
2005	1698.6	997.5	24.1	10.5
2006	1680.8	1037.2	24.2	12.0
2007	1662.7	1065.6	24.7	13.6
2008	1,606.4	1,062.0	24.7	14.5
2009	1,621.1	1,071.7	22.7	14.6

Source: Derived from FHWA (1996 through 2009).
[a] FHWA data on vehicle miles traveled from the VM-1 table were not available for 2009 due to a delay caused by changes in data collection procedures. Based on data from FHWA's Traffic Volume Trends Program, the overall increase in VMT between 2008 and 2009 was estimated to be 0.2%. Total VMT was distributed among vehicle classes based on trends in fuel consumption by fuel type between 2008 and 2009

Table A- 90: Vehicle Miles Traveled for Diesel On-Road Vehicles (10⁹ Miles)[a]

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles
1990	16.9	19.7	125.5
1991	16.3	21.6	129.3
1992	16.5	23.4	133.5
1993	17.9	24.7	140.3
1994	18.3	25.3	150.5
1995	17.3	26.9	158.7
1996	14.7	27.8	164.3
1997	13.5	29.0	173.4
1998	12.4	30.5	178.4
1999	9.4	32.6	185.3
2000	8.0	35.2	188.0
2001	8.1	37.0	191.1
2002	8.3	38.9	196.4
2003	8.3	39.6	199.1
2004	8.4	41.3	201.6
2005	8.4	41.9	202.8
2006	8.3	43.5	201.4
2007	8.1	44.6	204.7
2008	7.8	44.4	205.5
2009	7.9	44.8	187.8

Source: Derived from FHWA (1996 through 2009).
[a] FHWA data on vehicle miles traveled from the VM-1 table were not available for 2009 due to a delay caused by changes in data collection procedures. Based on data from FHWA's Traffic Volume Trends Program, the overall increase in VMT between 2008 and 2009 was estimated to be 0.2%. Total VMT was distributed among vehicle classes based on trends in fuel consumption by fuel type between 2008 and 2009

Table A- 91: Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (10⁹ Miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles
1990	0.2	0.7	1.1
1991	0.2	0.6	1.0
1992	0.3	0.6	0.9
1993	0.3	0.6	1.3
1994	0.3	0.5	1.2
1995	0.4	0.6	1.2
1996	0.5	0.7	1.2
1997	0.6	0.9	1.3

1998	0.6	1.0	1.4
1999	0.6	1.0	1.3
2000	0.8	1.2	1.5
2001	0.9	1.2	1.8
2002	1.0	1.3	2.0
2003	1.2	1.4	2.1
2004	1.3	1.6	2.2
2005	1.4	1.6	2.1
2006	1.5	1.8	3.7
2007	1.6	2.0	4.6
2008	1.7	2.2	4.3
2009	1.8	2.3	4.8

Source: Derived from Browning (2003).

Table A- 92: Detailed Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (10^6 Miles)

Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009
Passenger Cars	**206.3**	**400.6**	**788.1**	**1,362.2**	**1,481.2**	**1,606.3**	**1,662.3**	**1,813.0**
Methanol-Flex Fuel ICE	-	40.9	13.2	-	-	-	-	-
Ethanol-Flex Fuel ICE	+	2.2	120.4	399.1	429.8	504.4	554.2	661.0
CNG ICE	10.6	28.0	68.9	118.8	125.0	129.2	129.7	135.3
CNG Bi-fuel	28.2	75.1	202.9	253.3	275.0	295.3	306.5	330.4
LPG ICE	20.6	40.3	41.9	31.3	24.9	18.5	16.5	11.8
LPG Bi-fuel	146.9	201.7	197.6	175.1	149.1	123.0	112.0	94.4
Biodiesel (BD20)	-	-	8.2	93.8	186.4	246.1	259.3	295.0
NEVs	-	5.2	62.4	135.5	135.7	136.0	136.2	136.5
Electric Vehicle	-	7.2	72.6	155.2	155.2	153.8	147.8	148.7
Light-Duty Trucks	**660.7**	**606.8**	**1,162.0**	**1,640.0**	**1,840.3**	**1,992.0**	**2,153.0**	**2,299.7**
Ethanol-Flex Fuel ICE	-	1.3	122.6	415.0	518.7	657.7	788.5	921.7
CNG ICE	10.9	29.6	145.9	163.8	169.3	175.4	181.8	186.3
CNG Bi-fuel	24.2	71.0	280.1	348.2	365.8	389.2	405.2	432.9
LPG ICE	56.9	48.5	58.4	57.3	54.6	38.4	36.1	32.9
LPG Bi-fuel	568.7	449.4	511.9	502.3	491.4	438.5	422.1	383.6
Biodiesel (BD20)	-	-	8.2	76.7	163.8	219.2	240.9	263.0
Electric Vehicle	-	7.1	35.0	76.4	76.4	73.1	77.8	78.4
Medium-Duty Trucks	**508.0**	**458.4**	**629.6**	**831.4**	**866.4**	**866.9**	**921.0**	**924.0**
CNG Bi-fuel	2.3	20.1	117.0	300.7	314.2	337.4	370.8	396.8
LPG ICE	24.3	20.0	29.7	36.8	33.8	31.3	30.9	31.0
LPG Bi-fuel	481.4	418.3	475.9	444.8	362.5	289.1	284.3	223.2
Biodiesel (BD20)	-	-	7.0	49.1	156.0	209.1	235.0	272.9
Heavy-Duty Trucks	**523.9**	**627.0**	**712.3**	**1,084.9**	**2,495.7**	**3,337.8**	**3,024.7**	**3,435.3**
Neat Methanol ICE	3.0	7.8	-	-	-	-	-	-
Neat Ethanol ICE	-	2.0	0.1	-	-	-	-	-
CNG ICE	12.7	32.2	83.7	218.7	252.8	332.1	495.3	516.8
LPG ICE	36.3	46.3	48.3	69.0	65.5	65.3	64.8	64.8
LPG Bi-fuel	471.9	531.9	529.7	569.4	524.1	512.9	505.2	502.2
LNG	-	6.9	22.2	117.3	126.5	141.8	158.1	174.2
Biodiesel (BD20)	-	-	28.3	110.4	1,526.8	2,285.7	1,801.4	2,177.3
Buses	**41.4**	**80.5**	**111.9**	**207.4**	**349.7**	**406.1**	**412.3**	**422.1**
Neat Methanol ICE	1.9	3.7	-	-	-	-	-	-
Neat Ethanol ICE	0.1	2.2	-	-	-	-	-	-
CNG ICE	11.2	37.5	53.4	122.9	123.4	131.7	139.2	148.8
LPG ICE	28.2	30.9	35.6	34.6	35.1	33.5	33.7	33.9
LNG	-	4.3	13.3	27.8	28.1	25.1	21.1	18.8
Biodiesel (BD20)	-	-	4.5	15.6	156.8	209.1	210.9	212.5
Electric	-	2.0	5.1	6.5	6.2	6.3	6.7	7.3
Total VMT	**1,940.3**	**2,173.4**	**3,403.9**	**5,125.9**	**7,033.3**	**8,209.0**	**8,173.3**	**8,894.0**

Source: Derived from Browning (2003).
Note: Throughout the rest of this Inventory, medium-duty trucks are grouped with heavy-duty trucks; they are reported separately here because these two categories may run on a slightly different range of fuel types.
+ Less than 0.05 million vehicle miles traveled
- Unreported or zero

Table A- 93: Age Distribution by Vehicle/Fuel Type for On-Road Vehicles,[a] 2009

Vehicle Age	LDGV	LDGT	HDGV	LDDV[b]	LDDT	HDDV	MC
0	5.2%	4.0%	5.2%	4.6%	4.1%	5.6%	6.2%
1	5.8%	5.0%	5.7%	5.2%	5.1%	6.2%	12.2%
2	6.4%	7.4%	5.9%	5.8%	6.8%	6.5%	11.0%
3	6.6%	7.5%	6.0%	5.9%	6.5%	7.9%	10.4%
4	6.4%	7.9%	6.0%	5.7%	6.8%	7.6%	9.1%
5	6.2%	7.6%	4.7%	5.5%	10.0%	6.0%	7.7%
6	6.1%	7.1%	3.8%	5.5%	7.2%	4.6%	6.6%
7	6.4%	6.7%	3.3%	5.7%	7.7%	4.2%	5.8%
8	6.4%	6.3%	3.9%	5.7%	8.0%	4.6%	5.0%
9	6.5%	5.8%	4.3%	0.0%	6.6%	5.5%	4.0%
10	6.0%	5.0%	4.3%	0.0%	7.1%	5.8%	3.0%
11	5.3%	4.5%	3.5%	0.0%	1.7%	4.5%	2.5%
12	4.9%	3.8%	2.7%	0.0%	4.3%	3.5%	2.4%
13	4.3%	3.4%	2.7%	0.0%	2.9%	3.3%	2.1%
14	3.7%	2.9%	3.2%	0.0%	2.8%	3.7%	1.6%
15	3.1%	2.6%	3.3%	0.0%	2.4%	3.2%	1.9%
16	2.3%	2.1%	2.5%	0.0%	1.8%	2.4%	1.5%
17	1.8%	1.6%	1.8%	0.0%	1.2%	1.6%	1.3%
18	1.4%	1.3%	1.8%	0.0%	1.0%	1.6%	1.0%
19	1.2%	1.3%	2.3%	0.0%	0.9%	1.8%	0.8%
20	1.0%	1.1%	3.1%	0.0%	0.8%	2.0%	0.6%
21	0.8%	1.1%	2.9%	0.0%	0.6%	1.7%	0.5%
22	0.6%	0.9%	2.5%	0.0%	0.5%	1.3%	0.5%
23	0.5%	0.8%	3.1%	0.0%	0.7%	1.4%	0.4%
24	0.4%	0.7%	2.4%	1.0%	0.6%	1.0%	0.4%
25	0.3%	0.5%	1.5%	1.1%	0.6%	0.6%	0.3%
26	0.2%	0.3%	2.3%	1.2%	0.5%	0.6%	0.2%
27	0.1%	0.2%	1.3%	1.6%	0.5%	0.3%	0.2%
28	0.1%	0.2%	1.2%	1.6%	0.1%	0.3%	0.2%
29	0.1%	0.2%	1.4%	0.8%	0.2%	0.3%	0.2%
30	0.1%	0.2%	1.6%	0.6%	0.1%	0.3%	0.3%
Total	**100%**	**100%**	**100%**	**57%**	**100%**	**100%**	**100%**

Source: EPA (2010).

[a] The following abbreviations correspond to vehicle types: LDGV (light-duty gasoline vehicles), LDGT (light-duty gasoline trucks), HDGV (heavy-duty gasoline vehicles), LDDV (light-duty diesel vehicles), LDDT (light-duty diesel trucks), HDDV (heavy-duty diesel vehicles), and MC (motorcycles).

[b] According to EPA's MOVES model, sales of diesel passenger cars in model years 9-23 was very small compared to total passenger car sales, so the calculated fraction of these vehicles in these model years was stored as zero.

Table A- 94: Annual Average Vehicle Mileage Accumulation per Vehicle[a] (miles)

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC[b]
0	14,910	19,906	20,218	14,910	26,371	28,787	4,786
1	14,174	18,707	18,935	14,174	24,137	26,304	4,475
2	13,475	17,559	17,100	13,475	22,095	24,038	4,164
3	12,810	16,462	16,611	12,810	20,228	21,968	3,853
4	12,178	15,413	15,560	12,178	18,521	20,078	3,543
5	11,577	14,411	14,576	11,577	16,960	18,351	3,232
6	11,006	13,454	13,655	11,006	15,533	16,775	2,921
7	10,463	12,541	12,793	10,463	14,227	15,334	2,611
8	9,947	11,671	11,987	9,947	13,032	14,019	2,300
9	9,456	10,843	11,231	9,456	11,939	12,817	1,989
10	8,989	10,055	10,524	8,989	10,939	11,719	1,678
11	8,546	9,306	9,863	8,546	10,024	10,716	1,368
12	8,124	8,597	9,243	8,124	9,186	9,799	1,368
13	7,723	7,925	8,662	7,723	8,420	8,962	1,368

14	7,342	7,290	8,028	7,342	7,718	8,196	1,368
15	6,980	6,690	7,610	6,980	7,075	7,497	1,368
16	6,636	6,127	7,133	6,636	6,487	6,857	1,368
17	6,308	5,598	6,687	6,308	5,948	6,273	1,368
18	5,997	5,103	6,269	5,997	5,454	5,739	1,368
19	5,701	4,642	5,877	5,701	5,002	5,250	1,368
20	5,420	4,214	5,510	5,420	4,588	4,804	1,368
21	5,152	3,818	5,166	5,152	4,209	4,396	1,368
22	4,898	3,455	4,844	4,898	3,861	4,023	1,368
23	4,656	3,123	4,542	4,656	3,542	3,681	1,368
24	4,427	2,822	4,259	4,427	3,250	3,369	1,368
25	4,427	2,822	4,259	4,427	3,250	3,369	1,368
26	4,427	2,822	4,259	4,427	3,250	3,369	1,368
27	4,427	2,822	4,259	4,427	3,250	3,369	1,368
28	4,427	2,822	4,259	4,427	3,250	3,369	1,368
29	4,427	2,822	4,259	4,427	3,250	3,369	1,368
30	4,427	2,822	4,259	4,427	3,250	3,369	1,368

Source: EPA (2000).

[a] The following abbreviations correspond to vehicle types: LDGV (light-duty gasoline vehicles), LDGT (light-duty gasoline trucks), HDGV (heavy-duty gasoline vehicles), LDDV (light-duty diesel vehicles), LDDT (light-duty diesel trucks), HDDV (heavy-duty diesel vehicles), and MC (motorcycles).

[b] Because of a lack of data, all motorcycles over 12 years old are considered to have the same emissions and travel characteristics, and therefore are presented in aggregate.

Table A- 95: VMT Distribution by Vehicle Age and Vehicle/Fuel Type, [a] 2009

Vehicle Age	LDGV	LDGT	HDGV	LDDV[b]	LDDT	HDDV	MC
0	7.56%	6.52%	9.50%	10.78%	7.43%	10.67%	9.53%
1	8.03%	7.67%	9.80%	11.44%	8.51%	10.80%	17.45%
2	8.49%	10.68%	9.15%	12.11%	10.26%	10.30%	14.68%
3	8.23%	10.14%	8.97%	11.74%	9.01%	11.49%	12.87%
4	7.65%	9.95%	8.40%	10.90%	8.65%	10.06%	10.36%
5	7.00%	8.98%	6.23%	9.98%	11.59%	7.30%	8.02%
6	6.59%	7.87%	4.64%	9.39%	7.68%	5.15%	6.13%
7	6.51%	6.85%	3.83%	9.28%	7.54%	4.27%	4.88%
8	6.24%	6.07%	4.20%	8.90%	7.14%	4.27%	3.65%
9	6.04%	5.20%	4.34%	0.00%	5.43%	4.69%	2.52%
10	5.25%	4.14%	4.08%	0.00%	5.32%	4.46%	1.60%
11	4.45%	3.40%	3.14%	0.00%	1.19%	3.18%	1.12%
12	3.92%	2.65%	2.26%	0.00%	2.69%	2.27%	1.07%
13	3.28%	2.20%	2.15%	0.00%	1.69%	1.95%	0.94%
14	2.63%	1.71%	2.33%	0.00%	1.46%	2.00%	0.71%
15	2.11%	1.42%	2.30%	0.00%	1.15%	1.57%	0.81%
16	1.52%	1.05%	1.60%	0.00%	0.80%	1.08%	0.66%
17	1.10%	0.75%	1.09%	0.00%	0.51%	0.68%	0.55%
18	0.81%	0.54%	1.01%	0.00%	0.36%	0.60%	0.44%
19	0.67%	0.49%	1.21%	0.00%	0.32%	0.64%	0.36%
20	0.52%	0.40%	1.56%	0.00%	0.24%	0.64%	0.26%
21	0.41%	0.33%	1.36%	0.00%	0.16%	0.50%	0.22%
22	0.29%	0.26%	1.08%	0.00%	0.13%	0.36%	0.22%
23	0.23%	0.20%	1.29%	0.00%	0.16%	0.33%	0.18%
24	0.16%	0.15%	0.94%	0.69%	0.13%	0.22%	0.15%
25	0.11%	0.12%	0.56%	0.78%	0.13%	0.14%	0.14%
26	0.07%	0.08%	0.87%	0.86%	0.12%	0.13%	0.10%
27	0.05%	0.05%	0.48%	1.11%	0.11%	0.07%	0.08%
28	0.04%	0.04%	0.48%	1.12%	0.03%	0.06%	0.08%
29	0.03%	0.04%	0.53%	0.54%	0.04%	0.06%	0.09%
30	0.03%	0.05%	0.62%	0.38%	0.02%	0.06%	0.14%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Note: Estimated by weighting data in Table A- 93 by data in Table A- 94.

[a] The following abbreviations correspond to vehicle types: LDGV (light-duty gasoline vehicles), LDGT (light-duty gasoline trucks), HDGV (heavy-duty gasoline vehicles), LDDV (light-duty diesel vehicles), LDDT (light-duty diesel trucks), HDDV (heavy-duty diesel vehicles), and MC (motorcycles).

[b] According to EPA's MOVES model, sales of diesel passenger cars in model years 9-23 was very small compared to total passenger car sales, so the calculated fraction of these vehicles in these model years was stored as zero.

Table A- 96: Fuel Consumption for Off-Road Sources by Fuel Type (million gallons)

Vehicle Type/Year	1990	1995	2000	2005	2006	2007	2008	2009
Aircraft[a]	**18,723.9**	**18,179.6**	**20,793.7**	**20,214.1**	**17,664.4**	**17,568.6**	**16,141.6**	**14,460.2**
Aviation Gasoline	374.2	329.3	301.9	294.2	278.3	262.8	235.3	221.0
Jet Fuel	18,349.7	17,850.3	20,491.9	19,919.9	17,386.1	17,305.8	15,906.2	14,239.3
Ships and Other								
Boats	**4,507.2**	**5,789.1**	**6,430.6**	**4,882.7**	**5,144.6**	**5,747.1**	**4,113.4**	**3,548.7**
Diesel	1,043.1	1,545.7	1,750.1	1,471.4	1,410.5	1,490.7	675.7	825.7
Gasoline	1,403.4	1,597.3	1,652.9	1,629.9	1,619.6	1,609.6	1,599.8	1,590.7
Residual	2,060.7	2,646.1	3,027.5	1,781.4	2,114.5	2,646.8	1,837.9	1,132.3
Construction/ Mining Equipment[b]	**4,160.3**	**4,834.7**	**5,439.1**	**6,520.5**	**6,656.4**	**6,683.7**	**6,835.0**	**6,960.0**
Diesel	3,674.4	4,386.9	5,094.9	5,823.4	5,968.2	6,112.9	6,257.7	6,402.5
Gasoline	485.9	447.8	344.2	697.1	688.3	570.8	577.3	557.5
Agricultural Equipment[c]	**3,133.7**	**3,698.3**	**3,874.5**	**4,715.0**	**4,947.8**	**4,861.5**	**4,516.6**	**4,640.9**
Diesel	2,320.9	2,771.6	3,222.3	3,637.2	3,719.1	3,800.9	3,882.8	3,964.6
Gasoline	812.8	926.7	652.3	1,077.8	1,228.7	1,060.6	633.8	676.3
Rail	**3,460.6**	**3,863.5**	**4,105.9**	**4,446.1**	**4,664.5**	**4,538.9**	**4,216.0**	**3,524.8**
Diesel	3,460.6	3,863.5	4,105.9	4,446.1	4,664.5	4,538.9	4,216.0	3,524.8
Other[d]	**5,916.5**	**6,524.8**	**6,826.1**	**8,281.2**	**8,396.1**	**8,255.6**	**8,386.7**	**8,481.6**
Diesel	1,423.3	1,720.0	2,016.0	2,340.3	2,405.4	2,470.6	2,535.8	2,601.0
Gasoline	4,493.2	4,804.7	4,810.2	5,940.9	5,990.7	5,785.0	5,850.9	5,880.7
Total	**39,902.2**	**42,890.0**	**47,470.0**	**49,059.5**	**47,473.8**	**47,655.5**	**44,209.2**	**41,616.4**

Sources: AAR (2008 through 2009), APTA (2007 through 2009), BEA (1991 through 2005), Benson (2002 through 2004), DHS (2008), DOC (1991 through 2008), DESC (2008), DOE (1993 through 2009), DOT (1991 through 2009), EIA (2002), EIA (2007b), EIA (2008), EIA (2007 through 2008), EIA (1991 through 2011), EPA (2007b), FAA (200), FAA (2006), Gaffney (2007), and Whorton (2006 through 2009).
[a] For aircraft, this is aviation gasoline. For all other categories, this is motor gasoline.
[b] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[d] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Table A- 97: Control Technology Assignments for Gasoline Passenger Cars (Percent of VMT)

Model Years	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	LEV	EPA Tier 2
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	-	-	1%	97%	2%	-
1997	-	-	0.5%	96.5%	3%	-
1998	-	-	<1%	87%	13%	-
1999	-	-	<1%	67%	33%	-
2000	-	-	-	44%	56%	-
2001	-	-	-	3%	97%	-
2002	-	-	-	1%	99%	-
2003	-	-	-	<1%	87%	13%
2004	-	-	-	<1%	41%	59%
2005	-	-	-	-	38%	62%
2006	-	-	-	-	18%	82%
2007	-	-	-	-	4%	96%
2008	-	-	-	-	2%	98%
2009	-	-	-	-	-	100%

Sources: EPA (1998), EPA (2007a), and EPA (2007b).
Note: Detailed descriptions of emissions control technologies are provided in the following section of this annex.

- Not applicable.

Table A- 98: Control Technology Assignments for Gasoline Light-Duty Trucks (Percent of VMT)[a]

Model Years	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	LEV [b]	EPA Tier 2
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	-	-	-	100%	-	-
1997	-	-	-	100%	-	-
1998	-	-	-	80%	20%	-
1999	-	-	-	57%	43%	-
2000	-	-	-	65%	35%	-
2001	-	-	-	1%	99%	-
2002	-	-	-	10%	90%	-
2003	-	-	-	<1%	53%	47%
2004	-	-	-	-	72%	28%
2005	-	-	-	-	38%	62%
2006	-	-	-	-	25%	75%
2007	-	-	-	-	14%	86%
2008	-	-	-	-	-	100%
2009	-	-	-	-	-	100%

Sources: EPA (1998), EPA (2007a), and EPA (2007b).
[a] Detailed descriptions of emissions control technologies are provided in the following section of this annex.
[b] The proportion of LEVs as a whole has decreased since 2001, as carmakers have been able to achieve greater emission reductions with certain types of LEVs, such as ULEVs. Because ULEVs emit about half the emissions of LEVs, a carmaker can reduce the total number of LEVs they need to build to meet a specified emission average for all of their vehicles in a given model year.
- Not applicable.

Table A- 99: Control Technology Assignments for Gasoline Heavy-Duty Vehicles (Percent of VMT)[a]

Model Years	Uncontrolled	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	LEV [b]	EPA Tier 2
≤1981	100%	-	-	-	-	-	-
1982-1984	95%	-	5%	-	-	-	-
1985-1986	-	95%	5%	-	-	-	-
1987	-	70%	15%	15%	-	-	-
1988-1989	-	60%	25%	15%	-	-	-
1990-1995	-	45%	30%	25%	-	-	-
1996	-	-	25%	10%	65%	-	-
1997	-	-	10%	5%	85%	-	-
1998	-	-	-	-	96%	4%	-
1999	-	-	-	-	78%	22%	-
2000	-	-	-	-	54%	46%	-
2001	-	-	-	-	64%	36%	-
2002	-	-	-	-	69%	31%	-
2003	-	-	-	-	65%	30%	5%
2004	-	-	-	-	5%	37%	59%
2005	-	-	-	-	-	23%	77%
2006	-	-	-	-	-	22%	78%
2007	-	-	-	-	-	21%	79%
2008	-	-	-	-	-	20%	80%
2009	-	-	-	-	-	19%	81%

Sources: EPA (1998), EPA (2007a), and EPA (2007b).
[a] Detailed descriptions of emissions control technologies are provided in the following section of this annex.
[b] The proportion of LEVs as a whole has decreased since 2000, as carmakers have been able to achieve greater emission reductions with certain types of LEVs, such as ULEVs. Because ULEVs emit about half the emissions of LEVs, a manufacturer can reduce the total number of LEVs they need to build to meet a specified emission average for all of their vehicles in a given model year.

- Not applicable.

Table A- 100: Control Technology Assignments for Diesel On-Road Vehicles and Motorcycles

Vehicle Type/Control Technology	Model Years
Diesel Passenger Cars and Light-Duty Trucks	
Uncontrolled	1960-1982
Moderate control	1983-1995
Advanced control	1996-2009
Diesel Medium- and Heavy-Duty Trucks and Buses	
Uncontrolled	1960-1990
Moderate control	1991-2003
Advanced control	2004-2006
Aftertreatment	2007-2009
Motorcycles	
Uncontrolled	1960-1995
Non-catalyst controls	1996-2009

Source: EPA (1998) and Browning (2005)
Note: Detailed descriptions of emissions control technologies are provided in the following section of this annex.

Table A- 101: Emission Factors for CH_4 and N_2O for On-Road Vehicles

Vehicle Type/Control Technology	N_2O (g/mi)	CH_4 (g/mi)
Gasoline Passenger Cars		
EPA Tier 2	0.0036	0.0173
Low Emission Vehicles	0.0150	0.0105
EPA Tier 1 [a]	0.0429	0.0271
EPA Tier 0 [a]	0.0647	0.0704
Oxidation Catalyst	0.0504	0.1355
Non-Catalyst Control	0.0197	0.1696
Uncontrolled	0.0197	0.1780
Gasoline Light-Duty Trucks		
EPA Tier 2	0.0066	0.0163
Low Emission Vehicles	0.0157	0.0148
EPA Tier 1 [a]	0.0871	0.0452
EPA Tier 0 [a]	0.1056	0.0776
Oxidation Catalyst	0.0639	0.1516
Non-Catalyst Control	0.0218	0.1908
Uncontrolled	0.0220	0.2024
Gasoline Heavy-Duty Vehicles		
EPA Tier 2	0.0134	0.0333
Low Emission Vehicles	0.0320	0.0303
EPA Tier 1 [a]	0.1750	0.0655
EPA Tier 0 [a]	0.2135	0.2630
Oxidation Catalyst	0.1317	0.2356
Non-Catalyst Control	0.0473	0.4181
Uncontrolled	0.0497	0.4604
Diesel Passenger Cars		
Advanced	0.0010	0.0005
Moderate	0.0010	0.0005
Uncontrolled	0.0012	0.0006
Diesel Light-Duty Trucks		
Advanced	0.0015	0.0010
Moderate	0.0014	0.0009
Uncontrolled	0.0017	0.0011
Diesel Medium- and Heavy-Duty **Trucks and Buses**		
Aftertreatment	0.0048	0.0051
Advanced	0.0048	0.0051
Moderate	0.0048	0.0051
Uncontrolled	0.0048	0.0051
Motorcycles		
Non-Catalyst Control	0.0069	0.0672
Uncontrolled	0.0087	0.0899

Source: ICF (2006b and 2004).

Table A- 102: Emission Factors for CH$_4$ and N$_2$O for Alternative Fuel Vehicles (g/mi)

	N$_2$O	CH$_4$
Light Duty Vehicles		
Methanol	0.067	0.018
CNG	0.050	0.737
LPG	0.067	0.037
Ethanol	0.067	0.055
Biodiesel (BD20)	0.001	0.0005
Medium- and Heavy-Duty Trucks		
Methanol	0.175	0.066
CNG	0.175	1.966
LNG	0.175	1.966
LPG	0.175	0.066
Ethanol	0.175	0.197
Biodiesel (BD20)	0.005	0.005
Buses		
Methanol	0.175	0.066
CNG	0.175	1.966
Ethanol	0.175	0.197
Biodiesel (BD20)	0.005	0.005

Source: Developed by ICF (2006a) using ANL (2006) and Lipman and Delucchi (2002).

Table A- 103: Emission Factors for CH$_4$ and N$_2$O Emissions from Non-Road Mobile Combustion (g/kg fuel)

Vehicle Type/Fuel Type	N$_2$O	CH$_4$
Ships and Boats		
Residual	0.16	0.03
Gasoline	0.08	0.23
Diesel	0.14	0.02
Rail		
Diesel	0.08	0.25
Agricultural Equipment[a]		
Gasoline	0.08	0.45
Diesel	0.08	0.45
Construction/Mining Equipment[c]		
Gasoline	0.08	0.18
Diesel	0.08	0.18
Other Non-Road		
All "Other" Categories[c]	0.08	0.18
Aircraft		
Jet Fuel	0.10	0.087
Aviation Gasoline	0.04	2.64

Source: IPCC/UNEP/OECD/IEA (1997) and ICF (2009).
a Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
b Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
c "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Table A- 104: NO$_x$ Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009
Gasoline On-Road	**5,746**	**4,560**	**3,812**	**3,102**	**2,897**	**2,693**	**2,488**	**2,212**
Passenger Cars	3,847	2,752	2,084	1,692	1,581	1,469	1,357	1,207
Light-Duty Trucks	1,364	1,325	1,303	1,073	1,002	931	860	765
Medium- and Heavy-Duty Trucks and Buses	515	469	411	326	304	283	261	232
Motorcycles	20	14	13	11	11	10	9	8
Diesel On-Road	**2,956**	**3,493**	**3,803**	**2,787**	**2,603**	**2,419**	**2,235**	**1,987**
Passenger Cars	39	19	7	5	5	4	4	3
Light-Duty Trucks	20	12	6	5	4	4	4	3

Medium- and Heavy-Duty Trucks and Buses	2,897	3,462	3,791	2,778	2,594	2,411	2,228	1,981
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**2,160**	**2,483**	**2,584**	**3,122**	**2,988**	**2,853**	**2,718**	**2,007**
Ships and Boats	402	488	506	646	618	590	562	415
Rail	338	433	451	576	551	527	502	371
Aircraft[b]	25	31	40	47	45	43	41	30
Agricultural Equipment[c]	437	478	484	565	540	516	491	363
Construction/Mining Equipment[d]	641	697	697	811	776	741	706	521
Other[e]	318	357	407	478	457	437	416	307
Total	**10,862**	**10,536**	**10,199**	**9,012**	**8,488**	**7,965**	**7,441**	**6,206**

[a] NO$_x$ emissions from alternative fuel on-road vehicles are included under gasoline and diesel on-road.
[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.
[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[e] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.
Note: Totals may not sum due to independent rounding.
IE = Included Elsewhere

Table A- 105: CO Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009
Gasoline On-Road	**98,328**	**74,673**	**60,657**	**43,374**	**40,492**	**37,610**	**34,727**	**34,199**
Passenger Cars	60,757	42,065	32,867	24,166	22,560	20,954	19,348	19,054
Light-Duty Trucks	29,237	27,048	24,532	17,264	16,117	14,969	13,822	13,612
Medium- and Heavy-Duty Trucks and Buses	8,093	5,404	3,104	1,844	1,721	1,599	1,476	1,454
Motorcycles	240	155	154	100	94	87	80	79
Diesel On-Road	**1,696**	**1,424**	**1,088**	**665**	**621**	**576**	**532**	**524**
Passenger Cars	35	18	7	4	4	4	4	4
Light-Duty Trucks	22	16	6	4	4	3	3	3
Medium- and Heavy-Duty Trucks and Buses	1,639	1,391	1,075	656	613	569	525	517
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**19,337**	**21,533**	**21,814**	**18,652**	**17,859**	**17,067**	**16,274**	**8,633**
Ships and Boats	1,559	1,781	1,825	1,534	1,469	1,404	1,339	710
Rail	85	93	90	75	72	69	66	35
Aircraft[b]	217	224	245	196	187	179	171	91
Agricultural Equipment[c]	581	628	626	520	498	476	454	241
Construction/Mining Equipment[d]	1,090	1,132	1,047	872	835	798	761	404
Other[e]	15,805	17,676	17,981	15,455	14,798	14,141	13,484	7,153
Total	**119,360**	**97,630**	**83,559**	**62,692**	**58,972**	**55,253**	**51,533**	**43,355**

[a] NO$_x$ emissions from alternative fuel on-road vehicles are included under gasoline and diesel on-road.
[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.
[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[e] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.
Note: Totals may not sum due to independent rounding.
IE = Included Elsewhere

Table A- 106: NMVOCs Emissions from Mobile Combustion (Gg)

Fuel Type/Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009
Gasoline On-Road	**8,110**	**5,819**	**4,615**	**3,558**	**3,358**	**3,158**	**2,958**	**2,878**
Passenger Cars	5,120	3,394	2,610	1,987	1,875	1,764	1,652	1,607
Light-Duty Trucks	2,374	2,019	1,750	1,382	1,304	1,226	1,149	1,118
Medium- and Heavy-Duty Trucks and Buses	575	382	232	171	162	152	142	138

Motorcycles	42	24	23	18	17	16	15	15
Diesel On-Road	**406**	**304**	**216**	**172**	**163**	**153**	**143**	**139**
Passenger Cars	16	8	3	3	2	2	2	2
Light-Duty Trucks	14	9	4	3	3	3	3	2
Medium- and Heavy-Duty Trucks and Buses	377	286	209	167	157	148	139	135
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**2,415**	**2,622**	**2,399**	**2,600**	**2,516**	**2,430**	**2,346**	**1,134**
Ships and Boats	608	739	744	798	772	746	720	348
Rail	33	36	35	39	37	36	35	17
Aircraft[b]	28	28	24	21	20	20	19	9
Agricultural Equipment[c]	85	86	76	79	77	74	71	35
Construction/Mining Equipment[d]	149	152	130	137	132	128	123	60
Other[e]	1,512	1,580	1,390	1,527	1,477	1,427	1,378	666
Total	**10,932**	**8,745**	**7,229**	**6,330**	**6,037**	**5,742**	**5,447**	**4,151**

[a] NO$_x$ emissions from alternative fuel on-road vehicles are included under gasoline and diesel on-road.
[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.
[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[e] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.
Note: Totals may not sum due to independent rounding.
IE = Included Elsewhere

Definitions of Emission Control Technologies and Standards

The N$_2$O and CH$_4$ emission factors used depend on the emission standards in place and the corresponding level of control technology for each vehicle type. Table A- 97 through Table A- 100 show the years in which these technologies or standards were in place and the penetration level for each vehicle type. These categories are defined below.

Uncontrolled

Vehicles manufactured prior to the implementation of pollution control technologies are designated as uncontrolled. Gasoline passenger cars and light-duty trucks (pre-1973), gasoline heavy-duty vehicles (pre-1984), diesel vehicles (pre-1983), and motorcycles (pre-1996) are assumed to have no 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.

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 1997. The two-way catalytic converter oxidizes HC and CO, significantly reducing emissions over 80 percent beyond non-catalyst-system capacity. One reason unleaded gasoline was introduced in 1975 was due to the fact that oxidation catalysts cannot function properly with leaded gasoline.

EPA 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 diagnostic computer and oxygen sensor. In addition, this type of catalyst includes a fuel metering system (carburetor or fuel injection) with electronic "trim" (also known as a "closed-loop system"). 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 1.0 g/mile by 1981.

EPA Tier 1

This emission standard created through the 1990 amendments to the Clean Air Act limited passenger car NO_x emissions to 0.4 g/mi, and HC emissions to 0.25 g/mi. These bounds respectively amounted to a 60 and 40 percent reduction from the EPA Tier 0 standard set in 1981. For light-duty trucks, this standard set emissions at 0.4 to 1.1 g/mi for NO_x, and 0.25 to 0.39 g/mi for HCs, depending on the weight of the truck. Emission reductions were met through the use of more advanced emission control systems, and applied to light-duty gasoline vehicles beginning in 1994. These advanced emission control systems included advanced three-way catalysts, electronically controlled fuel injection and ignition timing, EGR, and air injection.

EPA Tier 2

This emission standard was specified in the 1990 amendments to the Clean Air Act, limiting passenger car NO_x emissions to 0.07 g/mi on average and aligning emissions standards for passenger cars and light-duty trucks. Manufacturers can meet this average emission level by producing vehicles in 11 emission "Bins", the three highest of which expire in 2006. These new emission levels represent a 77 to 95% reduction in emissions from the EPA Tier 1 standard set in 1994. Emission reductions were met through the use of more advanced emission control systems and lower sulfur fuels and are applied to vehicles beginning in 2004. These advanced emission control systems include improved combustion, advanced three-way catalysts, electronically controlled fuel injection and ignition timing, EGR, and air injection.

Low Emission Vehicles (LEV)

This emission standard requires a much higher emission control level than the Tier 1 standard. Applied to light-duty gasoline passenger cars and trucks beginning in small numbers in the mid-1990s, LEV includes multi-port fuel injection with adaptive learning, an advanced computer diagnostics systems and advanced and close coupled catalysts with secondary air injection. LEVs as defined here include transitional low-emission vehicles (TLEVs), low emission vehicles, ultra-low emission vehicles (ULEVs) and super ultra-low emission vehicles (SULEVs). In this analysis, all categories of LEVs are treated the same due to the fact that there are very limited CH_4 or N_2O emission factor data for LEVs to distinguish among the different types of vehicles. Zero emission vehicles (ZEVs) are incorporated into the alternative fuel and advanced technology vehicle assessments.

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. 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 level of emission control necessary to comply with standards in place from 1996 through 2006.

Aftertreatment

Use of diesel particulate filters (DPFs), oxidation catalysts and NOx absorbers or selective catalytic reduction (SCR) systems are designated as aftertreatment control. These technologies provide diesel vehicles with a level of emission control necessary to comply with standards in place from 2007 on.

Supplemental Information on GHG Emissions from Transportation and Other Mobile Sources

This section of this Annex includes supplemental information on the contribution of transportation and other mobile sources to U.S. greenhouse gas emissions. In the main body of the Inventory report, emission estimates are generally presented by greenhouse gas, with separate discussions of the methodologies used to estimate CO_2, N_2O, CH_4, and HFC emissions. Although the inventory is not required to provide detail beyond what is contained in the body of this report, the IPCC allows presentation of additional data and detail on emission sources. The purpose of this sub-annex, within the annex that details the calculation methods and data used for non- CO_2 calculations, is to provide all transportation estimates presented throughout the repot in one place.

This section of this Annex reports total greenhouse gas emissions from transportation and other (non-transportation) mobile sources in CO_2 equivalents, with information on the contribution by greenhouse gas and by mode, vehicle type, and fuel type. In order to calculate these figures, additional analyses were conducted to develop estimates of CO_2 from non-transportation mobile sources (e.g., agricultural equipment, construction/mining equipment, recreational vehicles), and to provide more detailed breakdowns of emissions by source.

Estimation of CO_2 from Non-Transportation Mobile Sources

The estimates of N_2O and CH_4 from fuel combustion presented in the Energy chapter of the inventory include both transportation sources and other mobile sources. Other mobile sources include construction/mining equipment, agricultural equipment, vehicles used off-road, and other sources that have utility associated with their movement but do not have a primary purpose of transporting people or goods (e.g., snowmobiles, riding lawnmowers, etc.). Estimates of CO_2 from non-transportation mobile sources, based on EIA fuel consumption estimates, are included in the agricultural, industrial, and commercial sectors. In order to provide comparable information on transportation and mobile sources, Table A- 107 provides estimates of CO_2 from these other mobile sources, developed from EPA's NONROAD model and FHWA's *Highway Statistics*. These other mobile source estimates were developed using the same fuel consumption data utilized in developing the N_2O and CH_4 estimates.

Table A- 107: CO_2 Emissions from Non-Transportation Mobile Sources (Tg CO_2 Eq.)

Fuel Type/Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009
Agricultural Equipment[a]	31.0	36.6	38.8	46.8	49.0	48.4	45.4	46.7
Construction/Mining Equipment[b]	42.0	48.9	55.3	65.9	67.3	67.8	69.3	70.6
Other Sources[c]	54.5	59.8	62.8	76.2	77.6	76.7	77.7	78.6
Total	**127.6**	**145.4**	**156.9**	**188.9**	**193.9**	**193.0**	**192.4**	**195.9**

[a] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[b] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[c] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Estimation of HFC Emissions from Transportation Sources

In addition to CO_2, N_2O and CH_4 emissions, transportation sources also result in emissions of HFCs. HFCs are emitted to the atmosphere during equipment manufacture and operation (as a result of component failure, leaks, and purges), as well as at servicing and disposal events. There are three categories of transportation-related HFC emissions; Mobile AC represents the emissions from air conditioning units in passenger cars and light-duty trucks, Comfort Cooling represents the emissions from air conditioning units in passenger trains and buses, and Refrigerated Transport represents the emissions from units used to cool freight during transportation.

Table A- 108 below presents these HFC emissions. Table A- 109 presents all transportation and mobile source greenhouse gas emissions, including HFC emissions.

Table A-108: HFC Emissions from Transportation Sources

Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009
Mobile AC	-	**16.7**	**46.0**	**59.4**	**58.3**	**54.7**	**50.7**	**45.9**
Passenger Cars	-	10.1	24.3	28.4	27.1	24.6	22.1	19.3
Light-Duty Trucks	-	6.5	21.7	31.0	31.2	30.1	28.6	26.6
Comfort Cooling for								
Trains and Buses	**-**	**+**	**0.1**	**0.2**	**0.3**	**0.3**	**0.4**	**0.4**
School and Tour Buses	-	+	0.1	0.2	0.3	0.3	0.3	0.4
Transit Buses	-	+	+	+	+	+	+	+
Rail	-	-	-	+	+	+	+	+
Refrigerated Transport	**-**	**2.3**	**9.6**	**13.2**	**13.6**	**13.8**	**13.8**	**13.9**
Medium- and Heavy-Duty								
Trucks	-	1.7	7.4	11.1	11.4	11.5	11.6	11.6
Rail	-	0.5	2.0	2.1	2.2	2.2	2.2	2.2
Ships and Other Boats	-	+	0.1	+	+	+	+	+
Total	**-**	**19.0**	**55.7**	**72.9**	**72.2**	**68.8**	**64.9**	**60.2**

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

Contribution of Transportation and Mobile Sources to Greenhouse Gas Emissions, by Mode/Vehicle Type/Fuel Type

Table A-109 presents estimates of greenhouse gas emissions from an expanded analysis including all transportation and additional mobile sources, as well as emissions from electricity generation by the consuming category, in CO_2 equivalents. In total, transportation and non-transportation mobile sources emitted 2,014.7 Tg CO_2 Eq. in 2009, an increase of 20 percent from 1990. Transportation sources account for 1,816.9 Tg CO_2 Eq. while non-transportation mobile sources account for 197.7 Tg CO_2 Eq. These estimates include HFC emissions for mobile AC, comfort cooling for trains and buses, and refrigerated transport. These estimates were generated using the estimates of CO_2 emissions from transportation sources reported in the Carbon Dioxide Emissions from Fossil Fuel Combustion section, and CH_4 emissions and N_2O emissions reported in the Mobile Combustion section of the Energy chapter; information on HFCs from mobile air conditioners, comfort cooling for trains and buses, and refrigerated transportation from Chapter 4; and estimates of CO_2 emitted from non-transportation mobile sources reported in Table A-107 above.

Although all emissions reported here are based on estimates reported throughout this inventory, some additional calculations were performed in order to provide a detailed breakdown of emissions by mode and vehicle category. In the case of N_2O and CH_4, additional calculations were performed to develop emissions estimates by type of aircraft and type of heavy-duty vehicle (i.e., medium- and heavy-duty trucks or buses) to match the level of detail for CO_2 emissions. N_2O and CH_4 estimates were developed for individual aircraft types by multiplying the emissions estimates for aircraft for each fuel type (jet fuel and aviation gasoline) by the portion of fuel used by each aircraft type (from FAA 2010, 2009, and 2006). Similarly, N_2O and CH_4 estimates were developed for medium- and heavy-duty trucks and buses by multiplying the emission estimates for heavy-duty vehicles for each fuel type (gasoline, diesel) from the Mobile Combustion section in the Energy chapter, by the portion of fuel used by each vehicle type (from DOE 1993 through 2010). Otherwise, the table and figure are drawn directly from emission estimates presented elsewhere in the inventory, and are dependent on the methodologies presented in Annex 2.1 (for CO_2), Chapter 4, and Annex 3.8 (for HFCs), and earlier in this Annex (for CH_4 and N_2O).

Transportation sources include on-road vehicles, aircraft, boats and ships, rail, and pipelines (note: pipelines are a transportation source but are stationary, not mobile sources). In addition, transportation-related greenhouse gas emissions also include HFC released from mobile air conditioners and refrigerated transportation, and the release of CO_2 from lubricants (such as motor oil) used in transportation. Together, transportation sources were responsible for 1,816.9 Tg CO_2 Eq. in 2009.

On-road vehicles were responsible for about 77 percent of all transportation and non-transportation mobile GHG emissions in 2009. Although passenger cars make up the largest component of on-road vehicle greenhouse gas emissions, light-duty and medium- and heavy-duty trucks have been the primary sources of growth in on-road vehicle emissions. Between 1990 and 2009, greenhouse gas emissions from passenger cars decreased 5 percent, while emissions from light-duty trucks increased 64 percent, largely due to the increased use of sport-utility vehicles and other light-duty trucks. Meanwhile, greenhouse gas emissions from medium- and heavy-duty trucks increased 58 percent, reflecting the increased volume of total freight movement and an increasing share transported by trucks.

Greenhouse gas emissions from aircraft decreased 22 percent between 1990 and 2009. Emissions from military aircraft decreased 59 percent and commercial aircraft emissions rose 2 percent between 1990 and 2007 then dropped 19 percent from 2007 to 2009.

Non-transportation mobile sources, such as construction/mining equipment, agricultural equipment, and industrial/commercial equipment, emitted approximately 197.7 Tg CO_2 Eq. in 2009. Together, these sources emitted more greenhouse gases than ships and boats, rail, and pipelines combined. Emissions from non-transportation mobile sources increased rapidly, growing approximately 54 percent between 1990 and 2009. CH_4 and N_2O emissions from these sources are included in the "Mobile Combustion" section and CO_2 emissions are included in the relevant economic sectors.

Contribution of Transportation and Mobile Sources to Greenhouse Gas Emissions, by Gas

Table A- 110 presents estimates of greenhouse gas emissions from transportation and other mobile sources broken down by greenhouse gas. As this table shows, CO_2 accounts for the vast majority of transportation greenhouse gas emissions (approximately 96 percent in 2009). Emissions of CO_2 from transportation and mobile sources increased by 300.2 Tg CO_2 Eq. between 1990 and 2009. In contrast, the combined emissions of CH_4 and N_2O decreased by 22.7 Tg CO_2 Eq. over the same period, due largely to the introduction of control technologies designed to reduce criteria pollutant emissions.[44] Meanwhile, HFC emissions from mobile air conditioners and refrigerated transport increased from virtually no emissions in 1990 to 60.2 Tg CO_2 Eq. in 2009 as these chemicals were phased in as substitutes for ozone depleting substances. It should be noted, however, that the ozone depleting substances that HFCs replaced are also powerful greenhouse gases, but are not included in national greenhouse gas inventories due to their mandated phase out.

Greenhouse Gas Emissions from Freight and Passenger Transportation

Table A- 111 and Table A- 112present greenhouse gas estimates from transportation, broken down into the passenger and freight categories. Passenger modes include light-duty vehicles, buses, passenger rail, aircraft (general aviation and commercial aircraft), recreational boats, and mobile air conditioners, and are illustrated in Table A- 111. Freight modes include medium- and heavy-duty trucks, freight rail, refrigerated transport, waterborne freight vessels, pipelines, and commercial aircraft and are illustrated in Table A- 112. Commercial aircraft do carry some freight, in addition to passengers, and for this Inventory, the emissions have been split between passenger and freight transportation. (In previous Inventories, all commercial aircraft emissions were considered passenger transportation.) The amount of commercial aircraft emissions to allocate to the passenger and freight categories was calculated using BTS data on freight shipped by commercial aircraft, and the total number of passengers enplaned. Each passenger was considered to weigh an average of 150 pounds, with a luggage weight of 50 pounds. The total freight weight and total passenger weight carried were used to determine percent shares which were used to split the total commercial aircraft emissions estimates. The remaining transportation and mobile emissions were from sources not considered to be either freight or passenger modes (e.g., construction/mining and agricultural equipment, lubricants).

The estimates in these tables are derived from the estimates presented in Table A- 109. In addition, estimates of fuel consumption from DOE (1993 through 2010) were used to allocate rail emissions between passenger and freight categories.

In 2009, passenger transportation modes emitted 1,322.1 Tg CO_2 Eq., while freight transportation modes emitted 475.3 Tg CO_2 Eq. Since 1990, the rate of growth of greenhouse gas emissions from freight sources has been 7 percent higher than emissions from passenger sources, due largely to the rapid increase in emissions associated with medium- and heavy-duty trucks.

Table A- 109: Total U.S. Greenhouse Gas Emissions from Transportation and Mobile Sources (Tg CO_2 Eq.)

Mode / Vehicle Type / Fuel Type	1990	1995	2000	2005	2006	2007	2008	2009	Percent Change 1990-2009
Transportation Total[a]	**1,548.3**	**1,698.5**	**1,935.8**	**2,022.2**	**1,999.0**	**2,008.9**	**1,895.4**	**1,816.9**	**17%**
On-Road Vehicles	**1,235.2**	**1,371.3**	**1,575.1**	**1,682.9**	**1,679.7**	**1,682.1**	**1,603.8**	**1,557.4**	**26%**
Passenger Cars	**657.4**	**646.0**	**695.3**	**709.5**	**682.9**	**672.0**	**632.5**	**627.4**	**-5%**
Gasoline	649.4	627.8	667.3	676.9	651.6	643.3	606.5	604.1	-7%
Diesel	7.9	7.9	3.7	4.2	4.1	4.1	3.9	3.9	-51%
AFVs	+	0.1	+	+	+	+	+	+	551%
HFCs from	+	10.1	24.3	28.4	27.1	24.6	22.1	19.3	NA

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[44] The decline in CFC emissions is not captured in the official transportation estimates.

Mobile AC									
Light-Duty Trucks	**336.6**	**436.6**	**512.1**	**551.3**	**564.0**	**570.3**	**553.8**	**551.0**	**64%**
Gasoline	324.5	414.6	469.8	493.0	504.7	511.8	496.5	495.8	53%
Diesel	11.5	14.9	20.1	25.9	26.8	27.3	26.9	26.7	133%
AFVs	0.6	0.5	0.5	1.4	1.3	1.0	1.8	1.9	227%
HFCs from Mobile AC	+	6.5	21.7	31.0	31.2	30.1	28.6	26.6	NA
Medium- and Heavy-Duty Trucks	**231.1**	**277.8**	**354.6**	**408.4**	**418.6**	**425.2**	**403.1**	**365.6**	**58%**
Gasoline	39.5	36.8	37.0	35.8	36.3	36.8	34.4	31.1	-21%
Diesel	190.7	238.6	309.9	361.0	370.4	376.4	356.3	322.0	69%
AFVs	0.9	0.6	0.3	0.5	0.6	0.5	0.8	0.8	-6%
HFCs from Refrigerated Transport	+	1.7	7.4	11.1	11.4	11.5	11.6	11.6	NA
Buses	**8.4**	**9.2**	**11.2**	**12.0**	**12.3**	**12.5**	**12.2**	**11.2**	**34%**
Gasoline	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	-1%
Diesel	8.0	8.7	10.2	10.6	10.8	10.8	10.3	9.3	17%
AFVs	+	0.1	0.5	0.9	0.8	1.0	1.1	1.1	40569%
HFCs from Comfort Cooling	+	+	0.1	0.2	0.3	0.3	0.4	0.4	NA
Motorcycles	**1.8**	**1.8**	**1.9**	**1.7**	**1.9**	**2.1**	**2.2**	**2.2**	**24%**
Gasoline	1.8	1.8	1.9	1.7	1.9	2.1	2.2	2.2	24%
Aircraft	**181.2**	**175.4**	**204.4**	**198.7**	**173.6**	**172.7**	**158.7**	**142.1**	**-22%**
Commercial Aircraft	**136.8**	**143.1**	**170.9**	**162.8**	**138.5**	**139.5**	**123.4**	**112.5**	**-18%**
Jet Fuel	136.8	143.1	170.9	162.8	138.5	139.5	123.4	112.5	-18%
General Aviation Aircraft	**9.6**	**8.2**	**12.1**	**17.5**	**18.5**	**16.9**	**18.8**	**15.3**	**59%**
Jet Fuel	6.4	5.4	9.6	15.0	16.2	14.6	16.8	13.4	109%
Aviation Gasoline	3.2	2.8	2.6	2.5	2.4	2.2	2.0	1.9	-41%
Military Aircraft	**34.8**	**24.1**	**21.3**	**18.3**	**16.5**	**16.3**	**16.4**	**14.3**	**-59%**
Jet Fuel	34.8	24.1	21.3	18.3	16.5	16.3	16.4	14.3	-59%
Ships and Boats[b]	**45.1**	**58.6**	**61.0**	**45.2**	**48.4**	**55.2**	**37.1**	**30.5**	**-32%**
Gasoline	12.6	14.1	10.0	14.2	14.1	14.0	13.6	13.5	7%
Distillate Fuel	9.6	14.9	17.1	11.4	10.9	11.7	3.2	4.8	-50%
Residual Fuel	22.9	29.5	33.8	19.6	23.4	29.5	20.2	12.2	-47%
HFCs from Refrigerated Transport	-	+	0.1	+	+	+	+	+	NA
Rail	**39.0**	**43.7**	**48.1**	**53.0**	**55.1**	**54.3**	**50.6**	**43.3**	**11%**
Distillate Fuel	35.8	40.0	42.5	46.0	48.3	47.0	43.6	36.5	2%
Electricity	3.1	3.1	3.5	4.8	4.5	5.0	4.7	4.4	45%
HFCs from Comfort Cooling	+	+	+	+	+	+	+	+	NA
HFCs from Refrigerated Transport	+	0.5	2.0	2.1	2.2	2.2	2.2	2.2	NA
Other Emissions from Rail Electricity Use	0.1	0.1	+	0.1	0.1	0.1	0.1	0.1	-9%
Pipelines[c]	**36.0**	**38.2**	**35.2**	**32.3**	**32.3**	**34.3**	**35.7**	**35.2**	**-2%**
Natural Gas	36.0	38.2	35.2	32.3	32.3	34.3	35.7	35.2	-2%
Other Transportation	**11.8**	**11.3**	**12.1**	**10.2**	**9.9**	**10.2**	**9.5**	**8.5**	**-28%**
Lubricants	11.8	11.3	12.1	10.2	9.9	10.2	9.5	8.5	-28%
Non-Transportation Mobile Total	**128.8**	**146.8**	**158.3**	**190.7**	**195.8**	**194.8**	**194.2**	**197.7**	**54%**
Agricultural Equipment[d]	**31.4**	**37.0**	**39.2**	**47.3**	**49.6**	**49.0**	**45.9**	**47.2**	**50%**

Gasoline	7.3	8.3	5.8	9.6	11.0	9.6	5.7	6.1	-17%
Diesel	24.1	28.7	33.4	37.7	38.6	39.4	40.3	41.1	71%
Construction/ Mining Equipment[e]	**42.4**	**49.4**	**55.8**	**66.5**	**67.9**	**68.4**	**69.9**	**71.2**	**68%**
Gasoline	4.4	4.0	3.1	6.2	6.2	5.1	5.2	5.0	14%
Diesel	38.0	45.4	52.7	60.3	61.8	63.3	64.8	66.3	74%
Other Equipment[f]	**55.0**	**60.4**	**63.4**	**76.9**	**78.3**	**77.4**	**78.4**	**79.3**	**44%**
Gasoline	40.3	42.6	42.5	52.7	53.4	51.8	52.2	52.4	30%
Diesel	14.7	17.8	20.9	24.2	24.9	25.6	26.2	26.9	83%
Transportation and Non-Transportation Mobile Total	**1,677.1**	**1,845.3**	**2,094.1**	**2,212.9**	**2,194.8**	**2,203.6**	**2,089.7**	**2,014.7**	**20%**

[a] Not including emissions from international bunker fuels.
[b] Fluctuations in emission estimates reflect data collection problems.
[c] Includes only CO_2 from natural gas used to power pipelines; does not include emissions from electricity use or non-CO_2 gases.
[d] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[e] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[f] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.
+ Less than 0.05 Tg CO_2 Eq.
- Unreported or zero
NA = Not Applicable, as there were no HFC emissions allocated to the transport sector in 1990, and thus a growth rate cannot be calculated.

Table A- 110: Transportation and Mobile Source Emissions by Gas (Tg CO₂ Eq.)

Gas	1990	1995	2000	2005	2006	2007	2008	2009	Percent Change 1990-2009
CO_2	1,628.4	1,767.9	1,981.9	2,100.4	2,086.5	2,102.2	1,996.5	1,928.6	18%
N_2O	43.9	54.0	53.2	36.9	33.6	30.3	26.1	23.9	-46%
CH_4	4.7	4.3	3.4	2.5	2.2	2.2	2.0	2.0	-58%
HFC	-	19.0	55.7	72.9	72.2	68.8	64.9	60.2	NA
Total	**1,677.0**	**1,845.2**	**2,094.1**	**2,212.8**	**2,194.7**	**2,203.5**	**2,089.6**	**2,014.6**	**20%**

- Unreported or zero
NA = Not Applicable, as there were no HFC emissions allocated to the transport sector in 1990, and thus a growth rate cannot be calculated.

Figure A-4: Domestic Greenhouse Gas Emissions by Mode and Vehicle Type, 1990 to 2009 (Tg CO₂ Eq.)

Table A- 111: Greenhouse Gas Emissions from Passenger Transportation (Tg CO₂ Eq.)

Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009	Percent Change 1990-2009
On-Road Vehicles	**1,004.1**	**1,093.5**	**1,220.5**	**1,274.5**	**1,261.1**	**1,256.9**	**1,200.8**	**1,191.7**	**19%**
Passenger Cars	657.4	646.0	695.3	709.5	682.9	672.0	632.5	627.4	-5%
Light-Duty Trucks	336.6	436.6	512.1	551.3	564.0	570.3	553.8	551.0	64%
Buses	8.4	9.2	11.2	12.0	12.3	12.5	12.2	11.2	34%
Motorcycles	1.8	1.8	1.9	1.7	1.9	2.1	2.2	2.2	24%
Aircraft	**122.7**	**126.5**	**153.4**	**154.4**	**135.3**	**136.0**	**124.3**	**111.4**	**-9%**
General Aviation	9.6	8.2	12.1	17.5	18.5	16.9	18.8	15.3	59%
Commercial Aircraft	113.1	118.3	141.3	136.8	116.7	119.2	105.5	96.1	-15%
Recreational Boats	**14.5**	**16.4**	**12.7**	**17.4**	**17.3**	**17.3**	**14.5**	**16.9**	**17%**
Passenger Rail	**4.4**	**4.5**	**5.2**	**6.2**	**6.0**	**6.5**	**6.2**	**6.0**	**37%**

| Total | 1,145.7 | | 1,241.0 | | 1,391.8 | | 1,452.5 | 1,419.7 | 1,416.8 | 1,345.8 | 1,326.1 | 16% |

Note: Data from DOE (1993 through 2010) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates.

Table A- 112: Greenhouse Gas Emissions from Domestic Freight Transportation (Tg CO_2 Eq.)

By Mode	1990		1995		2000		2005	2006	2007	2008	2009	Percent Change 1990-2009
Trucking	231.1		277.8		354.6		408.4	418.6	425.2	403.1	365.6	58%
Freight Rail	34.5		39.1		42.8		46.7	49.0	47.8	44.5	37.2	8%
Ships and Other Boats	30.6		42.2		48.3		27.9	31.1	37.9	22.6	13.5	-56%
Pipelines	36.0		38.2		35.2		32.2	32.3	34.3	35.7	35.2	-2%
Commercial Aircraft	23.7		24.8		29.6		26.0	21.8	20.3	18.0	16.4	-31%
Total	**356.0**		**422.1**		**510.5**		**541.1**	**552.8**	**565.5**	**523.7**	**467.9**	**31%**

Note: Data from DOE (1993 through 2010) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates.

3.3.   Methodology for Estimating CH$_4$ Emissions from Coal Mining

The methodology for estimating CH$_4$ 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 CH$_4$ 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 CH4 Liberated and CH4 Emitted from Underground Mines

Underground mines generate CH$_4$ from ventilation systems and from degasification systems. Some mines recover and use CH$_4$ generated from degasification systems, thereby reducing emissions to the atmosphere. Total CH$_4$ emitted from underground mines equals the CH$_4$ liberated from ventilation systems, plus the CH$_4$ liberated from degasification systems, minus CH$_4$ recovered and used.

Step 1.1: Estimate CH$_4$ Liberated from Ventilation Systems

All coal mines with detectable CH$_4$ emissions[45] use ventilation systems to ensure that CH$_4$ levels remain within safe concentrations. Many coal mines do not have detectable levels of CH$_4$, 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 CH$_4$ emissions levels at underground mines. MSHA maintains a database of measurement data from all underground mines with detectable levels of CH$_4$ in their ventilation air. Based on the four quarterly measurements, MSHA estimates average daily CH$_4$ liberated at each of the underground mines with detectable emissions.

For the years 1990 through 1996, 1998 through 2006, 2008 and 2009, 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 A- 113. Well over 90 percent of all ventilation emissions were concentrated in these subsets. For 1997 and 2007, the complete MSHA databases for all 586 mines (in 1997) and 730 mines (in 2007) with detectable CH$_4$ emissions were obtained. These mines were assumed to account for 100 percent of CH$_4$ 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 A- 113). The proportion was then applied to the years 1990 through 2006 to account for the less than 5 percent of ventilation emissions coming from mines without MSHA data.

For 1990 through 1999, average daily CH$_4$ emissions were multiplied by the number of days in the year (i.e., coal mine assumed in operation for all four quarters) to determine the annual emissions for each mine. For 2000 through 2009, MSHA provided quarterly emissions. The average daily CH$_4$ 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 CH$_4$ emissions were multiplied by 92 days. Total ventilation emissions for a particular year were estimated by summing emissions from individual mines.

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[45] 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 A-113: 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)*
2001	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
2002	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
2003	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
2004	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
2005	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
2006	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)*
2007	All Mines with Detectable Emissions (Assumed to Account for 100% of Total)
2008	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)**
2009	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)**

* Factor derived from a complete set of individual mine data collected for 1997.
** Factor derived from a complete set of individual mine data collected for 2007.

Step 1.2: Estimate CH_4 Liberated from Degasification Systems

Coal mines use several different types of degasification systems to remove CH_4, including vertical wells and horizontal boreholes to recover CH_4 prior to mining of the coal seam. Gob wells and cross-measure boreholes recover CH_4 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 CH_4 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 CH_4 liberated from their degasification systems. For these mines, this reported information was used as the estimate. In other cases in which mines sell CH_4 recovered from degasification systems to a pipeline, gas sales were used to estimate CH_4 liberated from degasification systems (see Step 1.3). Finally, for those mines that do not sell CH_4 to a pipeline and have not provided information to EPA, CH_4 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 CH_4 liberated from the mine.

Step 1.3: Estimate CH_4 Recovered from Degasification Systems and Utilized (Emissions Avoided)

In 2009, fourteen active coal mines had CH_4 recovery and use projects. Thirteen mines sold the recovered CH_4 to a pipeline, one used the CH_4 on site to heat mine ventilation air, and one of the coal mines used CH_4 to generate electricity. One of the mines that sold gas to a pipeline also used CH_4 to fuel a thermal coal dryer. 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 CH_4 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 at 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 CH$_4$ Emitted from Surface Mines and Post-Mining Activities

Mine-specific data were not available for estimating CH$_4$ emissions from surface coal mines or for post-mining activities. For surface mines and post-mining activities, basin-specific coal production was multiplied by a basin-specific emission factor to determine CH$_4$ emissions.

Step 2.1: Define the Geographic Resolution of the Analysis and Collect Coal Production Data

The first step in estimating CH$_4$ 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 A- 114, which presents coal basin definitions by basin and by state.

The Energy Information Administration's (EIA) Annual Coal Report includes 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 A- 114. 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 A- 115 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* CH$_4$ 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* CH$_4$ content in the basin. For this analysis, the surface mining emission factor was determined to be twice the *in situ* CH$_4$ content in the basin. Furthermore, the post-mining emission factors used were estimated to be 25 to 40 percent of the average *in situ* CH$_4$ content in the basin. For this analysis, the post-mining emission factor was determined to be 32.5 percent of the *in situ* CH$_4$ content in the basin. Table A- 116 presents the average *in situ* content for each basin, along with the resulting emission factor estimates.

Step 2.3: Estimate CH$_4$ Emitted

The total amount of CH$_4$ emitted was calculated by multiplying the coal production in each basin by the appropriate emission factors.

Total annual CH$_4$ emissions are equal to the sum of underground mine emissions plus surface mine emissions plus post-mining emissions. Table A- 117 and Table A- 118 present estimates of CH$_4$ liberated, used, and emitted for 1990 through 2008. Table A- 119 provides emissions by state.

Table A- 114: 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 A- 115: Annual Coal Production (Thousand Short Tons)

Basin	1990	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Underground Coal Production	**423,556**	**399,102**	**396,249**	**409,850**	**420,657**	**417,729**	**391,791**	**372,766**	**380,627**	**357,384**	**352,785**	**367,558**	**368,611**	**359,020**	**351,791**	**357,074**	**332,061**
N. Appalachia	103,865	100,122	98,103	106,729	112,135	116,718	107,575	105,374	107,025	98,643	98,369	106,915	111,151	107,827	106,024	105,228	99,629
Cent. Appalachia	198,412	170,893	166,495	171,845	177,720	171,279	157,058	150,584	152,457	137,224	130,724	128,559	123,083	117,738	110,103	114,998	98,689
Warrior	17,531	14,471	17,605	18,217	18,505	17,316	14,799	15,895	15,172	14,916	15,375	16,114	13,295	10,737	11,462	12,281	11,505
Illinois	69,167	69,050	69,009	67,046	64,728	64,463	63,529	53,720	54,364	54,016	51,780	56,320	59,180	61,726	61,924	64,609	67,186
S. West/Rockies	32,754	41,681	42,994	43,088	44,503	45,983	46,957	45,742	51,193	52,121	56,111	59,039	60,865	59,670	58,815	55,781	50,416
N. Great Plains	1,722	2,738	2,018	2,788	2,854	1,723	1,673	1,210	-	-	32	201	572	840	2,869	3,669	4,248
West Interior	105	147	25	137	212	247	200	241	415.623	464	394	410	465	482	594	508	388
Northwest	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Surface Coal Production	**602,753**	**634,401**	**636,726**	**654,007**	**669,271**	**699,806**	**708,639**	**700,608**	**745,306**	**735,912**	**717,869**	**743,553**	**762,191**	**802,975**	**793,689**	**813,321**	**740,175**
N. Appalachia	60,761	44,960	39,372	39,788	40,179	41,043	33,928	34,908	35,334	30,088	27,370	28,174	28,873	28,376	26,121	30,413	26,552
Cent. Appalachia	94,343	106,129	106,250	108,869	113,275	108,345	107,507	110,479	116,983	111,340	99,419	103,968	112,222	118,388	116,226	118,962	97,778
Warrior	11,413	8,795	7,036	6,420	5,963	5,697	4,723	4,252	4,796	6,320	8,437	9,742	11,599	11,889	11,410	11,172	10,731
Illinois	72,000	51,868	40,376	44,754	46,862	45,715	40,474	33,631	40,894	39,380	36,675	34,016	33,702	33,362	33,736	34,266	34,837
S. West/Rockies	43,863	49,119	46,643	43,814	48,374	49,635	50,349	49,587	52,180	50,006	41,237	42,558	42,756	36,798	34,310	34,283	32,167
N. Great Plains	249,356	308,279	331,367	343,404	349,612	385,438	407,683	407,670	438,367	441,346	444,007	466,224	474,056	518,136	523,695	538,387	496,290
West Interior	64,310	58,791	59,116	60,912	59,061	57,951	58,309	54,170	50,613	50,459	53,411	51,706	52,263	52,021	46,867	44,361	39,960
Northwest	6,707	6,460	6,566	6,046	5,945	5,982	5,666	5,911	6,138	6,973	7,313	7,165	6,720	4,005	1,324	1,477	1,860
Total Coal Production	**931,068**	**937,594**	**937,115**	**965,131**	**988,783**	**1,013,828**	**998,310**	**973,765**	**1,021,446**	**991,838**	**971,297**	**1,008,000**	**1,025,864**	**1,054,162**	**1,039,178**	**1,170,395**	**1,072,236**
N. Appalachia	164,626	145,082	137,475	146,517	152,314	157,761	141,503	140,282	142,360	128,731	125,739	135,089	140,024	136,203	132,143	135,641	126,181
Cent. Appalachia	292,755	277,022	272,745	280,714	290,995	279,624	264,565	261,063	269,440	248,564	230,143	232,527	235,305	236,126	226,328	233,960	196,467
Warrior	28,944	23,266	24,641	24,637	24,468	23,013	19,522	20,147	19,967	21,236	23,812	25,856	24,894	22,626	22,872	23,453	22,236
Illinois	141,167	120,918	109,385	111,800	111,590	110,178	104,003	87,351	95,258	93,396	88,455	90,336	92,882	95,088	95,660	98,875	102,023
S. West/Rockies	76,617	90,800	89,637	86,902	92,877	95,618	97,306	95,329	103,373	102,127	97,348	101,597	103,621	96,468	93,125	90,064	82,583
N. Great Plains	251,078	311,017	333,385	346,192	352,466	387,161	409,356	408,880	438,367	441,346	444,039	466,425	474,628	518,976	526,564	542,056	500,538
West Interior	64,415	58,938	59,141	61,049	59,273	58,198	58,509	54,411	51,028	50,923	53,805	52,116	52,728	52,503	47,462	44,869	40,348
Northwest	6,707	6,460	6,566	6,046	5,945	5,982	5,666	5,911	6,138	6,973	7,313	7,165	6,720	4,005	1,324	1,477	1,860

Source for 1990-2009 data: EIA (1990 through 2009), Annual Coal Report. U.S. Department of Energy, Washington, DC, Table 1.

Note: Totals may not sum due to independent rounding.

Table A- 116: Coal Surface and Post-Mining CH₄ Emission Factors (ft³ 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	59.5	138.4	119.0	19.3	45.0
Central Appalachia (WV)	24.9	136.8	49.8	8.1	44.5
Central Appalachia (VA)	24.9	399.1	49.8	8.1	129.7
Central Appalachia (E KY)	24.9	61.4	49.8	8.1	20.0
Warrior	30.7	266.7	61.4	10.0	86.7
Illinois	34.3	64.3	68.6	11.1	20.9
Rockies (Piceance Basin)	33.1	196.4	66.2	10.8	63.8
Rockies (Uinta Basin)	16.0	99.4	32.0	5.2	32.3
Rockies (San Juan Basin)	7.3	104.8	14.6	2.4	34.1
Rockies (Green River Basin)	33.1	247.2	66.2	10.8	80.3
Rockies (Raton Basin)	33.1	127.9	66.2	10.8	41.6
N. Great Plains (WY, MT)	20.0	15.8	40.0	6.5	5.1
N. Great Plains (ND)	5.6	15.8	11.2	1.8	5.1
West Interior (Forest City, Cherokee Basins)	34.3	64.3	68.6	11.1	20.9
West Interior (Arkoma Basin)	74.5	331.2	149.0	24.2	107.6
West Interior (Gulf Coast Basin)	11.0	127.9	22.0	3.6	41.6
Northwest (AK)	16.0	160.0	32.0	1.8	52.0
Northwest (WA)	16.0	47.3	32.0	5.2	15.4

Sources: 1986 USBM Circular 9067, *Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins*, 1983 U.S. DOE Report (DOE/METC/83-76), *Methane Recovery from Coalbeds: A Potential Energy Source*, 1986-88 Gas Research Institute Topical Reports, A Geologic Assessment of Natural Gas from Coal Seams; *Surface Mines Emissions Assessment*, U.S. EPA Draft Report, November 2005.

Table A- 117: Underground Coal Mining CH₄ Emissions (Billion Cubic Feet)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Ventilation Output	112	NA	NA	95	96	100	90	96	94	92	87	84	79	76	83	75	79	81	100	114
Adjustment Factor for Mine Data[*]	97.8%	NA	NA	97.8%	97.8%	91.4%	91.4%	100.0%	97.8%	97.8%	97.8%	97.8%	97.8%	97.8%	97.8%	97.8%	97.8%	100.0%	99.0%	99.0%
Adjusted Ventilation Output	114	NA	NA	97	98	109	99	96	96	94	89	86	80	77	84	77	80	81	101	115
Degasification System Liberated	54	NA	NA	45	46	36	52	43	49	40	45	49	51	50	45	48	54	44	49	51
Total Underground Liberated	168	164	162	142	144	146	150	139	146	134	135	135	131	127	130	124	134	125	150	166
Recovered & Used	(14)	(15)	(17)	(23)	(27)	(30)	(37)	(28)	(35)	(31)	(37)	(41)	(43)	(38)	(40)	(37)	(46)	(37)	(40)	(41)
Total	**154**	**150**	**145**	**120**	**117**	**116**	**113**	**111**	**110**	**103**	**98**	**95**	**88**	**89**	**90**	**87**	**88**	**88**	**110**	**125**

* Refer to Table A- 113.
Note: Totals may not sum due to independent rounding.

Table A- 118: Total Coal Mining CH₄ Emissions (Billion Cubic Feet)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Underground Mining	154	150	145	120	117	116	113	111	110	103	98	95	88	89	90	87	88	88	110	125
Surface Mining	30	28	28	28	29	28	29	30	31	31	30	33	32	31	32	33	35	34	35	32
Post-Mining (Underground)	19	18	18	16	17	17	18	18	18	17	17	17	16	16	16	16	15	15	15	14
Post-Mining (Surface)	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	6	6	6	5
Total	**208**	**201**	**195**	**167**	**168**	**166**	**165**	**164**	**165**	**156**	**149**	**149**	**140**	**141**	**144**	**141**	**144**	**143**	**166**	**176**

Note: Totals may not sum due to independent rounding.

Table A- 119: Total Coal Mining CH₄ Emissions by State (Million Cubic Feet)

State	1990	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Alabama	32,272	29,630	33,735	29,556	26,426	26,440	25,702	23,342	21,896	18,686	19,288	18,246	15,912	14,699	17,159	21,120	23,975
Alaska	63	58	63	55	54	50	58	61	56	43	40	56	54	53	49	55	69
Arizona	192	222	203	177	199	192	200	223	228	217	205	216	205	139	135	136	127
Arkansas	7	8	5	4	3	4	4	2	2	2	1	1	1	4	144	237	119
California	1	-	-	-	-	+	+	+	+	+	+	+	+	+	+	-	-
Colorado	10,325	9,192	7,582	5,972	9,189	9,181	9,390	10,808	11,117	12,082	13,216	12,582	13,608	13,102	13,180	12,998	14,100
Illinois	10,502	10,585	11,563	10,876	8,534	7,847	7,810	8,542	7,270	5,972	4,744	5,798	6,586	6,954	4,493	7,759	7,322
Indiana	2,795	2,495	2,025	2,192	2,742	2,878	2,650	2,231	3,373	3,496	3,821	3,531	3,702	4,029	4,347	5,452	6,155
Iowa	30	4	-	-	-	+	+	+	+	+	+	+	+	+	+	-	-
Kansas	57	23	23	19	29	27	33	16	14	16	12	6	14	34	33	18	15
Kentucky	10,956	11,259	10,269	8,987	10,451	10,005	9,561	9,105	9,363	8,464	8,028	7,926	7,494	9,135	9,278	10,641	12,617
Louisiana	81	89	95	82	91	82	76	94	95	97	103	97	106	105	80	98	94
Maryland	519	237	237	259	267	251	225	331	340	401	391	411	421	435	261	325	273
Mississippi	-	-	-	-	-	0	1	57	43	165	264	256	254	271	253	203	246
Missouri	211	67	44	57	32	30	31	35	29	20	43	46	48	31	19	20	36
Montana	1,749	1,936	1,834	1,756	1,906	1,992	1,911	1,783	1,820	1,738	1,719	1,853	1,870	1,931	2,016	2,076	1,804
Mew Mexico	451	679	586	408	459	489	497	464	630	1,280	1,864	2,052	3,001	2,970	2,660	3,479	3,904
North Dakota	380	420	392	389	385	389	405	407	397	401	401	390	390	396	385	386	390
Ohio	5,065	4,583	4,189	4,068	4,349	4,350	3,914	3,519	3,619	2,831	2,649	3,183	3,385	3,413	2,672	3,959	4,746
Oklahoma	285	359	323	286	385	395	469	454	620	660	620	849	877	658	774	970	646

Pennsylvania	22,735		24,024	25,611	26,440	30,026	30,888	24,867	24,830	22,252	19,668	20,281	20,020	18,289	18,727	19,519	21,044	23,216
Tennessee	296		101	112	143	148	116	119	99	142	142	124	136	140	117	120	105	84
Texas	1,426		1,339	1,347	1,411	1,364	1,345	1,357	1,240	1,152	1,157	1,215	1,173	1,175	1,165	1,073	998	898
Utah	3,587		2,626	2,570	2,810	3,566	3,859	3,633	2,816	2,080	2,709	3,408	5,253	4,787	5,445	3,678	5,524	5,449
Virginia	46,137		26,742	20,059	19,771	16,851	13,978	13,321	12,065	11,506	11,227	11,906	11,389	8,790	9,830	10,118	9,334	8,172
Washington	186		182	181	170	167	173	153	159	172	217	232	210	196	96	+	-	-
West Virginia	49,039		30,664	30,552	36,384	33,554	35,566	33,599	30,563	33,985	31,405	28,474	29,465	30,612	29,510	29,654	37,406	41,241
Wyoming	8,496		10,912	12,185	12,838	12,994	14,549	15,607	15,725	17,147	17,352	17,497	18,435	18,784	20,752	20,974	21,601	19,903
Total	**207,844**		**168,433**	**165,785**	**165,109**	**164,171**	**165,075**	**155,568**	**149,371**	**149,348**	**140,449**	**140,544**	**143,581**	**140,698**	**144,004**	**143,076**	**165,945**	**175,598**

- Zero Cubic Feet

+ 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.

3.4. Methodology for Estimating CH_4 and CO_2 Emissions from Natural Gas Systems

The following steps were used to estimate CH_4 and non-energy CO_2 emissions from natural gas systems.

Step 1: Calculate Emission Estimates for Base Year 1992 Using EPA Adjusted GRI/EPA Study

The first step in estimating CH_4 and non-energy related (i.e., fugitive, vented and flared) CO_2 emissions from natural gas systems was to develop a detailed base year estimate of emissions. The study by EPA/GRI (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 activity data for some of the components in the system have been updated based on publicly available data. For other sources where annual activity data are not available, a set of industry activity factor drivers was developed that can be used to update activity data. Table A-120 through Table A-123 display the 2009 activity levels, CH_4 emission factors, and CH_4 emissions for each stage. These data are shown to illustrate the kind of data used to calculate CH_4 and non-energy CO_2 emissions from all stages. Many emission factors determined by EPA/GRI (1996) were assumed to be representative of emissions from each source type over the period 1990 through 2009.

However, several emission factors have been updated since publication of the EPA/GRI 1996 study. Notably, emission factors for gas well cleanups (EPA 2006a, HPDI 2009), condensate storage tanks (EPA 1999, HPDI 2009, TERC 2009), and centrifugal compressors (EPA 2006b, WGC 2009) have been revised. Emissions for gas well completions and workovers (re-completions) with hydraulic fracturing (i.e. unconventional) (EPA 2004, 2007), which were not included in the EPA/GRI study, have also been added. The EPA/GRI study and Inventory did, however, include an estimate for well completions without hydraulic fracturing under the source category Completion Flaring.. The revised 2009 emission factor for centrifugal compressors will be reevaluated in the next Inventory cycle.

For most sources, the CH_4 emission factors were adjusted for CO_2 content when estimating fugitive and vented non-energy CO_2 emissions. In the case of non-energy CO_2 emissions from flared sources, acid gas removal units and condensate tanks, specific industry data related to those sources was used to derive their respective emission factors.

The activity levels and CH_4 emission factors in Table A-120 are arranged into regions designated by the National Energy Modeling System (NEMS) for Oil and Gas Supply. NEMS for Oil and Gas Supply splits the continental United States into 6 regions: Northeast, Midcontinent, Rocky Mountain, South West, West Coast and Gulf Coast. GRI, however, does not evaluate activity data for each of these regions separately. The GRI national AF estimates were allocated to the NEMS oil and gas supply module regions using the NEMS regional gas well counts to national well count ratios.

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 2009, activity levels were estimated using aggregate statistics on key drivers, including: number of producing wells (EIA 2010a-b, New Mexico 2010a-b, Texas 2010a-b), number of gas plants (AGA 1991-1997; OGJ 1998-2010), number of shallow and deep offshore platforms (BOEMRE 2010a-d), miles of transmission pipeline (OPS 2010a), miles of distribution pipeline (OPS 2010b), miles of distribution services (OPS 2010b), and energy consumption (EIA 2010c). Table A-124 provides the activity levels of some of the key drivers in the natural gas analysis.

Step 3: Estimate CH_4 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 accounting for CH_4 reductions reported to the Natural Gas STAR Program and CH_4 reductions resulting from regulations such as National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations.

Industry partners report CH_4 emission reductions by project to the Natural Gas STAR Program. The reductions are estimates using actual measurement data or equipment-specific emission factors. The reductions undergo quality assurance and quality control checks to identify errors, inconsistencies, or irregular data before being incorporated into the Inventory. These quality assurance and quality control checks include matching Natural Gas STAR reported reductions to

specific inventory sources to make sure that a reported reduction for one source is not greater than the emission estimate for that source. Total emissions are estimated by adding the emission estimates from each stage. The base year of the inventory is 1992; therefore any reductions reported for 1992 or earlier are considered to be already included in the base-year emission factors and are not subtracted from the inventory estimate. If the reported reduction occurred between 1990 and 1992, then the reduction is added back into the estimate for the appropriate year(s). The reductions are also adjusted to remove the sunsetting time period which is relevant to Natural Gas STAR accounting but not the Inventory. For example, replacing a gas-assisted pump with an electric pump permanently reduces the vented methane emissions from that source, even after the Natural Gas STAR sunsetting period. CH_4 emission reductions from the Natural Gas STAR Program beyond the efforts reflected in the 1992 base year are summarized in Table A-125.

The 1990 Clean Air Act (CAA) sets the limits on the amount of hazardous air pollutants (HAPs) that can be emitted in the United States. The NESHAP regulations set the standards to limit emissions of HAPs. The emission sources are required to use the Maximum Achievable Control Technology, giving the operators flexibility to choose the type of control measure(s) to implement. In regards to the oil and natural gas industry, the NESHAP regulation addresses HAPs from the oil and natural gas production sectors and the natural gas transmission and storage sectors of the industry. Though the regulation deals specifically with HAPs reductions, methane emissions are also reduced.

The NESHAP regulation requires that glycol dehydration unit vents and storage tanks that have HAP emissions and exceed a gas throughput and liquids throughput value, respectively, be connected to a closed loop emission control system that reduces emissions by 95 percent. Also, gas processing plants exceeding the threshold natural gas throughput limit are required to routinely implement Leak Detection and Survey (LDAR) programs. The emissions reductions achieved as a result of NESHAP regulations were estimated using data provided in the Federal Register Background Information Document (BID) for this regulation. The BID provides the levels of control measures in place before the enactment of regulation. The emissions reductions were estimated by analyzing the portion of the industry without control measures already in place that would be impacted by the regulation. The reductions are representative of the control measures in both the oil and natural gas industry. CH_4 emission reductions from regulations, such as NESHAP, are summarized in Table A-126.

Additionally, some states, such as Wyoming, may require that natural gas produced during well completions not be vented. In these regions emissions from natural gas well completions and re-completions are either recovered for sales or must be flared. The volume of gas recovered by bringing equipment to the wellsite for the treatment and injection of the produced completion gas into the sales pipeline is reported by Natural Gas STAR. The remaining volume of completion gas from states that do not allowing the venting of this gas is flared.

Step 4: Estimate CO_2 Emissions for Each Year and Stage

The same procedure for estimating CH_4 emissions holds true for estimating non-energy related CO_2 emissions, except the emission estimates are not corrected for reductions due to the Natural Gas STAR program or other regulations.

Produced natural gas is composed of primarily CH_4, but as shown in Table A-131, the natural gas contains, in some cases, as much as 8 percent CO_2. The same vented and fugitive emissions of natural gas that led to CH_4 emissions also contain a certain volume of CO_2. Accordingly, the CO_2 emissions for each sector can be estimated using the same methane activity and emissions factors for these vented and fugitive sources. The primary difference is that EPA/GRI emission factors are adjusted for CO_2 content in each sector.

Using the default CH_4 content of produced natural gas from EPA/GRI (1996) of 78.8 percent, the corresponding amount of CO_2 emissions from the production sector can be estimated. Each sector of the natural gas system has varying CO_2 contents, similar to the way the CH_4 content varies among the sectors. Table A-131 shows the CO_2 content for the different well types in the production sector of the natural gas system. In the estimation of CO_2 emissions from the production sector, the production sector CH_4 emission factors were used as a basis to estimate CO_2 emissions; however, they were converted to CO_2 emission factors by multiplication by a conversion factor. This conversion factor is the ratio of CO_2 content in the gas stream (in this case the production concentrations provided in Table A-131) to the corresponding CH_4 content of the same gas stream. The three exceptions to this methodology are CO_2 emissions from flares, acid gas removal units, and condensate tanks. In the case of flare emissions, a direct CO_2 emission factor from EIA (1996) was used. This emission factor was applied to the portion of offshore gas that is not vented and all of the gas reported as vented and flared onshore by EIA. The amount of CO_2 emissions from an acid gas unit in a processing plant is equal to the difference in CO_2 concentrations between produced natural gas and pipeline quality gas applied to the throughput of the plant. This methodology was applied to the national gas throughput using national average CO_2 concentrations in produced gas (3.45 percent) and transmission quality gas (1 percent). For condensate tanks, a series of E&P Tank (EPA

1999) simulations provide the total CO_2 vented per barrel of condensate throughput from fixed roof tank flash gas for condensate gravities of API 45 degree and higher. The ratios of emissions to throughput were used to estimate the CO_2 emission factor for condensate passing through fixed roof tanks. The detailed source emission estimates for CH_4 and CO_2 from the production sector are presented in Table A-127 and

Table A-132, respectively.

In the processing sector, the CO_2 content of the natural gas remains the same as the CO_2 content in the production sector for the equipment upstream of the acid gas removal unit because produced natural gas is usually only minimally treated after being produced and then transported to natural gas processing plants via gathering pipelines. The CO_2 content in gas for the remaining equipment that is downstream of the acid gas removal is the same as in pipeline quality gas. The EPA/GRI study estimates the average CH_4 content of natural gas in the processing sector to be 87 percent CH_4. Consequently, the processing sector CH_4 emission factors were proportioned to reflect the CO_2 content of either produced natural gas or pipeline quality gas using the same methodology as the production sector. The detailed source emission estimates for CH_4 and CO_2 from the processing sector are presented in Table A-128 and Table A-133, respectively.

For the transmission sector, CO_2 content in natural gas transmission pipelines was estimated for the top twenty transmission pipeline companies in the United States (separate analyses identified the top twenty companies based on gas throughput and total pipeline miles). The weighted average CO_2 content in the transmission pipeline quality gas in both cases—total gas throughput and total miles of pipeline—was estimated to be about 1 percent. To estimate the CO_2 emissions for the transmission sector the CH_4 emission factors were proportioned from the 93.4 percent CH_4 reported in EPA/GRI (1996) to reflect the 1 percent CO_2 content found in transmission quality natural gas. The detailed source emissions estimates for CH_4 and CO_2 for the transmission sector are presented in Table A-129 and Table A-134, respectively.

The natural gas in the distribution sector of the system has the same characteristics as the natural gas in the transmission sector. The CH_4 content (93.4 percent) and CO_2 content (1 percent) are identical due to the absence of any further treatment between sector boundaries. Thus, the CH_4 emissions factors were converted to CO_2 emission factors using the same methodology as discussed for the transmission sector. The detailed source emission estimates for CH_4 and CO_2 for the distribution sector are presented in Table A-130 and Table A-135, respectively.

Because Partners report only CH_4 emission reductions to the Natural Gas STAR Program, there was no need to adjust for the Natural Gas STAR program in the CO_2 emissions estimates for any of the sectors in the natural gas system. The impact of regulations, such as NESHAP, on CO_2 emission reductions are not currently addressed in the CO_2 emission estimates.

Table A-120: 2009 Data and CH_4 Emissions (Mg) for the Natural Gas Production Stage

Activity	2009 EPA Inventory Values		
	Activity Data	Emission Factor	Emissions (Mg)
North East			
Gas Wells			
NE - Associated Gas Wells[1,2]	46,914 wells	NA	NA
NE - Non-associated Gas Wells (less Unconventional)	183,834 wells	7.59 scfd/well	9,804.22
NE - Unconventional Gas Wells[3]	0 wells	NE scfd/well	0
Field Separation Equipment			
Heaters	368 heaters	15.13 scfd/heater	39.10
Separators	130,522 separators	0.96 scfd/sep	877.52
Dehydrators	1,213 dehydrators	23.15 scfd/dehy	197.33
Meters/Piping	9,230 meters	9.59 scfd/meter	622.25
Gathering Compressors			
Small Reciprocating Compressors	184 compressors	284.95 scfd/comp	368.26
Large Reciprocating Compressors	24 compressors	16,182 scfd/comp	2,730.18
Large Reciprocating Stations	3 stations	8,776.43 scfd/station	185.09
Pipeline Leaks	87,900 miles	56.57 scfd/mile	34,954.19
Drilling and Well Completion			
Completion Flaring	266 completions/yr	780 scf/comp	4.00
Unconventional Gas Well Completions	0 completions/yr	7,694,435 scf/comp	0
Well Drilling	8,170 Wells	2,706 scf/well	425.89
Normal Operations			
Pneumatic Device Vents	89,343 controllers	367 scfd/device	230,608.23
Chemical Injection Pumps	919 active pumps	264 scfd/pump	1,705.46

Activity	2009 EPA Inventory Values		
	Activity Data	**Emission Factor**	**Emissions (Mg)**
Kimray Pumps	354,971 MMscf/yr	1,056 scf/MMscf	7,217.80
Dehydrator Vents	398,396 MMscf/yr	293.3 scf/MMscf	2,250.58
Condensate Tank Vents			
Condensate Tanks without Control Devices	0 MMbbl/yr	21.87 scf/bbl	0
Condensate Tanks with Control Devices	0 MMbbl/yr	4.37 scf/bbl	0
Compressor Exhaust Vented			
Gas Engines	0 MMHPhr	0.26 scf/HPhr	0
Well Workovers			
Conventional Gas Wells	7,997 workovers/yr	2,612 scf/w.o.	402.26
Unconventional Gas Wells	0 workovers/yr	7,694,435 scf/w.o.	0
Well Clean Ups (LP Gas Wells)	75,923 LP Gas Wells	1,361,786 scfy/LP well	1,991,319.86
Blowdowns			
Vessel BD	132,103 vessels	83 scfy/vessel	211.21
Pipeline BD	87,900 miles (gathering)	329 scfy/mile	556.73
Compressor BD	184 compressors	4,016 scfy/comp	14.22
Compressor Starts	184 compressors	8,985 scfy/comp	31.81
Upsets			
Pressure Relief Valves	352,630 PRV	36 scfy/PRV	245.75
Mishaps	21,975 miles	712 scf/mile	301.34
Midcontinent			
Gas Wells			
MC - Associated Gas Wells[1,2]	72,935 wells	NA	NA
MC - Non-associated Gas Wells	73,913 wells	7.54 scfd/well	3,918.89
MC - Unconventional Gas Wells	13,277 wells	4.71 scfd/well	439.78
Field Separation Equipment			
Heaters	35,399 heaters	15.08 scfd/heater	3,753.52
Separators	37,928 separators	0.95 scfd/sep	254.26
Dehydrators	12,518 dehydrators	96.70 scfd/dehy	8,510.31
Meters/Piping	119,028 meters	9.56 scfd/meter	8,001.30
Gathering Compressors			
Small Reciprocating Compressors	9,852 compressors	284.13 scfd/comp	19,679.53
Large Reciprocating Compressors	16 compressors	16,135 scfd/comp	1,814.87
Large Reciprocating Stations	2 stations	8,751.13 scfd/station	123.04
Pipeline Leaks	68,424 miles	56.40 scfd/mile	27,130.93
Drilling and Well Completion			
Completion Flaring	126 completions/yr	778 scf/comp	1.89
Unconventional Gas Well Completions	575 completions/yr	7,672,247 scf/comp	84,966.30
Well Drilling	3,875 wells	2,699 scf/well	201.41
Normal Operations			
Pneumatic Device Vents	135,232 controllers	366 scfd/device	348,046.02
Chemical Injection Pumps	12,381 active pumps	263 scfd/pump	22,905.82
Kimray Pumps	3,664,068 MMscf/yr	1,053 scf/MMscf	74,288.52
Dehydrator Vents	4,112,309 MMscf/yr	292.5 scf/MMscf	23,163.89
Condensate Tank Vents			
Condensate Tanks without Control Devices	13 MMbbl/yr	302.75 scf/bbl	75,803.69
Condensate Tanks with Control Devices	13 MMbbl/yr	60.55 scf/bbl	15,160.74
Compressor Exhaust Vented			
Gas Engines	16,304 MMHPhr	0.25 scf/HPhr	79,973.26
Well Workovers			
Conventional Gas Wells	3,793 workovers/yr	2,604 scf/w.o.	190.24
Unconventional Gas Wells	1,328 workovers/yr	7,672,247 scf/w.o.	196,190.87
Well Clean Ups (LP Gas Wells)	30,526 LP Gas Wells	711,385 scfy/LP well	418,245.79
Blowdowns			
Vessel BD	85,845 vessels	83 scfy/vessel	136.85
Pipeline BD	68,424 miles (gathering)	328 scfy/mile	432.13
Compressor BD	9,852 compressors	4,005 scfy/comp	759.96
Compressor Starts	9,852 compressors	8,960 scfy/comp	1,700.15
Upsets			
Pressure Relief Valves	167,248 PRV	36 scfy/PRV	116.22
Mishaps	17,106 miles	710 scf/mile	233.90
Rocky Mountain			
Gas Wells			

Activity	2009 EPA Inventory Values		
	Activity Data	Emission Factor	Emissions (Mg)
RM - Associated Gas Wells[1,2]	14,948 wells	NA	NA
RM - Non-associated Gas Wells	75,418 wells	35.62 scfd/well	18,882.55
RM - Unconventional Gas Wells	23,417 wells	6.97 scfd/well	1,147.38
Field Separation Equipment			
Heaters	45,069 heaters	57.43 scfd/heater	18,196.66
Separators	49,319 separators	121.42 scfd/sep	42,097.53
Dehydrators	14,190 dehydrators	90.68 scfd/dehy	9,046.43
Meters/Piping	114,129 meters	52.65 scfd/meter	42,238.56
Gathering Compressors			
Small Reciprocating Compressors	10,971 compressors	266.44 scfd/comp	20,549.03
Large Reciprocating Compressors	32 compressors	15,131 scfd/comp	3,403.78
Large Reciprocating Stations	4 stations	8,206.34 scfd/station	230.76
Pipeline Leaks	125,062 miles	52.89 scfd/mile	46,501.51
Drilling and Well Completion			
Completion Flaring[1]	143 completions/yr	729 scf/comp	2.01
Unconventional Gas Well Completions	0 completions/yr	7,194,624 scf/comp	0
Well Drilling	4,393 wells	2,531 scf/well	214.10
Normal Operations			
Pneumatic Device Vents	144,695 controllers	343 scfd/device	349,219.02
Chemical Injection Pumps	17,593 active pumps	247 scfd/pump	30,521.75
Kimray Pumps	4,153,459 MMscf/yr	987 scf/MMscf	78,968.46
Dehydrator Vents	4,661,570 MMscf/yr	274.3 scf/MMscf	24,623.14
Condensate Tank Vents			
Condensate Tanks without Control Devices	12 MMbbl/yr	21.87 scf/bbl	5,054.59
Condensate Tanks with Control Devices	12 MMbbl/yr	4.37 scf/bbl	1,010.92
Compressor Exhaust Vented			
Gas Engines	18,481 MMHPhr	0.24 scf/HPhr	85,011.32
Well Workovers			
Conventional Gas Wells	4,299 workovers/yr	2,442 scf/w.o.	202.20
Unconventional Gas Wells	2,342 workovers/yr	7,194,624 scf/w.o.	324,485.75
Well Clean Ups (LP Gas Wells)	31,148 LP Gas Wells	710,583 scfy/LP well	426,283.58
Blowdowns			
Vessel BD	108,578 vessels	78 scfy/vessel	162.32
Pipeline BD	125,062 miles (gathering)	307 scfy/mile	740.65
Compressor BD	10,971 compressors	3,756 scfy/comp	793.54
Compressor Starts	10,971 compressors	8,402 scfy/comp	1,775.27
Upsets			
Pressure Relief Valves	189,586 PRV	34 scfy/PRV	123.54
Mishaps	31,266 miles	666 scf/mile	400.89
Coal Bed Methane			
	gal produced	Gg/gallon water	
Powder River	28,577,932,572 water	2.002E-09 drainage	57,494.47
South West			
Gas Wells			
SW - Associated Gas Wells[1,2]	56,810 wells	NA	NA
SW - Non-associated Gas Wells	27,802 wells	37.24 scfd/well	7,278.09
SW - Unconventional Gas Wells	13,740 wells	36.52 scfd/well	3,527.07
Field Separation Equipment			
Heaters	11,258 heaters	58.97 scfd/heater	4,667.26
Separators	23,347 separators	124.68 scfd/sep	20,462.48
Dehydrators	5,964 dehydrators	93.12 scfd/dehy	3,904.30
Meters/Piping	50,678 meters	54.06 scfd/meter	19,258.70
Gathering Compressors			
Small Reciprocating Compressors	5,650 compressors	273.59 scfd/comp	10,866.09
Large Reciprocating Compressors	16 compressors	15,536 scfd/comp	1,747.51
Large Reciprocating Stations	2 stations	8,426.34 scfd/station	118.47
Pipeline Leaks	60,894 miles	54.31 scfd/mile	23,249.07
Drilling and Well Completion			
Completion Flaring	60 completions/yr	749 scf/comp	0.87
Unconventional Gas Well Completions	3,594 completions/yr	7,387,499 scf/comp	511,365.92
Well Drilling	1,846 wells	2,598 scf/well	92.40
Normal Operations			
Pneumatic Device Vents	55,168 controllers	353 scfd/device	136,716.45
Chemical Injection Pumps	2,534 active pumps	253 scfd/pump	4,514.24

Activity	2009 EPA Inventory Values		
	Activity Data	Emission Factor	Emissions (Mg)
Kimray Pumps	1,745,768 MMscf/yr	1,014 scf/MMscf	34,081.57
Dehydrator Vents	1,959,335 MMscf/yr	281.6 scf/MMscf	10,626.97
Condensate Tank Vents			
Condensate Tanks without Control Devices	7 MMbbl/yr	302.75 scf/bbl	40,817.37
Condensate Tanks with Control Devices	7 MMbbl/yr	60.55 scf/bbl	8,163.47
Compressor Exhaust Vented			
Gas Engines	7,768 MMHPhr	0.25 scf/HPhr	36,689.57
Well Workovers			
Conventional Gas Wells	1,807 workovers/yr	2,507 scf/w.o.	87.27
Unconventional Gas Wells	1,374 workovers/yr	7,387,499 scf/w.o.	195,497.16
Well Clean Ups (LP Gas Wells)	11,482 LP Gas Wells	864,974 scfy/LP well	191,288.32
Blowdowns			
Vessel BD	40,569 vessels	80 scfy/vessel	62.27
Pipeline BD	60,894 miles (gathering)	316 scfy/mile	370.30
Compressor BD	5,650 compressors	3,856 scfy/comp	419.62
Compressor Starts	5,650 compressors	8,627 scfy/comp	938.74
Upsets			
Pressure Relief Valves	79,686 PRV	35 scfy/PRV	53.32
Mishaps	15,224 miles	684 scf/mile	200.44
West Coast			
Gas Wells			
WC - Associated Gas Wells[1,2]	24,548 wells	NA	NA
WC - Non-associated Gas Wells	1,786 wells	42.49 scfd/well	533.50
WC - Unconventional Gas Wells[3]	0 wells	NE	0
Field Separation Equipment			
Heaters	1,786 heaters	67.29 scfd/heater	844.89
Separators	1,304 separators	142.27 scfd/sep	1,303.93
Dehydrators	256 dehydrators	106.25 scfd/dehy	191.54
Meters/Piping	3,364 meters	61.68 scfd/meter	1,458.59
Gathering Compressors			
Small Reciprocating Compressors	2,074 compressors	312.19 scfd/comp	4,550.68
Large Reciprocating Compressors	8 compressors	17,728 scfd/comp	997.03
Large Reciprocating Stations	1 stations	9,615.15 scfd/station	67.59
Pipeline Leaks	16,367 miles	61.97 scfd/mile	7,130.46
Drilling and Well Completion			
Completion Flaring	3 completions/yr	855 scf/comp	0.04
Unconventional Gas Well Completions	0 completions/yr	8,429,754 scf/comp	0
Well Drilling	79 wells	2,965 scf/well	4.53
Normal Operations			
Pneumatic Device Vents	1,790 controllers	402 scfd/device	5,060.58
Chemical Injection Pumps	1,213 active pumps	289 scfd/pump	2,465.10
Kimray Pumps	75,055 MMscf/yr	1,157 scf/MMscf	1,671.97
Dehydrator Vents	84,237 MMscf/yr	321.3 scf/MMscf	521.34
Condensate Tank Vents			
Condensate Tanks without Control Devices	0 MMbbl/yr	21.87 scf/bbl	0
Condensate Tanks with Control Devices	0 MMbbl/yr	4.37 scf/bbl	0
Compressor Exhaust Vented			
Gas Engines	334 MMHPhr	0.28 scf/HPhr	1,799.92
Well Workovers			
Conventional Gas Wells	78 workovers/yr	2,861 scf/w.o.	4.30
Unconventional Gas Wells	0 workovers/yr	8,429,754 scf/w.o.	0
Well Clean Ups (LP Gas Wells)	738 LP Gas Wells	1,491,925 scfy/LP well	21,195.07
Blowdowns			
Vessel BD	3,346 vessels	91 scfy/vessel	5.86
Pipeline BD	16,367 miles (gathering)	360 scfy/mile	113.57
Compressor BD	2,074 compressors	4,400 scfy/comp	175.73
Compressor Starts	2,074 compressors	9,844 scfy/comp	393.14
Upsets			
Pressure Relief Valves	3,426 PRV	40 scfy/PRV	2.62
Mishaps	4,092 miles	780 scf/mile	61.48
Gulf Coast			
Gas Wells			

Activity	2009 EPA Inventory Values		
	Activity Data	Emission Factor	Emissions (Mg)
GC - Associated Gas Wells[1,2]	27,134 wells	NA	NA
GC - Non-associated Gas Wells	75,046 wells	40.97 scfd/well	21,613.40
GC - Unconventional Gas Wells[3]	0 wells	NE scfd/well	0
Field Separation Equipment			
Heaters	16,810 heaters	64.88 scfd/heater	7,667.69
Separators	49,381 separators	137.17 scfd/sep	47,618.06
Dehydrators	10,775 dehydrators	102.45 scfd/dehy	7,760.09
Meters/Piping	87,505 meters	59.48 scfd/meter	36,586.28
Gathering Compressors			
Small Reciprocating Compressors	6,079 compressors	301.01 scfd/comp	12,863.02
Large Reciprocating Compressors	24 compressors	17,094 scfd/comp	2,884.00
Large Reciprocating Stations	3 stations	9,270.90 scfd/station	195.52
Pipeline Leaks	98,419 miles	59.75 scfd/mile	41,342.16
Drilling and Well Completion			
Completion Flaring	109 completions/yr	824 scf/comp	1.73
Unconventional Gas Well Completions	0 completions/yr	8,127,942 scf/comp	0
Well Drilling	3,335 wells	2,859 scf/well	183.66
Normal Operations			
Pneumatic Device Vents	52,157 controllers	388 scfd/device	142,210.39
Chemical Injection Pumps	2,477 active pumps	279 scfd/pump	4,853.92
Kimray Pumps	3,153,749 MMscf/yr	1,115 scf/MMscf	67,739.71
Dehydrator Vents	3,539,561 MMscf/yr	309.8 scf/MMscf	21,121.91
Condensate Tank Vents			
Condensate Tanks without Control Devices	33 MMbbl/yr	21.87 scf/bbl	13,900.13
Condensate Tanks with Control Devices	33 MMbbl/yr	4.37 scf/bbl	2,780.03
Compressor Exhaust Vented			
Gas Engines	14,033 MMHPhr	0.27 scf/HPhr	72,923.33
Well Workovers			
Conventional Gas Wells	3,265 workovers/yr	2,759 scf/w.o.	173.49
Unconventional Gas Wells	0 workovers/yr	8,127,942 scf/w.o.	0
Well Clean Ups (LP Gas Wells)	30,994 LP Gas Wells	2,522,975 scfy/LP well	1,506,084
Blowdowns			
Vessel BD	76,966 vessels	88 scfy/vessel	129.99
Pipeline BD	98,419 miles (gathering)	347 scfy/mile	658.48
Compressor BD	6,079 compressors	4,243 scfy/comp	496.73
Compressor Starts	6,079 compressors	9,492 scfy/comp	1,111.26
Upsets			
Pressure Relief Valves	143,954 PRV	38 scfy/PRV	105.98
Mishaps	24,605 miles	752 scf/mile	356.41
Coal Bed Methane			
Black Warrior	5,026 wells	0.0023 Gg/well	11,693.03
Offshore Platforms			
Shallow water Gas Platforms (GoM and Pacific)	Shallow water 2,072 gas platforms	19,178 scfd/platform	279,356
Deepwater Gas Platforms (GoM and Pacific)	Deepwater gas 40 platforms	79,452 scfd/platform	22,389

[1] Emissions from oil wells that produce associated gas are estimated in the Petroleum Systems model. Here the oil wells count is used as a driver only.

[2] NA = not applicable; i.e. this data is not applicable for the Natural Gas systems model.

[3] NE = not estimate; some emission factors were not estimated because there is no corresponding activity for that region.

Table A-121: 2009 Data and CH4 Emissions (Mg) for the Natural Gas Processing Stage

Activity	2009 EPA Inventory Values				
	Activity Data		Emission Factor		Emissions(Mg)
Plants	578	plants	7,906	scfd/plant	32,124
Recip. Compressors	4,876	compressors	11,196	scfd/comp	383,767
Centrifugal Compressors (wet seals)	646	compressors	51,370	scfd/comp	233,371
Centrifugal Compressors (dry seals)	140	compressors	25,189	scfd/comp	24,725
Compressor Exhaust					
Gas Engines	35,030	MMHPhr	0.24	scf/HPhr	161,923
Gas Turbines	41,535	MMHPhr	0.01	scf/HPhr	4,560

	2009 EPA Inventory Values				
Activity	**Activity Data**		**Emission Factor**		**Emissions(Mg)**
AGR Vents	293	AGR units	6,083	scfd/AGR	12,527
Kimray Pumps	1,269,018	MMscf/yr	178	scf/MMscf	4,344
Dehydrator Vents	11,432,591	MMscf/yr	122	scf/MMscf	26,764
Pneumatic Devices	578	gas plants	164,721	scfy/plant	1,834
Blowdowns/Venting	578	gas plants	4,060	Mscfy/plant	45,197

Table A-122: 2009 Data and CH$_4$ Emissions (Mg) for the Natural Gas Transmission Stage

	2009 EPA Inventory Values				
Activity	**Activity Data**		**Emission Factor**		**Emissions(Mg)**
Pipeline Leaks	301,546	miles	1.55	Scfd/ mile	3,294
Compressor Stations (Transmission)					
Station	1,790	Stations	8,778	Scfd/station	110,458
Recip Compressor	7,197	Compressors	15,205	Scfd/ comp	769,264
Centrifugal Compressor (wet seals)	667	Compressors	50,222	Scfd/ comp	235,445
Centrifugal Compressor (dry seals)	55	Compressors	32,208	Scfd/ comp	12,436
Compressor Stations (Storage)					
Station	392	Stations	21,507	Scfd/ comp	59,230
Recip Compressor	1,152	Compressors	21,116	Scfd/ comp	171,007
Centrifugal Compressor (wet seals)	84	Compressors	45,441	Scfd/ comp	26,819
Centrifugal Compressor (dry seals)	29	Compressors	31,989	Scfd/ comp	6,532
Wells (Storage)	18,267	Wells	115	Scfd/ comp	14,704
M&R (Trans. Co. Interconnect)	2,684	Stations	3,984	scfd/station	75,180
M& R (Farm Taps + Direct Sales)	79,592	Stations	31	scfd/station	17,457
Dehydrator vents (Transmission)	1,141,012	MMscf/Year	94	scf/MMscf	2,060
Dehydrator vents (Storage)	2,029,824	MMscf/Year	117	scf/MMscf	4,581
Compressor Exhaust					
Engines (Transmission)	45,546	MMHPhr	0.24	scf/HPhr	210,531
Turbines (Transmission)	10,868	MMHPhr	0.01	scf/HPhr	1,193
Engines (Storage)	4,995	MMHPhr	0.24	scf/HPhr	23,091
Turbines (Storage)	1,755	MMHPhr	0.01	scf/HPhr	193
Generators (Engines)	2,229	MMHPhr	0.24	scf/HPhr	10,302
Generators (Turbines)	26	MMHPhr	0.01	scf/HPhr	3
Pneumatic Devices Trans + Stor					
Pneumatic Devices Trans	70,458	Devices	162,197	Scfy/device	220,104
Pneumatic Devices Storage	15,421	Devices	162,197	Scfy/device	48,174
Routine Maintenance/Upsets					
Pipeline venting	301,546	Miles	32	Mscfy/mile	183,816
Station Venting Trans + Storage					
Station Venting Transmission	1,790	Compressor Stations	4,359	Mscfy/station	150,278
Station Venting Storage	392	Compressor Stations	4,359	Mscfy/station	32,890
LNG Storage					
LNG Stations	70	Stations	21,507	scfd/station	10,623
LNG Reciprocating Compressors	270	Compressors	21,116	scfd/comp	40,147
LNG Centrifugal Compressors	64	Compressors	30,573	scfd/comp	13,766
LNG Compressor Exhaust					
LNG Engines	718	MMHPhr	0.24	scf/HPhr	3,320
LNG Turbines	113	MMHPhr	0.01	scf/HPhr	12
LNG Station Venting	70	Stations	4,359	Mscfy/station	5,899
LNG Import Terminals					
LNG Stations	9	Stations	21,507	scfd/station	1,376
LNG Reciprocating Compressors	44	Compressors	21,116	scfd/comp	6,561
LNG Centrifugal Compressors	8	Compressors	30,573	scfd/comp	1,676
LNG Compressor Exhaust					
LNG Engines	1,904	MMHPhr	0.24	scf/HPhr	8,802
LNG Turbines	461	MMHPhr	0.01	scf/HPhr	51

Activity	2009 EPA Inventory Values				
	Activity Data		Emission Factor		Emissions(Mg)
LNG Station Venting	9	Stations	4,359	Mscfy/station	764

Table A-123: 2009 Data and CH₄ Emissions (Mg) for the Natural Gas Distribution Stage

Activity	2009 EPA Inventory Values				
	Activity Data		Emission Factor		Emissions(Mg)
Pipeline Leaks					
Mains—Cast Iron	35,429	miles	239	Mscf/mile-yr	162,880
Mains—Unprotected steel	67,331	miles	110	Mscf/mile-yr	142,893
Mains—Protected steel	484,337	miles	3	Mscf/mile-yr	28,609
Mains—Plastic	621,404	miles	10	Mscf/mile-yr	118,605
Services—Unprotected steel	5,218,497	services	2	Mscf/service	170,941
Services Protected steel	15,389,666	services	0.2	Mscf/service	52,314
Services—Plastic	42,601,520	services	0.01	Mscf/service	7,629
Services—Copper	1,083,539	services	0.3	Mscf/service	5,308
Meter/Regulator (City Gates)					
M&R >300	3,945	stations	180	scfh/station	119,685
M&R 100-300	14,398	stations	96	scfh/station	232,233
M&R <100	7,696	stations	4	scfh/station	5,596
Reg >300	4,314	stations	162	scfh/station	117,825
R-Vault >300	2,533	stations	1	scfh/station	556
Reg 100-300	13,049	stations	41	scfh/station	89,166
R-Vault 100-300	5,863	stations	0.2	scfh/station	178
Reg 40-100	39,159	stations	1	scfh/station	6,871
R-Vault 40-100	34,726	stations	0.1	scfh/station	507
Reg <40	16,604	stations	0.1	scfh/station	373
Customer Meters					
Residential	40,646,493	outdr meters	143	scfy/meter	112,160
Commercial/Industry	4,121,452	meters	48	scfy/meter	3,802
Routine Maintenance					
Pressure Relief Valve Releases	1,208,501	mile main	0.1	Mscf/mile	1,164
Pipeline Blowdown	1,316,917	miles	0.1	Mscfy/mile	2,587
Upsets					
Mishaps (Dig-ins)	1,316,917	miles	2	Mscfy/mile	40,328

Table A-124: Key Activity Data Drivers

Variable	Units	1990	1992	1995	2000	2005	2006	2007	2008	2009
Transmission Pipelines Length	miles	291,990	291,468	296,947	298,957	300,663	300,458	301,180	303,388	301,546
Wells										
NE—Associated Gas Wells*	# wells	68,261	67,489	66,102	58,671	46,471	47,034	46,646	47,088	46,914
NE—Non-associated Gas Wells*	# wells	124,241	129,157	129,789	143,922	158,238	164,322	172,493	174,682	183,834
MC—Associated Gas Wells*	# wells	64,379	70,640	72,483	67,880	65,652	65,903	69,234	72,622	72,935
MC—Non-associated Gas Wells*	# wells	53,940	59,358	65,585	51,217	71,379	73,914	80,650	82,705	87,190
RM—Associated Gas Wells*	# wells	13,749	14,142	13,745	12,328	13,327	13,437	12,021	14,763	14,948
RM—Non-associated Gas Wells*	# wells	24,339	26,323	32,668	64,539	72,438	75,170	70,532	91,395	98,835
SW—Associated Gas Wells*	# wells	69,339	68,130	59,954	54,830	55,502	54,550	55,251	56,787	56,810
SW—Non-associated Gas Wells*	# wells	24,217	22,609	27,392	32,346	34,194	35,417	38,049	40,176	41,542
WC—Associated Gas Wells*	# wells	20,672	19,819	19,109	20,494	21,562	22,189	22,110	24,271	24,548
WC—Non-associated Gas Wells*	# wells	1,292	1,254	1,114	1,338	1,424	1,503	1,506	1,693	1,786
GC—Associated Gas Wells*	# wells	36,279	35,376	34,792	32,497	28,090	27,319	26,234	27,661	27,134
GC—Non-associated Gas Wells*	# wells	41,753	37,307	41,978	48,316	57,600	60,715	68,188	72,047	75,046
Platforms										
Gulf of Mexico and Pacific OCS Off-shore Platforms	# platforms	3,943	3,966	3,981	4,020	3,911	3,914	3,839	3,761	3,583
GoM and Pacific OCS Deep Water Platforms	# platforms	17	19	23	38	59	67	63	65	68
Gas Plants	**# gas plants**	**761**	**732**	**675**	**585**	**566**	**571**	**574**	**577**	**578**
Distribution Services	**# of services**	**47,883,083**	**49,142,008**	**54,644,033**	**56,761,042**	**58,556,335**	**62,255,435**	**63,524,388**	**63,559,296**	**64,293,222**
Steel—Unprotected	# of services	7,633,526	7,138,563	6,151,653	5,675,520	5,308,375	5,642,470	5,448,804	5,388,623	5,218,497
Steel—Protected	# of services	19,781,581	19,742,086	21,002,455	17,855,560	15,883,423	15,732,037	15,756,048	15,456,866	15,389,666
Plastic	# of services	18,879,865	20,692,674	26,044,545	31,795,871	36,152,277	39,632,313	41,092,515	41,573,069	42,601,520
Copper	# of services	1,588,111	1,568,685	1,445,380	1,434,091	1,212,260	1,248,615	1,227,021	1,140,738	1,083,539
Distribution Mains	**miles**	**944,157**	**888,925**	**1,001,706**	**1,048,485**	**1,093,909**	**1,209,419**	**1,198,585**	**1,188,714**	**1,208,501**
Cast Iron	miles	58,292	52,917	50,625	44,750	37,371	36,977	37,669	36,462	35,429
Steel—Unprotected	miles	108,941	99,619	94,058	82,800	69,291	71,738	69,525	69,374	67,331
Steel—Protected	miles	465,538	469,106	503,288	471,510	461,459	481,811	489,815	479,502	484,337
Plastic	miles	311,386	267,283	353,735	449,425	525,788	618,893	601,575	603,377	621,404

* NEMS (National Energy Modeling System) projects the production, imports, conversion, consumption, and prices of energy, subject to assumptions on macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, cost and performance characteristics of energy technologies, and demographics

Table A-125: CH₄ Reductions Derived from the Natural Gas STAR Program (Gg)

Process	1992*		1995		2000		2005	2006	2007	2008	2009
Production	0		75		318		1,425	1,471	1,863	2,239	1,993
Processing	0		5		23		129	140	139	145	83
Transmission and Storage	0		121		258		500	480	454	440	367
Distribution	0		19		27		35	48	35	28	41
Total	**0**		**220**		**626**		**2,090**	**2,138**	**2,492**	**2,852**	**2,484**

*Reductions are relative to 1992; therefore, there are zero reductions in 1992.
Note: These reductions will not match the Natural Gas STAR program reductions. These numbers are adjusted for reductions prior to the 1992 base year, and do not include a sunsetting period. Totals may not sum due to independent rounding.

Table A-126: CH₄ Reductions Derived from Regulations (Gg)

Process	1990		1995		2000		2005	2006	2007	2008	2009
Production	9.8		24.1		303.6		278.4	1,572	783.5	966.5	733.7
Processing	NA		NA		12.9		12.1	12.4	13.0	13.7	14.2
Transmission and Storage	NA		NA		NA		NA	NA	NA	NA	NA
Distribution	NA		NA		NA		NA	NA	NA	NA	NA
Total	**9.8**		**24.1**		**316.5**		**290.5**	**1,584**	**796.5**	**980.2**	**747.9**

NA Not applicable
Note: NESHAP regulations went into effect in 1999. Totals may not sum due to independent rounding.

Table A-127: CH₄ Emission Estimates from the Natural Gas Production Stage Excluding Reductions from the Natural Gas STAR Program and Regulations (Gg)

Activity	1990		1992		1995		2000		2005	2006	2007	2008	2009
Normal Fugitives													
Associated Gas Wells													
Non-Associated Gas Wells (less conventional)	30.82		31.68		37.42		48.05		52.88	50.86	52.48	58.63	62.03
Unconventional Gas Wells	0.01		0.02		0.04		0.26		0.53	1.32	1.53	1.67	1.59
Field Separation Equipment													
Heaters	12.57		13.28		16.48		23.56		26.90	28.01	28.36	33.09	35.17
Separators	43.83		44.16		54.79		76.51		86.43	90.24	94.09	106.73	112.61
Dehydrators	14.75		15.76		17.89		20.77		23.95	24.93	26.17	28.07	29.61
Meter/ Piping	43.61		44.95		54.89		73.80		83.74	87.18	90.23	102.50	108.17
Gathering Compressors													
Small Reciprocating Comp.	30.22		32.15		38.27		45.57		53.85	56.10	58.49	65.19	68.88
Large Reciprocating Comp.	7.50		8.56		9.80		11.70		12.60	12.59	12.71	13.58	13.58
Large Reciprocating Stations	0.51		0.58		0.66		0.79		0.85	0.85	0.86	0.92	0.92
Pipeline Leaks	98.03		102.22		114.49		133.58		148.45	152.97	160.02	172.60	180.31
Vented and Combusted													
Drilling and Well Completion													
Completion Flaring	0.01		0.01		0.01		0.01		0.01	0.01	0.01	0.01	0.01
Unconventional Gas Well Completions	16.48		23.53		31.66		422.38		203.69	2,502.62	855.93	1,089.76	596.33
Well Drilling	0.74		0.54		0.53		1.01		1.63	1.85	1.90	1.93	1.12
Coal Bed Methane													
Powder River	0.04		0.47		1.48		28.76		46.38	56.38	54.60	57.58	57.49
Black Warrior	2.72		4.84		6.25		6.82		9.88	10.45	11.09	11.69	11.69
Normal Operations													
Pneumatic Device Vents	569.76		607.88		697.61		810.83		954.88	991.35	1,043.32	1,145.65	1,211.86
Chemical Injection Pumps	26.89		29.38		35.04		43.44		51.88	53.93	54.93	62.93	66.97
Kimray Pumps	131.82		140.65		159.45		185.01		213.32	222.04	233.36	250.28	263.97
Dehydrator Vents	41.10		43.86		49.72		57.69		66.52	69.24	72.76	78.04	82.31
Condensate Tank Vents													

Activity	1990	1992	1995	2000	2005	2006	2007	2008	2009
Condensate Tanks without Control Device	77.69	59.56	58.09	67.47	99.33	109.76	114.96	135.58	135.58
Condensate Tanks with Control Device	15.54	11.91	11.62	13.49	19.87	21.95	22.99	27.12	27.12
Compressor Exhaust Vented									
Gas Engines	119.06	125.48	151.43	180.03	215.10	224.16	235.19	261.65	276.40
Well Workovers Conventional Gas Wells	0.56	0.58	0.64	0.73	0.84	0.87	0.94	1.00	1.06
Unconventional Gas Wells	2.92	7.16	16.07	98.40	241.50	492.00	574.10	685.67	716.17
Well Clean Ups (LP Gas Wells)	2,651.65	2,699.26	2,931.40	3,330.18	3,755.97	3,804.83	4,134.53	4,333.13	4,554.42
Blowdowns									
Vessel BD	0.36	0.38	0.42	0.49	0.56	0.58	0.62	0.67	0.71
Pipeline BD	1.56	1.63	1.82	2.13	2.36	2.44	2.55	2.75	2.87
Compressor BD	1.17	1.24	1.48	1.76	2.08	2.17	2.26	2.52	2.66
Compressor Starts	2.61	2.78	3.31	3.94	4.65	4.85	5.05	5.63	5.95
Upsets									
Pressure Relief Valves	0.34	0.35	0.39	0.45	0.51	0.53	0.57	0.61	0.65
Mishaps	0.85	0.88	0.99	1.15	1.28	1.32	1.38	1.49	1.55
Offshore									
Offshore water Gas Platforms (GoM & Pacific)	290.64	298.00	307.56	324.06	321.98	321.51	305.25	298.98	279.36
Deepwater Gas Platforms (GoM & Pacific)	5.21	5.94	7.40	12.81	20.43	23.20	21.10	21.78	22.39
Total	**4,242**	**4,360**	**4,819**	**6,028**	**6,725**	**9,423**	**8,274**	**9,059**	**8,931**

Note: Totals may not sum due to independent rounding.

Table A-128: CH₄ Emission Estimates from the Natural Gas Processing Plants Excluding Reductions from the Natural Gas STAR Program and Regulations (Gg)

Activity	1990	1992	1995	2000	2005	2006	2007	2008	2009
Normal Fugitives									
Plants	42.30	40.68	37.52	32.51	31.46	31.74	31.90	32.07	32.12
Reciprocating Compressors	324.94	324.74	338.42	349.51	327.87	337.12	351.55	371.25	383.77
Centrifugal Compressors (wet seals)	240.29	240.15	248.60	251.32	229.24	229.92	230.99	232.45	233.37
Centrifugal Compressors (dry seals)	0.00	0.00	0.81	3.50	6.48	9.50	14.21	20.64	24.73
Vented and Combusted									
Normal Operations Compressor Exhaust									
Gas Engines	137.10	137.02	142.79	147.47	138.34	142.24	148.33	156.64	161.92
Gas Turbines	3.86	3.86	4.02	4.15	3.90	4.01	4.18	4.41	4.56
AGR Vents	16.49	15.87	14.63	12.68	12.27	12.38	12.44	12.51	12.53
Kimray Pumps	3.68	3.68	3.83	3.96	3.71	3.82	3.98	4.20	4.34
Dehydrator Vents	22.66	22.65	23.60	24.38	22.87	23.51	24.52	25.89	26.76
Pneumatic Devices	2.41	2.32	2.14	1.86	1.80	1.81	1.82	1.83	1.83
Routine Maintenance Blowdowns/Venting	59.51	57.24	52.78	45.74	44.26	44.65	44.88	45.12	45.20
Total	853.24	848.20	869.16	877.08	822.18	840.69	868.81	907.01	931.14

Note: Totals may not sum due to independent rounding.

Table A-129: CH$_4$ Emission Estimates from the Natural Gas Transmission and Storage Excluding Reductions from the Natural Gas STAR Program and Regulations (Gg)

Activity	1990	1992	1995	2000	2005	2006	2007	2008	2009
Fugitives									
Pipelines Leaks	3.19	3.18	3.24	3.27	3.28	3.28	3.29	3.31	3.29
Compressor Stations (Transmission)									
Station	106.96	106.77	108.77	109.51	110.13	110.06	110.32	111.13	110.46
Recip Compressor	744.89	743.55	757.53	762.66	767.01	766.49	768.33	773.96	769.26
Centrifugal Compressor (wet seals)	246.76	246.32	249.68	245.59	236.93	236.75	236.81	237.00	235.44
Centrifugal Compressor (dry seals)	0.00	0.00	0.81	4.53	11.01	11.01	11.36	12.44	12.44
Compressor Stations (Storage)									
Station	54.64	58.36	60.35	62.17	60.06	54.36	58.76	60.62	59.23
Recip Compressor	157.80	168.48	174.27	179.62	173.53	157.05	169.67	175.16	171.01
Centrifugal Compressor (wet seals)	33.22	35.46	36.55	34.41	30.91	27.39	27.65	27.78	26.82
Centrifugal Compressor (dry seals)	0.00	0.00	0.13	2.54	4.10	4.10	5.72	6.53	6.53
Wells (Storage)	13.56	14.49	14.98	15.43	14.91	13.49	14.59	15.05	14.70
M&R (Trans. Co. Interconnect)	72.80	72.67	74.03	74.53	74.96	74.91	75.09	75.64	75.18
M&R (Farm Taps + Direct Sales)	16.90	16.87	17.19	17.31	17.41	17.39	17.44	17.56	17.46
Vented and Combusted									
Normal Operation									
Dehydrator Vents (Transmission)	1.99	1.99	2.03	2.04	2.05	2.05	2.06	2.07	2.06
Dehydrator Vents (Storage)	4.23	4.51	4.67	4.81	4.65	4.20	4.54	4.69	4.58
Compressor Exhaust									
Engines (Transmission)	176.92	186.65	204.91	215.30	203.10	200.09	213.12	214.32	210.53
Turbines (Transmission)	1.00	1.06	1.16	1.22	1.15	1.13	1.21	1.21	1.19
Engines (Storage)	21.30	22.75	23.53	24.24	23.41	21.19	22.91	23.63	23.09
Turbines (Storage)	0.18	0.19	0.20	0.20	0.20	0.18	0.19	0.20	0.19
Generators (Engines)	8.66	9.13	10.03	10.54	9.94	9.79	10.43	10.49	10.30
Generators (Turbines)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pneumatic Devices Trans+Stor									
Pneumatic Devices Trans	213.13	212.75	216.75	218.21	219.46	219.31	219.84	221.45	220.10
Pneumatic Devices Storage	44.44	47.46	49.09	50.56	48.85	44.21	47.79	49.31	48.17
Routine Maintenance/Upsets									
Pipeline Venting	177.99	177.67	181.01	182.24	183.28	183.15	183.59	184.94	183.82
Station venting Trans+Storage									
Station Venting Transmission	145.52	145.26	147.99	148.99	149.84	149.74	150.10	151.20	150.28
Station Venting Storage	30.34	32.41	33.51	34.52	33.35	30.18	32.63	33.66	32.89
LNG Storage									
LNG Stations	9.24	9.45	9.77	10.30	10.62	10.62	10.62	10.62	10.62
LNG Reciprocating Compressors	34.50	35.37	36.67	38.84	40.15	40.15	40.15	40.15	40.15
LNG Centrifugal Compressors	11.78	12.09	12.55	13.31	13.77	13.77	13.77	13.77	13.77
LNG Compressor Exhaust									
LNG Engines	3.21	3.23	3.26	3.30	3.32	3.32	3.32	3.32	3.32
LNG Turbines	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
LNG Station Venting	5.13	5.25	5.43	5.72	5.90	5.90	5.90	5.90	5.90

Activity	1990	1992	1995	2000	2005	2006	2007	2008	2009
LNG Import Terminals									
LNG Stations	0.21	0.21	0.21	0.21	0.42	0.42	0.42	1.06	1.38
LNG Reciprocating Compressors	1.01	1.01	1.01	1.01	2.02	2.02	2.02	5.05	6.56
LNG Centrifugal Compressors	0.26	0.26	0.26	0.26	0.52	0.52	0.52	1.29	1.68
LNG Compressor Exhaust									
LNG Engines	1.74	0.96	0.49	4.41	12.18	11.28	14.81	6.91	8.80
LNG Turbines[1]	0.01	0.00	0.00	0.03	0.07	0.07	0.09	0.04	0.05
LNG Station Venting	0.12	0.12	0.12	0.12	0.24	0.24	0.24	0.59	0.76
Total	**2,344**	**2,376**	**2,442**	**2,482**	**2,473**	**2,430**	**2,479**	**2,502**	**2,482**

[1] Emissions are not actually 0, but too small to show at this level of precision.

Note: Totals may not sum due to independent rounding.

Table A-130: CH$_4$ Emission Estimates from the Natural Gas Distribution Stage Excluding Reductions from the Natural Gas STAR Program (Gg)

Activity	1990	1992	1995	2000	2005	2006	2007	2008	2009
Pipeline Leaks									
Mains—Cast Iron	267.99	243.28	232.74	205.73	171.81	170.00	173.18	167.63	162.88
Mains—Unprotected steel	231.20	211.42	199.62	175.72	147.05	152.25	147.55	147.23	142.89
Mains—Protected steel	27.50	27.71	29.73	27.85	27.26	28.46	28.93	28.32	28.61
Mains—Plastic	59.43	51.02	67.52	85.78	100.36	118.13	114.82	115.16	118.61
Services—Unprotected steel	250.05	233.84	201.51	185.91	173.89	184.83	178.49	176.51	170.94
Services Protected steel	67.24	67.11	71.39	60.70	53.99	53.48	53.56	52.54	52.31
Services—Plastic	3.38	3.71	4.66	5.69	6.47	7.10	7.36	7.44	7.63
Services—Copper	7.78	7.68	7.08	7.02	5.94	6.12	6.01	5.59	5.31
Meter/Regulator (City Gates)									
M&R >300	110.41	117.93	121.96	125.62	121.36	109.84	118.73	122.50	119.68
M&R 100-300	214.25	228.82	236.64	243.76	235.49	213.13	230.38	237.70	232.23
M&R <100	5.16	5.51	5.70	5.87	5.67	5.14	5.55	5.73	5.60
Reg >300	108.70	116.09	120.06	123.67	119.48	108.13	116.88	120.60	117.83
R-Vault >300	0.51	0.55	0.57	0.58	0.56	0.51	0.55	0.57	0.56
Reg 100-300	82.26	87.86	90.86	93.59	90.42	81.83	88.45	91.26	89.17
R-Vault 100-300	0.16	0.18	0.18	0.19	0.18	0.16	0.18	0.18	0.18
Reg 40-100	6.34	6.77	7.00	7.21	6.97	6.31	6.82	7.03	6.87
R-Vault 40-100	0.47	0.50	0.52	0.53	0.51	0.47	0.50	0.52	0.51
Reg <40	0.34	0.37	0.38	0.39	0.38	0.34	0.37	0.38	0.37
Customer Meters									
Residential	103.47	110.51	114.29	117.72	113.73	102.93	111.26	114.80	112.16
Commercial/Industry	3.97	4.25	4.78	4.66	3.95	3.85	3.98	4.03	3.80
Routine Maintenance									
Pressure Relief Valve Releases	0.91	0.86	0.96	1.01	1.05	1.16	1.15	1.14	1.16
Pipeline Blowdown	2.39	2.55	2.64	2.72	2.62	2.37	2.57	2.65	2.59
Upsets									
Mishaps (Dig-ins)	37.20	39.74	41.09	42.33	40.89	37.01	40.01	41.28	40.33
Total	**1,591**	**1,568**	**1,562**	**1,524**	**1,430**	**1,394**	**1,437**	**1,451**	**1,422**

Note: Totals may not sum due to independent rounding.

Table A-131: U.S. Production Sector CO$_2$ Content in Natural Gas by NEMS Region and Natural Gas Well type

Well Types	North East	Midcontinent	Gulf Coast	South West	Rocky Mountain	West Coast	Lower-48 States
Conventional	0.92%	0.79%	2.17%	3.81%	7.95%	0.16%	3.41%
Un-conventional	7.42%	0.31%	0.23%	NA	0.64%	NA	4.83%
All types	3.04%	0.79%	2.17%	3.81%	7.58%	0.16%	3.45%

Table A-132: CO₂ Emission Estimates from the Natural Gas Production Stage (Gg)

Activity	1990	1992	1995	2000	2005	2006	2007	2008	2009
Normal Fugitives									
Gas Wells									
Non-Associated Gas Wells	3.56	3.57	4.25	6.46	7.00	6.18	5.86	7.33	8.00
Unconventional Gas Wells[2]	0.00	0.00	0.00	0.01	0.01	0.03	0.03	0.03	0.03
Field Separation Equipment									
Heaters	1.86	1.91	2.32	3.95	4.44	4.61	4.48	5.54	5.95
Separators	6.04	5.97	7.17	11.29	12.68	13.20	13.16	15.78	16.82
Dehydrators	1.50	1.54	1.73	2.58	2.83	2.94	2.93	3.38	3.60
Meter/ Piping	5.85	5.85	6.95	10.90	12.21	12.69	12.57	15.14	16.15
Gathering Compressors									
Small Reciprocating Comp.	2.95	2.98	3.57	5.46	6.17	6.41	6.38	7.63	8.15
Large Reciprocating Comp.	0.69	0.91	1.02	1.33	1.40	1.40	1.40	1.62	1.62
Large Reciprocating Stations	0.05	0.06	0.07	0.09	0.09	0.09	0.09	0.11	0.11
Pipeline Leaks	10.75	10.85	11.99	16.04	17.64	18.21	18.25	20.80	21.94
Vented and Combusted									
Drilling and Well Completion									
Completion Flaring[2]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Unconventional Gas Well Completions	2.19	1.58	5.27	122.20	21.29	748.86	166.74	108.05	85.45
Well Drilling	0.07	0.05	0.05	0.12	0.18	0.21	0.20	0.22	0.13
Coal Bed Methane									
Powder River[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Black Warrior[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Normal Operations									
Pneumatic Device Vents	58.49	60.24	69.38	101.86	114.87	119.29	118.75	139.81	149.18
Chemical Injection Pumps	2.95	3.11	3.75	6.33	7.18	7.45	7.20	8.94	9.61
Kimray Pumps	13.41	13.71	15.43	22.91	25.15	26.12	26.05	30.04	31.99
Dehydrator Vents	4.18	4.28	4.81	7.14	7.84	8.15	8.12	9.37	9.98
Condensate Tank Vents									
Condensate Tanks without Control Device	10.25	9.43	8.79	9.34	10.25	11.26	11.17	11.90	11.90
Condensate Tanks with Control Device	2.05	1.89	1.76	1.87	2.05	2.25	2.23	2.38	2.38
Compressor Exhaust Vented Gas Engines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Well Workovers									
Gas Wells	0.06	0.06	0.06	0.08	0.09	0.10	0.10	0.11	0.12
Unconventional Gas Wells	0.47	0.84	2.35	22.89	43.99	118.88	135.55	146.36	145.24
Well Clean Ups (LP Gas Wells)	251.41	252.88	273.66	339.56	375.89	367.69	377.12	413.61	439.94
Blowdowns									
Vessel BD	0.04	0.04	0.04	0.06	0.06	0.07	0.07	0.08	0.08
Pipeline BD	0.17	0.17	0.19	0.26	0.28	0.29	0.29	0.33	0.35
Compressor BD	0.11	0.12	0.14	0.21	0.24	0.25	0.25	0.29	0.31
Compressor Starts	0.25	0.26	0.31	0.47	0.53	0.55	0.55	0.66	0.70
Upsets									
Pressure Relief Valves	0.03	0.03	0.04	0.05	0.06	0.06	0.06	0.07	0.07
Mishaps	0.09	0.09	0.10	0.14	0.15	0.16	0.16	0.18	0.19
Flaring Emissions - Onshore	9,092.72	10,172.49	17,167.79	5,525.04	7,193.00	7,812.35	8,664.25	10,024.82	9,545.39
Offshore									
Offshore water Gas Platforms (GoM & Pacific)	1.48	1.51	1.56	1.64	1.63	1.63	1.55	1.52	1.42
Deepwater Gas Platforms (GoM & Pacific)	0.03	0.03	0.04	0.07	0.10	0.12	0.11	0.11	0.11
Flaring Emissions - Offshore	230.37	163.13	197.22	204.31	180.66	146.48	160.05	360.00	360.00
Total	**9,704**	**10,720**	**17,792**	**6,425**	**8,050**	**9,438**	**9,746**	**11,336**	**10,877**

[1] Energy use CO₂ emissions not estimated to avoid double counting. NE = not estimated.
[2] Emissions are not actually 0, but too small to show at this level of precision.
Note: Totals may not sum due to independent rounding.

Table A-133: CO_2 Emission Estimates from the Natural Gas Processing Plants (Gg)

Activity	1990	1992	1995	2000	2005	2006	2007	2008	2009
Normal Fugitives									
Plants – Before CO_2 removal	2.56	2.46	2.27	1.97	1.90	1.92	1.93	1.94	1.94
Plants – After CO_2 removal	0.57	0.55	0.50	0.44	0.42	0.43	0.43	0.43	0.43
Reciprocating Compressors – Before CO_2 removal	19.67	19.66	20.49	21.16	19.85	20.41	21.28	22.47	23.23
Reciprocating Compressors – After CO_2 removal	4.37	4.36	4.55	4.70	4.41	4.53	4.72	4.99	5.16
Centrifugal Compressors (wet seals) – Before CO_2 removal	14.55	14.54	15.05	15.21	13.88	13.92	13.98	14.07	14.13
Centrifugal Compressors (wet seals) – After CO_2 removal	3.23	3.23	3.34	3.38	3.08	3.09	3.10	3.12	3.14
Centrifugal Compressors (dry seals) – Before CO_2 removal	0	0	0.05	0.21	0.39	0.58	0.86	1.25	1.50
Centrifugal Compressors (dry seals) – After CO_2 removal	0	0	0.01	0.05	0.09.	0.13	0.19	0.28	0.33
Vented and Combusted									
Normal Operations									
Compressor Exhaust									
Gas Engines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Gas Turbines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
AGR Vents	27,708	26,652	24,577	23,288	21,694	21,161	21,144	21,328	21,130
Kimray Pumps	0.39	0.39	0.41	0.42	0.40	0.41	0.43	0.45	0.46
Dehydrator Vents	2.42	2.42	2.52	2.61	2.45	2.51	2.62	2.77	2.86
Pneumatic Devices	0.29	0.27	0.25	0.22	0.21	0.21	0.22	0.22	0.22
Routine Maintenance									
Blowdowns/Venting	6.36	6.12	5.64	4.89	4.73	4.78	4.80	4.83	4.83
Total	**27,763**	**26,706**	**24,632**	**23,343**	**21,746**	**21,214**	**21,199**	**21,385**	**21,189**

[1] Energy use CO_2 emissions not estimated to avoid double counting. NE = not estimated.
Note: Totals may not sum due to independent rounding.

Table A-134: CO_2 Emission Estimates from the Natural Gas Transmission and Storage (Gg)

Activity	1990	1992	1995	2000	2005	2006	2007	2008	2009
Fugitives									
Pipelines Leaks	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.10	0.10
Compressor Stations (Transmission)									
Station	3.09	3.08	3.14	3.16	3.18	3.17	3.18	3.21	3.19
Recip Compressor	21.49	21.45	21.85	22.00	22.12	22.11	22.16	22.33	22.19
Centrifugal Compressor (wet seals)	7.12	7.11	7.20	7.08	6.83	6.83	6.83	6.84	6.79
Centrifugal Compressor (dry seals)	0	0	0.02	0.13	0.32	0.32	0.33	0.36	0.36
Compressor Stations (Storage)									
Station	1.58	1.68	1.74	1.79	1.73	1.57	1.69	1.75	1.71
Recip Compressor	4.55	4.86	5.03	5.18	5.01	4.53	4.89	5.05	4.93
Centrifugal Compressor (wet seals)	0.96	1.02	1.05	0.99	0.89	0.79	0.80	0.80	0.77
Centrifugal Compressor (dry seals)	0	0	0.00	0.07	0.12	0.12	0.17	0.19	0.19
Wells (Storage)	0.39	0.42	0.43	0.45	0.43	0.39	0.42	0.43	0.42
M&R (Trans. Co. Interconnect)	2.10	2.10	2.14	2.15	2.16	2.16	2.17	2.18	2.17
M&R (Farm Taps + Direct Sales)	0.49	0.49	0.50	0.50	0.50	0.50	0.50	0.51	0.50
Vented and Combusted									
Normal Operation									
Dehydrator Vents (Transmission)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Dehydrator Vents (Storage)	0.12	0.13	0.13	0.14	0.13	0.12	0.13	0.14	0.13
Compressor Exhaust									
Engines (Transmission)[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Turbines (Transmission)[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE

Activity	1990	1992	1995	2000	2005	2006	2007	2008	2009
Engines (Storage)[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Turbines (Storage)[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Generators (Engines)[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Generators (Turbines)[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
Pneumatic Devices Trans+Stor									
Pneumatic Devices Trans	6.15	6.14	6.25	6.29	6.33	6.33	6.34	6.39	6.35
Pneumatic Devices Storage	1.28	1.37	1.42	1.46	1.41	1.28	1.38	1.42	1.39
Routine Maintenance/Upsets									
Pipeline Venting	5.13	5.13	5.22	5.26	5.29	5.28	5.30	5.33	5.30
Station venting Trans+Storage									
Station Venting Transmission	4.20	4.19	4.27	4.30	4.32	4.32	4.33	4.36	4.33
Station Venting Storage	0.88	0.93	0.97	1.00	0.96	0.87	0.94	0.97	0.95
LNG Storage									
LNG Stations	0.31	0.32	0.33	0.35	0.36	0.36	0.36	0.36	0.36
LNG Reciprocating Compressors	1.16	1.18	1.23	1.30	1.34	1.34	1.34	1.34	1.34
LNG Centrifugal Compressors	0.39	0.41	0.42	0.45	0.46	0.46	0.46	0.46	0.46
LNG Compressor Exhaust									
LNG Engines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
LNG Turbines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
LNG Station Venting	0.17	0.18	0.18	0.19	0.20	0.20	0.20	0.20	0.20
LNG Import Terminals									
LNG Stations	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.04	0.05
LNG Reciprocating Compressors	0.03	0.03	0.03	0.03	0.07	0.07	0.07	0.17	0.22
LNG Centrifugal Compressors	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.04	0.06
LNG Compressor Exhaust									
LNG Engines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
LNG Turbines[1]	NE	NE	NE	NE	NE	NE	NE	NE	NE
LNG Station Venting[2]	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.03
Total	**61.75**	**62.37**	**63.73**	**64.44**	**64.36**	**63.31**	**64.18**	**65.04**	**64.55**

[1] Energy use CO_2 emissions not estimated to avoid double counting. NE = not estimated.

2 Emissions are not actually 0, but too small to show at this level of precision.

Note: Totals may not sum due to independent rounding.

Table A-135: CO_2 Emission Estimates from the Natural Gas Distribution Stage (Gg)

Activity	1990	1992	1995	2000	2005	2006	2007	2008	2009
Pipeline Leaks									
Mains—Cast Iron	7.73	7.02	6.71	5.93	4.96	4.90	5.00	4.84	4.70
Mains—Unprotected steel	6.67	6.10	5.76	5.07	4.24	4.39	4.26	4.25	4.12
Mains—Protected steel	0.79	0.80	0.86	0.80	0.79	0.82	0.83	0.82	0.83
Mains—Plastic	1.71	1.47	1.95	2.47	2.89	3.41	3.31	3.32	3.42
Total Pipeline Miles									
Services—Unprotected steel	7.21	6.75	5.81	5.36	5.02	5.33	5.15	5.09	4.93
Services Protected steel	1.94	1.94	2.06	1.75	1.56	1.54	1.54	1.52	1.51
Services—Plastic	0.10	0.11	0.13	0.16	0.19	0.20	0.21	0.21	0.22
Services—Copper	0.22	0.22	0.20	0.20	0.17	0.18	0.17	0.16	0.15
Meter/Regulator (City Gates)									
M&R >300	3.18	3.40	3.52	3.62	3.50	3.17	3.42	3.53	3.45
M&R 100-300	6.18	6.60	6.83	7.03	6.79	6.15	6.65	6.86	6.70
M&R <100	0.15	0.16	0.16	0.17	0.16	0.15	0.16	0.17	0.16
Reg >300	3.14	3.35	3.46	3.57	3.45	3.12	3.37	3.48	3.40
R-Vault >300	0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02
Reg 100-300	2.37	2.53	2.62	2.70	2.61	2.36	2.55	2.63	2.57
R-Vault 100-300	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01
Reg 40-100	0.18	0.20	0.20	0.21	0.20	0.18	0.20	0.20	0.20
R-Vault 40-100	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
Reg <40	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Customer Meters									
Residential	2.98	3.19	3.30	3.40	3.28	2.97	3.21	3.31	3.24
Commercial/Industry	0.11	0.12	0.14	0.13	0.11	0.11	0.11	0.12	0.11
Routine Maintenance									

Activity	1990		1992		1995		2000		2005	2006	2007	2008	2009
Pressure Relief Valve Releases	0.03		0.02		0.03		0.03		0.03	0.03	0.03	0.03	0.03
Pipeline Blowdown	0.07		0.07		0.08		0.08		0.08	0.07	0.07	0.08	0.07
Upsets													
Mishaps (Dig-ins)	1.07		1.15		1.19		1.22		1.18	1.07	1.15	1.19	1.16
Total	**45.90**		**45.24**		**45.05**		**43.97**		**41.25**	**40.20**	**41.46**	**41.85**	**41.03**

[1] Emissions are not actually 0, but too small to show at this level of precision.

Note: Totals may not sum due to independent rounding.

3.5. Methodology for Estimating CH$_4$ and CO$_2$ Emissions from Petroleum Systems

The methodology for estimating CH$_4$ and non-combustion CO$_2$ 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 the study, *Methane Emissions from the U.S. Petroleum Industry* (EPA/GRI 1996). Sixty-four activities that emit CH$_4$ and thirty activities that emit non-combustion CO$_2$ from petroleum systems were examined from these reports. Most of the activities analyzed involve crude oil production field operations, which accounted for about 98 percent of total oil industry CH$_4$ emissions. Crude transportation and refining accounted for the remaining CH$_4$ emissions of less than one half and about one and a half percent, respectively. Non-combustion CO$_2$ emissions were analyzed for production operations and asphalt blowing in refining operations. Non-combustion CO$_2$ emissions from transportation operations are not included because they are negligible. The following steps were taken to estimate CH$_4$ and CO$_2$ emissions from petroleum systems.

Step 1: Determine Emission Factors for all Activities

The CH$_4$ emission factors for the majority of the activities for 1995 are taken from the 1999 EPA draft report, which contained the most recent and comprehensive determination of CH$_4$ emission factors for the 64 CH$_4$-emitting activities in the oil industry at that time. Emission factors for pneumatic devices in the production sector were recalculated in 2002 using emissions data in the EPA/GRI 1996c study. The gas engine emission factor is taken from the EPA/GRI 1996b study. The oil tank venting emission factor is taken from the API E&P Tank Calc weighted average for API gravity less than 45 API degrees with the distribution of gravities taken from a sample of production data from the HPDI database. Offshore emissions from shallow water and deep water oil platforms are taken from analysis of the Gulf-wide Offshore Activity Data System (GOADS) report (EPA 2005, BOEMRE 2004). The emission factors determined for 1995 were assumed to be representative of emissions from each source type over the period 1990 through 2009. Therefore, the same emission factors are used for each year throughout this period.

The CO$_2$ emission factors were derived from the corresponding source CH$_4$ emission factors. The amount of CO$_2$ in the crude oil stream changes as it passes through various equipment in petroleum production operations. As a result, four distinct stages/streams with varying CO$_2$ contents exist. The four streams that are used to estimate the emissions factors are the associated gas stream separated from crude oil, hydrocarbons flashed out from crude oil (such as in storage tanks), whole crude oil itself when it leaks downstream, and gas emissions from offshore oil platforms. The standard approach used to estimate CO$_2$ emission factors was to use the existing CH$_4$ emissions factors and multiply them by a conversion factor, which is the ratio of CO$_2$ content to methane content for the particular stream. Ratios of CO$_2$ to CH$_4$ volume in emissions are presented in Table A-5. The two exceptions are the emissions factor for storage tanks, which is estimated using API E&P Tank Calc simulation runs of tank emissions for crude oil of different gravities less than 45 API degrees; and the emissions factor for uncontrolled asphalt blowing, which is estimated using the data and methods provided by API (2009).

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, refinery runs. Some change in proportion to the number of facilities: oil wells, petroleum refineries. Some factors change proportional to both the rate and number of facilities.

For most sources, activity levels found in the EPA/GRI 1996 for the 1995 base year are extrapolated to other years using publicly-available data sources. For the remaining sources, the activity levels are obtained directly from publicly available data and are not extrapolated from the 1995 base year.

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. Publicly-reported data from the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), Energy Information Administration (EIA), American Petroleum Institute (API), the Oil & Gas Journal (O&GJ), the Interstate Oil and Gas Compact Commission (IOGCC), and the U.S Army Corps of Engineers (USACE) were used to extrapolate the activity levels from the base year to each year between 1990 and 2009. Data used include total domestic crude oil production, number of domestic crude oil wells, total imports and exports of crude oil, total petroleum refinery crude runs, and number of oil-producing offshore platforms. The activity data for the total crude transported in the transportation sector is not available. In this case, all the crude oil that was transported was assumed to go to refineries. Therefore, the activity data for the refining sector was used also for the transportation sector. In the few cases where no data was located, oil industry data based on expert judgment was used. In the case of non-combustion CO$_2$ emission sources, the activity factors remain the same as for CH$_4$ emission sources.

Step 3: Estimate Methane and Carbon Dioxide Emissions for Each Activity for Each Year

Annual CH_4 emissions from each of the 64 petroleum system activities and CO_2 emissions from the 30 petroleum system activities were estimated by multiplying the activity data for each year by the corresponding emission factor. These annual emissions for each activity were then summed to estimate the total annual CH_4 and CO_2 emissions, respectively. Table A- 140 provides the CO2 content in natural gas for equipment in different crude streams to estimate CO2 emission factors using CH4 [emission] factors.

Table A-136, Table A-137, Table A-138, and Table A-141 provide 2009 activity factors, emission factors, and emission estimates and Table A-139 and Table A-142 provide a summary of emission estimates for the years 1990, 1995, 2000, and 2005 through 2009. Table A- 140 provides the CO_2 content in natural gas for equipment in different crude streams to estimate CO_2 emission factors using CH_4 emission factors.

Table A-136: 2009 CH₄ Emissions from Petroleum Production Field Operations

Activity/Equipment	2009 EPA Inventory Values		Emissions (Bcf/yr)	Emissions (Gg/yr)
	Emission Factor	Activity Factor		
Vented Emissions			**67.625**	**1,300**
Oil Tanks	7.39 scf of CH₄/bbl crude	1,490 MMbbl/yr (non stripper wells)	11.016	211.8
Pneumatic Devices, High Bleed	330 scfd CH₄/device	139,797 No. of high-bleed devices	16.859	324.2
Pneumatic Devices, Low Bleed	52 scfd CH₄/device	259,624 No. of low-bleed devices	4.928	94.76
Chemical Injection Pumps	248 scfd CH₄/pump	28,166 No. of pumps	2.550	49.04
Vessel Blowdowns	78 scfy CH₄/vessel	182,451 No. of vessels	0.014	0.274
Compressor Blowdowns	3,775 scf/yr of CH₄/compressor	2,473 No. of compressors	0.009	0.179
Compressor Starts	8,443 scf/yr. of CH₄/compressor	2,473 No. of compressors	0.021	0.401
Stripper wells	2,345 scf/yr of CH₄/stripper well	317,230 No. of stripper wells vented	0.744	14.31
Well Completion Venting	733 scf/completion	11,804 Oil well completions	0.009	0.166
Well Workovers	96 scf CH₄/workover	39,450 Oil well workovers	0.004	0.073
Pipeline Pigging	2.40 scfd of CH₄/pig station	0 No. of crude pig stations	-	-
Offshore Platforms, Shallow water Oil, fugitive, vented and combusted	54,795 scfd CH₄/platform	1,441 No. of shallow water oil platforms	28.823	554.3
Offshore Platforms, Deepwater oil, fugitive, vented and combusted	260,274 scfd CH₄/platform	28 No. of deep water oil platforms	2.649	50.93
Fugitive Emissions			**2.539**	**49**
Oil Wellheads (heavy crude)	0.13 scfd/well	14,718 No. of hvy. crude wells	0.001	0.013
Oil Wellheads (light crude)	16.6 scfd/well	194,052 No. of lt. crude wells	1.178	22.65
Separators (heavy crude)	0.15 scfd CH₄/separator	10,740 No. of hvy. crude seps.	0.001	0.012
Separators (light crude)	14 scfd CH₄/separator	97,745 No. of lt. crude seps.	0.494	9.504
Heater/Treaters (light crude)	19 scfd CH₄/heater	73,966 No. of heater treaters	0.518	9.965
Headers (heavy crude)[1]	0.08 scfd CH₄/header	13,721 No. of hvy. crude hdrs.	0.000	0.007
Headers (light crude)	11 scfd CH₄/header	42,536 No. of lt. crude hdrs.	0.169	3.241
Floating Roof Tanks	338,306 scf CH₄/floating roof tank/yr.	24 No. of floating roof tanks	0.008	0.159
Compressors	100 scfd CH₄/compressor	2,473 No. of compressors	0.090	1.736
Large Compressors	16,360 scfd CH₄/compressor	0 No. of large comprs.	-	-
Sales Areas	41 scf CH₄/loading	1,630,377 Loadings/year	0.066	1.271
Pipelines	NE scfd of CH₄/mile of pipeline	11,249 Miles of gathering line	NE	NE
Well Drilling	NE scfd of CH₄/oil well drilled	13,255 No. of oil wells drilled	NE	NE
Battery Pumps	0.24 scfd of CH₄/pump	157,800 No. of battery pumps	0.014	0.266
Combustion Emissions			**4.7926**	**92.22**
Gas Engines	0.24 scf CH₄/HP-hr	15,577 MMHP-hr	3.739	71.89
Heaters	0.52 scf CH₄/bbl	1956.8 MMbbl/yr	1.020	19.61
Well Drilling	2,453 scf CH₄/well drilled	13,255 Oil wells drilled	0.033	0.625

Activity/Equipment	2009 EPA Inventory Values		Emissions (Bcf/yr)	Emissions (Gg/yr)
	Emission Factor	Activity Factor		
Flares	20 scf CH_4/Mcf flared	242,355 Mcf flared/yr	0.005	0.932
Process Upset Emissions			**0.116**	**2.233**
Pressure Relief Valves	35 scf/yr/PR valve	163,449 No. of PR valves	0.006	0.109
Well Blowouts Onshore	2.5 MMscf/blowout	44.2 No. of blowouts/yr	0.110	2.124
Total			**75.08**	**1,444**

- Zero Emissions

[1] Emissions are not actually 0, but too small to show at this level of precision.

NE: Not estimated for lack of data

Table A-137: 2009 CH₄ Emissions from Petroleum Transportation

Activity/Equipment	Emission Factor	Units	Activity Factor	Units	Emissions (Bcf/yr)	Emissions (Gg/yr)
Vented Emissions					**0.209**	**4.024**
Tanks	0.021	scf CH_4/yr/bbl of crude delivered to refineries	5,233	MMbbl crude feed/yr	0.108	2.073
Truck Loading	0.520	scf CH_4/yr/bbl of crude transported by truck	67.8	MMbbl trans. by truck	0.035	0.678
Marine Loading	2.544	scf CH_4/1000 gal. crude marine loadings	19,609,664	1,000 gal./yr loaded	0.050	0.959
Rail Loading	0.520	scf CH_4/yr/bbl of crude transported by rail	4.2	MMbbl Crude by rail/yr	0.002	0.042
Pump Station Maintenance[1]	36.80	scf CH_4/station/yr	496	No. of pump stations	0.000	0.000
Pipeline Pigging	39	scfd of CH_4/pig station	992	No. of pig stations	0.014	0.271
Fugitive Emissions					**0.050**	**0.958**
Pump Stations	25	scf CH_4/mile/yr.	49,585	No. of miles of crude p/l	0.001	0.024
Pipelines	NE	scf CH_4/bbl crude transported by pipeline	6,431	MMbbl crude piped	NE	NE
Floating Roof Tanks	58,965	scf CH_4/floating roof tank/yr.	824	No. of floating roof tanks	0.049	0.934
Combustion Emissions					**NE**	**NE**
Pump Engine Drivers	0.24	scf CH_4/hp-hr	NE	No. of hp-hrs	NE	NE
Heaters	0.521	scf CH_4/bbl burned	NE	No. of bbl Burned	NE	NE
Total					**0.259**	**4.982**

[1] Emissions are not actually 0, but too small to show at this level of precision.

NE: Not estimated for lack of data

Table A-138: 2009 CH₄ Emissions from Petroleum Refining

Activity/Equipment	2009 EPA Inventory Values		Emissions (Bcf/yr)	Emissions (Gg/yr)
	Emission Factor	Activity Factor		
Vented Emissions			**1.065**	**20.48**
Tanks	20.6 scf CH_4/Mbbl	1,839 Mbbl/calendar day heavy crude feed	0.014	0.266
System Blowdowns	137 scf CH_4/Mbbl	14,336 Mbbl/calendar day refinery feed	0.716	13.77
Asphalt Blowing	2,555 scf CH_4/Mbbl	359 Mbbl/calendar day production	0.335	6.445
Fugitive Emissions			**0.088**	**1.702**
Fuel Gas System	439 Mscf CH_4/refinery/yr	150 Refineries	0.066	1.266
Floating Roof Tanks[1]	587 scf CH_4/floating roof tank/yr.	767 No. of floating roof tanks	0.000	0.009
Wastewater Treating	1.88 scf CH_4/Mbbl	14,336 Mbbl/calendar day refinery feed	0.010	0.189
Cooling Towers	2.36 scf CH_4/Mbbl	14,336 Mbbl/calendar day refinery feed	0.012	0.237
Combustion Emissions			**0.090**	**1.723**
Atmospheric Distillation	3.61 scf CH_4/Mbbl	14,659 Mbbl/calendar day refinery feed	0.019	0.371
Vacuum Distillation	3.61 scf CH_4/Mbbl	6,503 Mbbl/calendar day feed	0.009	0.165

Activity/Equipment	2009 EPA Inventory Values			
	Emission Factor	Activity Factor	Emissions (Bcf/yr)	Emissions (Gg/yr)
Thermal Operations	6.01 scf CH$_4$/Mbbl	2,034 Mbbl/calendar day feed	0.004	0.086
Catalytic Cracking	5.17 scf CH$_4$/Mbbl	4,694 Mbbl/calendar day feed	0.009	0.170
Catalytic Reforming	7.22 scf CH$_4$/Mbbl	2,970 Mbbl/calendar day feed	0.008	0.150
Catalytic Hydrocracking	7.22 scf CH$_4$/Mbbl	1,393 Mbbl/calendar day feed	0.004	0.071
Hydrorefining	2.17 scf CH$_4$/Mbbl	2,067 Mbbl/calendar day feed	0.002	0.031
Hydrotreating	6.50 scf CH$_4$/Mbbl	9,480 Mbbl/calendar day feed	0.022	0.432
Alkylation/Polymerization	12.6 scf CH$_4$/Mbbl	1,027 Mbbl/calendar day feed	0.005	0.091
Aromatics/Isomeration	1.80 scf CH$_4$/Mbbl	956 Mbbl/calendar day feed	0.001	0.012
Lube Oil Processing	0.00 scf CH$_4$/Mbbl	165 Mbbl/calendar day feed	0.000	0.000
Engines	0.006 scf CH$_4$/hp-hr	1,128 MMhp-hr/yr	0.006	0.124
Flares	0.189 scf CH$_4$/Mbbl	14,336 Mbbl/calendar day refinery feed	0.001	0.019
Total			**1.243**	**23.90**

[1] Emissions are not actually 0, but too small to show at this level of precision.

Table A-139: Summary of CH$_4$ Emissions from Petroleum Systems (Gg)

Activity	1990		1995		2000		2005	2006	2007	2008	2009
Production Field Operations	**1,653**		**1,557**		**1,468**		**1,366**	**1,365**	**1,396**	**1,409**	**1,444**
Pneumatic device venting	489		463		428		397	396	398	416	419
Tank venting	250		226		214		187	188	192	189	212
Combustion & process upsets	88		82		76		71	71	72	75	94
Misc. venting & fugitives	799		762		727		691	693	714	707	696
Wellhead fugitives	26		25		22		19	17	20	23	23
Crude Oil Transportation	**7**		**6**		**5**		**5**	**5**	**5**	**5**	**5**
Refining	**25**		**26**		**28**		**28**	**28**	**27**	**25**	**24**
Total	**1,685**		**1,589**		**1,501**		**1,398**	**1,398**	**1,427**	**1,439**	**1,473**

Note: Totals may not sum due to independent rounding.

Table A-140: Ratios of CO$_2$ to CH$_4$ Volume in Emissions from Petroleum Production Field Operations

	Whole Crude, Post-Separator	Associated Gas	Tank Flash Gas	Offshore
Ratio %CO$_2$ / %CH$_4$	0.052	0.020	0.017	0.004

Table A-141: 2009 CO$_2$ Emissions from Petroleum Production Field Operations and Petroleum Refining

Activity/Equipment	2009 EPA Inventory Values			
	Emission Factor	Activity Factor	Emissions (Bcf/yr)	Emissions (Gg/yr)
Vented Emissions			**5.972**	**316.5**
Oil Tanks	3.53 scf of CO$_2$/bbl crude	1,490 MMbbl/yr (non stripper wells)	5.256	278.6
Pneumatic Devices, High Bleed	6.704 scfd CO$_2$/device	139,797 No. of high-bleed devices	0.342	18.13
Pneumatic Devices, Low Bleed	1.055 scfd CO$_2$/device	259,624 No. of low-bleed devices	0.100	5.299
Chemical Injection Pumps	5.033 scfd CO$_2$/pump	28,166 No. of pumps	0.052	2.742
Vessel Blowdowns[1]	1.583 scfy CO$_2$/vessel	182,451 No. of vessels	0.000	0.015
Compressor Blowdowns[1]	77 scf/yr of CO$_2$/compressor	2,473 No. of compressors	0.000	0.010
Compressor Starts[1]	171 scf/yr. of CO$_2$/compressor	2,473 No. of compressors	0.000	0.022
Stripper wells	48 scf/yr of CO$_2$/stripper well	317,230 No. of stripper wells vented	0.015	0.800
Well Completion Venting[1]	14.87 scf/completion	11,804 Oil well completions	0.000	0.009
Well Workovers[1]	1.95 scf CO$_2$/workover	39,450 Oil well workovers	0.000	0.004
Pipeline Pigging	NE scfd of CO$_2$/pig station	NE No. of crude pig stations	NE	NE
Offshore Platforms, Shallow water Oil, fugitive, vented and combusted	358 scfd CO$_2$/platform	1,441 No. of shallow water oil platforms	0.188	9.984
Offshore Platforms, Deepwater oil,	1,701 scfd CO$_2$/platform	28 No. of deep water oil	0.017	0.917

Activity/Equipment	2009 EPA Inventory Values			Emissions (Bcf/yr)	Emissions (Gg/yr)
	Emission Factor		Activity Factor		
fugitive, vented and combusted	platforms				
Fugitive Emissions				**0.052**	**2.776**
Oil Wellheads (heavy crude)[1]	0.003	scfd/well	14,718 No. of hvy. crude wells	0.000	0.001
Oil Wellheads (light crude)	0.337	scfd/well	194,052 No. of lt. crude wells	0.024	1.267
Separators (heavy crude)[1]	0.003	scfd CO_2/separator	10,740 No. of hvy. crude seps.	0.000	0.001
Separators (light crude)	0.281	scfd CO_2/separator	97,745 No. of lt. crude seps.	0.010	0.531
Heater/Treaters (light crude)	0.319	scfd CO_2/heater	73,966 No. of heater treaters	0.009	0.456
Headers (heavy crude)[1]	0.002	scfd CO_2/header	13,721 No. of hvy. crude hdrs.	0.000	0.000
Headers (light crude)	0.220	scfd CO_2/header	42,536 No. of lt. crude hdrs.	0.003	0.181
Floating Roof Tanks[1]	17,490	scf CO_2/floating roof tank/yr.	24 No. of floating roof tanks	0.000	0.023
Compressors	2.029	scfd CO_2/compressor	2,473 No. of compressors	0.002	0.097
Large Compressors	332	scfd CO_2/compressor	0 No. of large comprs.	0.000	0.000
Sales Areas	2.096	scf CO_2/loading	1,630,377 Loadings/year	0.003	0.181
Pipelines	NE	scfd of CO_2/mile of pipeline	11,249 Miles of gathering line	NE	NE
Well Drilling	NE	scfd of CO_2/oil well drilled	13,255 No. of oil wells drilled	NE	NE
Battery Pumps	0.012	scfd of CO_2/pump	157,800 No. of battery pumps	0.001	0.038
Process Upset Emissions				**0.003**	**0.134**
Pressure Relief Valves[1]	1.794	scf/yr/PR valve	163,499 No. of PR valves	0.000	0.016
Well Blowouts Onshore	0.051	MMscf/blowout	44 No. of blowouts/yr	0.002	0.119
Refining Emissions				**2.720**	**144.2**
Asphalt Blowing[2]	20,736	scf CO_2/Mbbl	359 Mbbl/calendar day production	2.720	144.2
Total				**8.747**	**463.6**

[1] Emissions are not actually 0, but too small to show at this level of precision.

[2] Asphalt Blowing emissions are the only significant vented emissions from the refining sector; other sources are too small to show at this level of precision.

NE: Not estimated for lack of data

Energy use CO_2 emissions not estimated to avoid double counting with fossil fuel combustion

Table A-142: Summary of CO_2 Emissions from Petroleum Systems (Gg)

Activity	1990	1995	2000	2005	2006	2007	2008	2009
Production Field Operations	**376**	**341**	**323**	**285**	**285**	**292**	**288**	**319**
Pneumatic device venting	27	26	24	22	22	22	23	23
Tank venting	328	296	281	246	246	252	247	278
Misc. venting & fugitives	18	18	17	16	16	16	16	16
Wellhead fugitives	1	1	1	1	1	1	1	1
Refining								
Asphalt Blowing	180	187	211	205	203	182	165	144
Total	**555**	**528**	**534**	**490**	**488**	**474**	**453**	**463**

3.6. Methodology for Estimating CO_2, N_2O and CH_4 Emissions from the Incineration of Waste

Emissions of CO_2 from the incineration of waste include CO_2 generated by the incineration of plastics, synthetic rubber and synthetic fibers in municipal solid waste (MSW), and incineration of tires (which are composed in part of synthetic rubber and C black) in a variety of other combustion facilities (e.g., cement kilns). Incineration of waste also results in emissions of N_2O and CH_4. The methodology for calculating emissions from each of these waste incineration sources is described in this Annex.

CO_2 from Plastics Incineration

In the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2011), the flows of plastics in the U.S. waste stream are reported for seven resin categories. For 2009, the quantity generated, recovered, and discarded for each resin is shown in Table A-143. The data set for 1990 through 2009 is incomplete, and several assumptions were employed to bridge the data gaps. The EPA reports do not provide estimates for individual materials landfilled and incinerated, although they do provide such an estimate for the waste stream as a whole. To estimate the quantity of plastics landfilled and incinerated, total discards were apportioned based on the proportions of landfilling and incineration for the entire U.S. waste stream for each year in the time series according to *Biocycle's State of Garbage in America* (van Haaren et al. 2010). For those years when distribution by resin category was not reported (1990 through 1994), total values were apportioned according to 1995 (the closest year) distribution ratios. Generation and recovery figures for 2002 and 2004 were linearly interpolated between surrounding years' data.

Table A-143: 2008 Plastics in the Municipal Solid Waste Stream by Resin (Gg)

Waste Pathway	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Generation	3,202	4,727	1,016	5,715	5,017	2,241	5,144	**27,261**
Recovery	662	535	0	290	45	18	372	**1,923**
Discard	2,540	4,191	1,016	5,425	4,971	2,223	4,772	**25,338**
Landfill	2,316	3,822	926	4,947	4,533	2,027	4,351	**23,104**
Combustion	224	369	90	478	438	196	421	**2,234**
Recovery*	21%	11%	0%	5%	1%	1%	7%	**7%**
Discard*	79%	89%	100%	95%	99%	99%	93%	**93%**
Landfill*	72%	81%	91%	87%	90%	90%	85%	**85%**
Combustion*	7%	8%	9%	8%	9%	9%	8%	**8%**

*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 were calculated as the product of plastic combusted, C content, and fraction oxidized (see Table A-144). The C 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 A-144: 2008 Plastics Incinerated (Gg), Carbon Content (%), Fraction Oxidized (%) and Carbon Incinerated (Gg)

Factor	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other[a]	Total
Quantity Combusted	224	369	90	478	438	196	421	2,234
Carbon Content of Resin	63%	86%	38%	86%	86%	92%	66%	-
Fraction Oxidized	98%	98%	98%	98%	98%	98%	98%	-
Carbon in Resin Combusted	137	310	34	402	368	177	271	1,700
Emissions (Tg CO_2 Eq.)	**0.5**	**1.1**	**0.1**	**1.5**	**1.3**	**0.6**	**1.0**	**6.2**

[a] Weighted average of other plastics produced.
Note: Totals may not sum due to independent rounding.

CO_2 from Incineration of Synthetic Rubber and Carbon Black in Tires

Emissions from tire incineration require two pieces of information: the amount of tires incinerated and the C content of the tires. *Scrap Tire Markets in the United States: 9th Biennial Report* (RMA 2009a) reports that 2,484.4

thousand of the 4,105.8 thousand tons of scrap tires generated in 2007 (approximately 61 percent of generation) were used for fuel purposes. Using RMA's estimates of average tire composition and weight, the mass of synthetic rubber and C black in scrap tires was determined:

- Synthetic rubber in tires was estimated to be 90 percent C by weight, based on the weighted average C contents of the major elastomers used in new tire consumption.[46] Table A- 145 shows consumption and C content of elastomers used for tires and other products in 2002, the most recent year for which data are available.

- C black is 100 percent C (Aslett Rubber Inc. n.d.).

Multiplying (a) the mass of scrap tires incinerated by (b) the total C content of the synthetic rubber and C black portions of scrap tires and (c) by a 98 percent oxidation factor yielded CO_2 emissions, as shown in Table A- 146. The disposal rate of rubber in tires (0.5 Tg C/yr) is smaller than the consumption rate for tires based on summing the elastomers listed in Table A- 145 (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 may also reflect the lag time between consumption and disposal of tires. Tire production and fuel use for 1990 through 2007 were taken from RMA 2006 and RMA 2009a; when data were not reported, they were linearly interpolated between bracketing years' data or, for the ends of time series, set equal to the closest year with reported data.

RMA 2009a changed the reporting of scrap tire data from millions of tires to thousands of short tons of scrap tire. As a result, the average weight and percent of the market of light duty and commercial scrap tires was used to convert the previous years from millions of tires to thousands of short tons (STMC 1990 through 1997; RMA 2002 through 2006, 2009b).

Table A- 145: Elastomers Consumed in 2002 (Gg)

Elastomer	Consumed	Carbon Content	Carbon Equivalent
Styrene butadiene rubber solid	**768**	**91%**	**700**
For Tires	660	91%	602
For Other Products*	108	91%	98
Polybutadiene	**583**	**89%**	**518**
For Tires	408	89%	363
For Other Products	175	89%	155
Ethylene Propylene	**301**	**86%**	**258**
For Tires	6	86%	5
For Other Products	295	86%	253
Polychloroprene	**54**	**59%**	**32**
For Tires	0	59%	0
For Other Products	54	59%	32
Nitrile butadiene rubber solid	**84**	**77%**	**65**
For Tires	1	77%	1
For Other Products	83	77%	64
Polyisoprene	**58**	**88%**	**51**
For Tires	48	88%	42
For Other Products	10	88%	9
Others	**367**	**88%**	**323**
For Tires	184	88%	161
For Other Products	184	88%	161
Total	**2,215**	**-**	**1,950**
For Tires	**1,307**	**-**	**1,174**

*Used to calculate C content of non-tire rubber products in municipal solid waste.
- Not applicable
Note: Totals may not sum due to independent rounding.

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[46] The carbon content of tires (1,158 Gg C) divided by the mass of rubber in tires (1,285 Gg) equals 90 percent.

Table A- 146: Scrap Tire Constituents and CO₂ Emissions from Scrap Tire Incineration in 2007

Material	Weight of Material (Tg)	Fraction Oxidized	Carbon Content	Emissions (Tg CO₂ Eq.)
Synthetic Rubber	0.5	98%	90%	1.8
Carbon Black	0.6	98%	100%	2.3
Total	**1.1**	-	-	**4.1**

- Not applicable

CO₂ from Incineration 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 incinerated by an average rubber C content. The amount of rubber discarded in the MSW stream was estimated from generation and recycling data[47] provided in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2011) and unpublished backup data (Schneider 2007). The reports divide 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. EPA (2011) did not report rubber found in the product category "containers and packaging;" however, containers and packaging from miscellaneous material types were reported for 2009. As a result, EPA assumes that rubber containers and packaging are reported under the "miscellaneous" category; and therefore, the quantity reported for 2009 was set equal to the quantity reported for 2008. Since there was negligible recovery for these product types, all the waste generated is considered to be discarded. Similar to the plastics method, discards were apportioned into landfilling and incineration based on their relative proportions, for each year, for the entire U.S. waste stream. The report aggregates rubber and leather in the MSW stream; an assumed synthetic rubber content of 70% was assigned to each product type, as shown in Table A-147.[48] A C content of 85 percent was assigned to synthetic rubber for all product types (based on the weighted average C content of rubber consumed for non-tire uses), and a 98 percent fraction oxidized was assumed.

Table A-147: Rubber and Leather in Municipal Solid Waste in 2009

Product Type	Incinerated (Gg)	Synthetic Rubber (%)	Carbon Content (%)	Fraction Oxidized (%)	Emissions (Tg CO₂ Eq.)
Durables (not Tires)	271	70%	85%	98%	0.8
Non-Durables	85	-	-	-	0.3
Clothing and Footwear	63	70%	85%	98%	0.2
Other Non-Durables	22	70%	85%	98%	0.1
Containers and Packaging	2	70%	85%	98%	+
Total	**358**	-	-	-	**1.1**

+ Less than 0.05 Tg CO₂ Eq.

- Not applicable.

CO₂ from Incineration of Synthetic Fibers

CO_2 emissions from synthetic fibers were estimated as the product of the amount of synthetic fiber discarded annually and the average C content of synthetic fiber. Fiber in the MSW stream was estimated from data provided in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2011) for textiles. Production data for the synthetic fibers was based on data from the American Chemical Society (FEB 2009). The amount of synthetic fiber in MSW was estimated by subtracting (a) the amount recovered from (b) the waste generated (see Table A-148). As with the other materials in the MSW stream, discards were apportioned based on the annually variable proportions of landfilling and incineration for the entire U.S. waste stream as found in van Haaren et al. (2010). 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 C content of 70 percent was assigned to synthetic fiber using the production-weighted average of the C contents of the four major fiber

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[47] Discards = Generation minus recycling.

[48] As a sustainably harvested biogenic material, the incineration of leather is assumed to have no net CO_2 emissions.

types (polyester, nylon, olefin, and acrylic) produced in 1999 (see Table A-149). The equation relating CO_2 emissions to the amount of textiles combusted is shown below.

$$CO_2 \text{ Emissions from the Incineration of Synthetic Fibers} = \text{Annual Textile Incineration (Gg)} \times$$
$$(\text{Percent of Total Fiber that is Synthetic}) \times (\text{Average C Content of Synthetic Fiber}) \times$$
$$(44g\ CO_2/12\ g\ C)$$

Table A-148: Synthetic Textiles in MSW (Gg)

Year	Generation	Recovery	Discards	Incineration
1990	2,884	328	2,557	332
1995	3,674	447	3,227	442
1996	3,832	472	3,361	467
1997	4,090	526	3,564	458
1998	4,269	556	3,713	407
1999	4,498	611	3,887	406
2000	4,686	655	4,031	415
2001	4,870	715	4,155	432
2002	5,123	750	4,373	459
2003	5,297	774	4,522	472
2004	5,451	884	4,567	473
2005	5,649	918	4,731	473
2006	5,893	933	4,959	479
2007	5,927	953	4,974	460
2008	6,170	948	5,222	460
2009	6,319	943	5376	474

Table A-149: Synthetic Fiber Production in 1999

Fiber	Production (Tg)	Carbon Content
Polyester	1.8	63%
Nylon	1.2	64%
Olefin	1.4	86%
Acrylic	0.1	68%
Total	**4.5**	**70%**

N_2O and CH_4 from Incineration of Waste

Estimates of N_2O emissions from the incineration of waste in the United States are based on the methodology outlined in the EPA's Compilation of Air Pollutant Emission Factors (EPA 1995) and presented in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2011) and unpublished backup data (Schneider 2007). According to this methodology, emissions of N_2O from waste incineration are the product of the mass of waste incinerated, an emission factor of N_2O emitted per unit mass of waste incinerated, and an N_2O emissions control removal efficiency. The mass of waste incinerated was derived from the information published in *BioCycle* (van Haaren et al. 2010). For waste incineration in the United States, an emission factor of 50 g N_2O/metric ton MSW based on the 2006 IPCC Guidelines and an estimated emissions control removal efficiency of zero percent were used (IPCC 2006). It was assumed that all MSW incinerators in the United States use continuously-fed stoker technology (Bahor 2009, ERC 2009).

Estimates of CH_4 emissions from the incineration of waste in the United States are based on the methodology outlined in IPCC's *2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). According to this methodology, emissions of CH_4 from waste incineration are the product of the mass of waste incinerated and an emission factor of CH_4 emitted per unit mass of waste incinerated. Similar to the N_2O emissions methodology, the mass of waste incinerated was derived from the information published in *Biocycle* (van Haaren et al. 2010). For waste incineration in the United States, an emission factor of 0.20 kg CH_4/Gg MSW was used based on the 2006 IPCC Guidelines and assuming that all MSW incinerators in the United States use continuously-fed stoker technology (Bahor 2009, ERC 2009). No information was available on the mass of waste incinerated from *Biocycle* in 2009, so the value was assumed to remain constant at the 2008 level.

Despite the differences in methodology and data sources, the two series of references (EPA's and BioCycle's) provide estimates of total solid waste incinerated that are relatively consistent (see Table A-150).

Table A-150: U.S. Municipal Solid Waste Incinerated, as Reported by EPA and BioCycle (Metric Tons)

Year	EPA	BioCycle
1990	28,939,680	30,632,057
1995	32,241,888	29,639,040
1996	32,740,848	29,707,171
1997	33,294,240	27,798,368
1998	31,216,752	25,489,893
1999	30,881,088	24,296,249
2000	30,599,856	25,974,978
2001	30,481,920	25,942,036[a]
2002	30,255,120	25,802,917
2003	30,028,320	25,930,542[b]
2004	28,585,872	26,037,823
2005	28,685,664	25,973,520[c]
2006	28,985,040	25,853,401
2007	29,003,184	24,788,539[d]
2008	28,622,160	23,674,017
2009	26,317,872	NA

NA (Not Available)
[a] Interpolated between 2000 and 2002 values.
[b] Interpolated between 2002 and 2004 values.
[c] Interpolated between 2004 and 2006 values.
[d] Interpolated between 2006 and 2008 values

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3.7. Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military

Bunker fuel emissions estimates for the Department of Defense (DoD) are developed using data generated by the Defense Energy Support Center (DESC) for aviation and naval fuels. The DESC of the Defense Logistics Agency (DLA) prepared a special report based on data in the Fuels Automated System (FAS), a database that recently replaced the Defense Fuels Automated Management System (DFAMS). Data for intermediate fuel oil, however, currently remains in the original DFAMS database. DFAMS/FAS contains data for 1995 through 2009, 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 in 1999 to better account for the jet fuel conversion from JP4 to JP8 that occurred within DoD between 1992 and 1995.

Step 1: Omit Extra-Territorial Fuel Deliveries

Beginning with the complete FAS 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 international fuel transactions/deliveries (i.e., sales abroad).

Step 2: Allocate JP-8 between Aviation and Land-based Vehicles

As a result of DoD[49] and NATO[50] policies on implementing the Single Fuel For the Battlefield concept, DoD activities have been increasingly replacing diesel fuel with JP8 (a type of jet fuel) in compression ignition and turbine engines in land-based equipment. Based on this concept and examination of all data describing jet fuel used in land-based vehicles, it was determined that a portion of JP8 consumption should be attributed to ground vehicle use. Based on available Service data and expert judgment, it was determined that a small fraction of the total JP8 use should be reallocated from the aviation subtotal to a new land-based jet fuel category for 1997 and subsequent years. The amount of JP8 reallocated was determined to be between 1.78 and 2.7 times the amount of diesel fuel used, depending on the Service. As a result of this reallocation, the JP8 use reported for aviation will be reduced and the total fuel use for land-based equipment will increase. DoD's total fuel use will not change.

Table A-151 displays DoD's consumption of fuels that remain at the completion of Step 1, summarized by fuel type. Table A-151 reflects the adjustments for jet fuel used in land-based equipment, as described above.

Step 3: Omit Land-Based Fuels

Navy and Air Force land-based fuels (i.e., fuel not used by ships or aircraft) were also omitted for the purpose of calculating international bunker fuels. The remaining fuels, listed below, were considered potential DoD 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).

Step 4: Omit Fuel Transactions Received by Military Services that are not Considered to be International Bunker Fuels

Next, the records were sorted by Military Service. The following assumptions were used regarding bunker fuel use by Service, leaving only the Navy and Air Force as users of military international bunker fuels.

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[49] DoD Directive 4140.43, Fuel Standardization, 1998; DoD Directive 4140.25, DoD Management Policy for Energy Commodities and Related Services, 1999.

[50] NATO Standard Agreement NATO STANAG 4362, Fuels for Future Ground Equipments Using Compression Ignition or Turbine Engines, 1987.

- Only fuel delivered to a ship, aircraft, or installation in the United States was considered a potential international bunker fuel. Fuel consumed in international aviation or marine transport was included in the bunker fuel estimate of the country where the ship or aircraft was fueled. Fuel consumed entirely within a country's borders was not considered a 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 were assumed to be zero.

- Marine Corps aircraft operating while embarked consumed fuel reported as delivered to the Navy. Bunker fuel emissions from embarked Marine Corps aircraft were reported in the Navy bunker fuel estimates. Bunker fuel emissions from other Marine Corps operations and training were assumed to be zero.

- Bunker fuel emissions from other DoD and non-DoD activities (i.e., other federal agencies) that purchased fuel from DESC were assumed to be zero.

Step 5: 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 end 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 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 for fiscal year 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. In 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. The percentage of time underway may vary from year-to-year. For example, for years prior to 2000, the bunker fuel percentage was 87 percent. Table A-152 and Table A-153 display DoD bunker fuel use totals for the Navy and Air Force.

Step 6: Calculate Emissions from International Bunker Fuels

Bunker fuel totals were multiplied by appropriate emission factors to determine GHG emissions. CO_2 emissions from Aviation Bunkers and distillate Marine Bunkers are the total of military aviation and marine bunker fuels, respectively.

The rows labeled "U.S. Military" and "U.S. Military Naval Fuels" in the tables in the International Bunker Fuels section of the Energy Chapter were based on the totals provided in Table A-152 and Table A-153, below. CO_2 emissions from aviation bunkers and distillate marine bunkers presented in Table A-156, and are based on emissions from fuels tallied in Table A-152 and Table A-153.

Table A-151: Transportation Fuels from Domestic Fuel Deliveries[a] (Million Gallons)

Vehicle Type/Fuel	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Aviation	**4,598.4**	**3,099.9**	**2,941.9**	**2,685.6**	**2,741.4**	**2,635.2**	**2,664.4**	**2,900.6**	**2,609.8**	**2,615.0**	**2,703.1**	**2,338.1**	**2,092.0**	**2,081.0**	**2,067.8**	**1,831.1**
Total Jet Fuels	4,598.4	3,099.9	2,941.9	2,685.6	2,741.4	2,635.2	2,664.4	2,900.6	2,609.6	2,614.9	2,703.1	2,338.0	2,091.9	2,080.9	2,067.7	1,830.9
JP8	285.7	2,182.8	2,253.1	2,072.0	2,122.5	2,066.5	2,122.7	2,326.2	2,091.4	2,094.3	2,126.2	1,838.8	1,709.3	1,618.5	1,616.2	1,374.9
JP5	1,025.4	691.2	615.8	552.8	515.6	505.5	472.1	503.2	442.2	409.1	433.7	421.6	325.5	376.1	362.2	361.4
Other Jet Fuels	3,287.3	225.9	72.9	60.9	103.3	63.3	69.6	71.2	76.1	111.4	143.2	77.6	57.0	86.3	89.2	94.6
Aviation Gasoline	+	+	+	+	+	+	+	+	0.1	0.1	+	0.1	0.1	0.2	0.1	0.2
Marine	**686.8**	**438.9**	**493.3**	**639.8**	**674.2**	**598.9**	**454.4**	**418.4**	**455.8**	**609.1**	**704.5**	**604.9**	**531.6**	**572.8**	**563.4**	**500.5**
Middle Distillate (MGO)	+	+	38.5	47.5	51.1	49.2	48.3	33.0	41.2	88.1	71.2	54.0	45.8	45.7	55.2	56.8
Naval Distillate (F76)	686.8	438.9	449.0	583.4	608.4	542.9	398.0	369.1	395.1	460.9	583.5	525.9	453.6	516.0	483.4	412.5
Intermediate Fuel Oil (IFO)[b]	+	+	5.9	9.0	14.7	6.7	8.1	16.3	19.5	60.2	49.9	25.0	32.2	11.1	24.9	31.2
Other [c]	**717.1**	**310.9**	**276.9**	**263.3**	**256.8**	**256.0**	**248.2**	**109.8**	**211.1**	**221.2**	**170.9**	**205.6**	**107.3**	**169.0**	**173.6**	**174.6**
Diesel	93.0	119.9	126.1	132.6	139.5	146.8	126.6	26.6	57.7	60.8	46.4	56.8	30.6	47.3	49.1	49.0
Gasoline	624.1	191.1	150.8	119.0	93.9	74.1	74.8	24.7	27.5	26.5	19.4	24.3	11.7	19.2	19.7	19.7
Jet Fuel [d]	+	+	+	11.7	23.4	35.0	46.7	58.4	125.9	133.9	105.1	124.4	65.0	102.6	104.8	105.9
Total (Including Bunkers)	**6,002.4**	**3,849.8**	**3,712.1**	**3,588.8**	**3,672.4**	**3,490.1**	**3,367.0**	**3,428.8**	**3,276.7**	**3,445.3**	**3,578.5**	**3,148.6**	**2,730.9**	**2,822.8**	**2,804.9**	**2,506.2**

Note: Totals may not sum due to independent rounding.

[a] Includes fuel consumption in the 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.

[c] Prior to 2001, gasoline and diesel fuel totals were estimated using data provided by the military Services for 1990 and 1996. The 1991 through 1995 data points were interpolated from the Service inventory data. The 1997 through 1999 gasoline and diesel fuel data were initially extrapolated from the 1996 inventory data. Growth factors used for other diesel and gasoline were 5.2 and -21.1 percent, respectively. However, prior diesel fuel estimates from 1997 through 2000 were reduced according to the estimated consumption of jet fuel that is assumed to have replaced the diesel fuel consumption in land-based vehicles. Data sets for other diesel and gasoline consumed by the military in 2000 were estimated based on ground fuels consumption trends. This method produced a result that was more consistent with expected consumption for 2000. In 2001, other gasoline and diesel fuel totals were generated by DESC.

[d] The fraction of jet fuel consumed in land-based vehicles was estimated using Service data, DESC data, and expert judgment.

+ Does not exceed 0.05 million gallons.

Table A-152: Total U.S. Military Aviation Bunker Fuel (Million Gallons)

Fuel Type/Service	1990		1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
JP8	**56.7**		**300.4**	**308.8**	**292.0**	**306.4**	**301.4**	**307.6**	**341.2**	**309.5**	**305.1**	**309.8**	**285.6**	**262.5**	**249.1**	**229.4**	**212.5**
Navy	56.7		38.3	39.8	46.9	53.8	55.5	53.4	73.8	86.6	76.3	79.2	70.9	64.7	62.7	59.2	56.4
Air Force	+		262.2	269.0	245.1	252.6	245.9	254.2	267.4	222.9	228.7	230.6	214.7	197.8	186.5	170.3	156.1
JP5	**370.5**		**249.8**	**219.4**	**194.2**	**184.4**	**175.4**	**160.3**	**169.7**	**158.3**	**146.1**	**157.9**	**160.6**	**125.0**	**144.5**	**139.2**	**136.9**
Navy	365.3		246.3	216.1	191.2	181.4	170.6	155.6	163.7	153.0	141.3	153.8	156.9	122.8	141.8	136.5	133.4
Air Force	5.3		3.5	3.3	3.0	3.0	4.8	4.7	6.1	5.3	4.9	4.1	3.7	2.3	2.7	2.6	3.5
JP4	**420.8**		**21.5**	**1.1**	**0.1**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Navy	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	0.0
Air Force	420.8		21.5	1.1	0.1	+	+	+	+	+	+	+	+	+	+	+	0.0
JAA	**13.7**		**9.2**	**10.3**	**9.4**	**10.8**	**10.8**	**12.5**	**12.6**	**13.7**	**21.7**	**30.0**	**15.5**	**11.7**	**15.6**	**16.8**	**18.1**
Navy	8.5		5.7	6.6	5.9	6.6	6.3	7.9	8.0	9.8	15.5	21.5	11.6	9.1	11.7	12.5	12.3
Air Force	5.3		3.5	3.7	3.5	4.2	4.5	4.5	4.6	3.8	6.2	8.6	3.9	2.6	3.9	4.3	5.8
JA1	**+**		**+**	**+**	**+**	**+**	**+**	**+**	**0.1**	**0.6**	**0.2**	**0.5**	**0.5**	**0.4**	**1.1**	**1.0**	**0.5**
Navy	+		+	+	+	+	+	+	+	+	+	+	+	+	0.1	0.1	+
Air Force	+		+	+	+	+	+	+	0.1	0.6	0.2	0.5	0.5	0.4	1.0	0.8	0.6
JAB	**+**		**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Navy	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Air Force	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Navy Subtotal	**430.5**		**290.2**	**262.5**	**244.0**	**241.8**	**232.4**	**216.9**	**245.5**	**249.4**	**233.1**	**254.4**	**239.4**	**196.6**	**216.3**	**208.3**	**202.1**
Air Force Subtotal	**431.3**		**290.7**	**277.0**	**251.7**	**259.9**	**255.2**	**263.5**	**278.1**	**232.7**	**239.9**	**243.7**	**222.9**	**203.1**	**194.0**	**178.1**	**166.1**
Total	**861.8**		**580.9**	**539.5**	**495.6**	**501.7**	**487.5**	**480.4**	**523.6**	**482.1**	**473.0**	**498.1**	**462.3**	**399.7**	**410.3**	**386.3**	**368.1**

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

Table A-153: Total U.S. DoD Maritime Bunker Fuel (Million Gallons)

Marine Distillates	1990		1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Navy—MGO	+		+	30.3	35.6	31.9	39.7	23.8	22.5	27.1	63.7	56.2	38.0	33.0	31.6	40.9	39.9
Navy—F76	522.4		333.8	331.9	441.7	474.2	466.0	298.6	282.6	305.6	347.8	434.4	413.1	355.9	404.1	376.9	320.0
Navy—IFO	+		+	4.6	7.1	11.6	5.3	6.4	12.9	15.4	47.5	39.4	19.7	25.4	8.8	19.0	24.1
Total	**522.4**		**333.8**	**366.8**	**484.3**	**517.7**	**511.0**	**328.8**	**318.0**	**348.2**	**459.0**	**530.0**	**470.7**	**414.3**	**444.4**	**436.7**	**384.0**

+ Does not exceed 0.005 million gallons.
Note: Totals may not sum due to independent rounding.

Table A-154: Aviation and Marine Carbon Contents (Tg Carbon/QBtu) and Fraction Oxidized

Mode (Fuel)	Carbon Content Coefficient	Fraction Oxidized
Aviation (Jet Fuel)	Variable	1.00
Marine (Distillate)	20.17	1.00
Marine (Residual)	20.48	1.00

Source: EPA (2010) and IPCC (2006)

Table A-155: Annual Variable Carbon Content Coefficient for Jet Fuel (Tg Carbon/QBtu)

Fuel	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Jet Fuel	19.40	19.34	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70

Source: EPA (2010)

Table A-156: Total U.S. DoD CO_2 Emissions from Bunker Fuels (Tg CO_2 Eq.)

Mode	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Aviation	8.1	5.5	5.2	4.8	4.9	4.7	4.7	5.1	4.7	4.6	4.8	4.5	3.9	4.0	3.8	3.6
Marine	5.4	3.4	3.8	5.0	5.3	5.2	3.4	3.3	3.6	4.7	5.4	4.8	4.2	4.6	4.5	3.9
Total	**13.4**	**9.0**	**9.0**	**9.8**	**10.2**	**10.0**	**8.0**	**8.3**	**8.3**	**9.3**	**10.3**	**9.3**	**8.1**	**8.5**	**8.2**	**7.5**

Note: Totals may not sum due to independent rounding.

3.8.   Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances

Emissions of HFCs and PFCs from the substitution of ozone depleting substances (ODS) are developed using a country-specific modeling approach. The Vintaging Model was developed as a tool for estimating the annual chemical emissions from industrial sectors that have historically used ODS in their products. Under the terms of the Montreal Protocol and the United States' Clean Air Act Amendments of 1990, the domestic U.S. consumption of ODS— chlorofluorocarbons (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 ODS 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 five ODS substitute end-use sectors: air-conditioning and refrigeration, foams, aerosols, solvents, and fire-extinguishing. Within these sectors, there are 59 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 ODS to alternatives, as well as the characteristics of each end-use such as market size or charge sizes and loss rates. As ODS are phased out, a percentage of the market share originally filled by the ODS 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 and ODS and ODS substitute in each of the end-uses. The simulation is considered to be a "business-as-usual" baseline case, and does not incorporate measures to reduce or eliminate the emissions of these gases other than those regulated by U.S. law or otherwise common in the industry. 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 Stratospheric Protection 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 conference proceedings from the International Conferences on Ozone Protection Technologies and Earth Technologies Forums. EPA also coordinates extensively with numerous trade associations and individual companies. For example, the Alliance for Responsible Atmospheric Policy; the Air-Conditioning, Heating 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 emission equations used in the Vintaging Model for each broad end-use category. These equations are applied separately for each chemical used within each of the 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 determining the transition path of each regulated ODS used in the early 1990s. Using data gleaned from a variety of sources, assessments are made regarding which alternatives have been used, and what fraction of the ODS market in each end-use has been 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.

Methodology

The Vintaging Model estimates the use and emissions of ODS alternatives by taking the following steps:

1.   *Gather historical data.* The Vintaging Model is populated with information on each end-use, taken from published sources and industry experts.

2.   *Simulate the implementation of new, non-ODS technologies.* The Vintaging Model uses detailed characterizations of the existing uses of the ODS, as well as data on how the substitutes are replacing the ODS, to simulate the implementation of new technologies that enter the market in compliance with ODS phase-out policies. As part of this simulation, the ODS substitutes are introduced in each of the end-uses over time as seen historically and as needed to comply with the ODS phase-out.

3.   *Estimate emissions of the ODS substitutes.* The chemical use is estimated from the amount of substitutes that are required each year for the manufacture, installation, use, or servicing of products. The emissions are estimated from the emission profile for each vintage of equipment or product in each end-use. By aggregating the emissions from each vintage, a time profile of emissions from each end-use is developed.

Each set of end-uses is discussed in more detail in the following sections.

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. For any given year, these lifetime emissions (for existing equipment) and disposal emissions (from discarded equipment) 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

Emissions from any piece of equipment include both the amount of chemical leaked during equipment operation and the amount emitted during service. 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 by weight.

i = Counter, runs from 1 to lifetime (k).

j = Year of emission.

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 year $j-k+1$, 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)).

j = Year of emission.

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 leakage and servicing (including recharging) of equipment.

Ed = Emissions from Equipment Disposed. Emissions in year j from the disposal of equipment.

j = Year of emission.

Assumptions

The assumptions used by the Vintaging Model to trace the transition of each type of equipment away from ODS are presented in Table A- 157, below. As new technologies replace older ones, it is generally assumed that there are improvements in their leak, service, and disposal emission rates. Additionally, the market for each equipment type is assumed to grow independently, according to annual growth rates.

Table A- 157: Refrigeration and Air-Conditioning Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
Centrifugal Chillers													
CFC-11	HCFC-123	1993	1993	45%	Unknown								0.5%
	HCFC-22	1991	1993	16%	HFC-134a	2000	2010	100%	None				
	HFC-134a	1992	1993	39%	None								
CFC-12	HFC-134a	1992	1994	53%	None								0.5%
	HCFC-22	1991	1994	16%	HFC-134a	2000	2010	100%	None				
	HCFC-123	1993	1994	31%	Unknown								
R-500	HFC-134a	1992	1994	53%	None								0.5%
	HCFC-22	1991	1994	16%	HFC-134a	2000	2010	100%	None				
	HCFC-123	1993	1994	31%	Unknown								
CFC-114	HFC-236fa	1993	1994	100%	HFC-236fa	1996	1996	100%	HFC-134a	1998	2009	100%	0.2%
Cold Storage													
CFC-12	HCFC-22	1990	1993	65%	R-404A	1996	2010	75%	None				2.5%
					R-507	1996	2010	25%	None				
	R-404A	1994	1996	26%	None								
	R-507	1994	1996	9%	None								
HCFC-22	HCFC-22	1992	1993	100%	R-404A	1996	2009	8%	None				2.5%
					R-507	1996	2009	3%	None				
					R-404A	2009	2010	68%	None				
					R-507	2009	2010	23%	None				
R-502	HCFC-22	1990	1993	40%	R-404A	1996	2010	38%	None				2.5%
					R-507	1996	2010	12%	None				
					Non-ODP/GWP	1996	2010	50%	None				
	R-404A	1993	1996	45%	None								
	R-507	1994	1996	15%	None								
Commercial Unitary Air Conditioners (Large)													
HCFC-22	HCFC-22	1992	1993	100%	R-410A	2001	2005	5%	None				0.8%
					R-407C	2006	2009	1%	None				
					R-410A	2006	2009	9%	None				
					R-407C	2009	2010	5%	None				
					R-410A	2009	2010	81%	None				
Commercial Unitary Air Conditioners (Small)													
HCFC-22	HCFC-22	1992	1993	100%	R-410A	1996	2000	3%	None				0.8%
					R-410A	2001	2005	18%	None				
					R-410A	2006	2009	8%	None				
					R-410A	2009	2010	71%	None				
Dehumidifiers													
HCFC-22	HFC-134a	1997	1997	89%	None								0.2%

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
	R-410A	2007	2010	11%	None								
Ice Makers													
CFC-12	HFC-134a	1993	1995	100%	None								2.5%
Industrial Process Refrigeration													
CFC-11	HCFC-123	1992	1994	70%	Unknown								2.5%
	HFC-134a	1992	1994	15%	None								
	HCFC-22	1991	1994	15%	HFC-134a	1995	2010	100%	None				
CFC-12	HCFC-22	1991	1994	10%	HFC-134a	1995	2010	15%	None				2.5%
					R-404A	1995	2010	50%	None				
					R-410A	1999	2010	20%	None				
					R-507	1995	2010	15%	None				
	HCFC-123	1992	1994	35%	Unknown								
	HFC-134a	1992	1994	50%	None								
	R-401A	1995	1996	5%	HFC-134a	1997	2000	100%	None				
HCFC-22	HCFC-22	1992	1993	100%	HFC-134a	1995	2009	2%	None				2.5%
					R-404A	1995	2009	5%	None				
					R-410A	1999	2009	2%	None				
					R-507	1995	2009	2%	None				
					HFC-134a	2009	2010	14%	None				
					R-404A	2009	2010	45%	None				
					R-410A	2009	2010	18%	None				
					R-507	2009	2010	14%	None				
Mobile Air Conditioners (Passenger Cars)													
CFC-12	HFC-134a	1992	1994	100%	None								1.9%
Mobile Air Conditioners (Light Duty Trucks)													
CFC-12	HFC-134a	1993	1994	100%	None								-0.4%
Mobile Air Conditioners (School and Tour Buses)													
CFC-12	HCFC-22	1994	1995	0.5%	HFC-134a	2006	2007	100%	None				2.6%
	HFC-134a	1994	1997	99.5%	None								
Mobile Air Conditioners (Transit Buses)													
HCFC-22	HFC-134a	1995	2009	100%	None								2.6%
Mobile Air Conditioners (Trains)													
HCFC-22	HFC-134a	2002	2009	50%	None								2.6%
	R-407C	2002	2009	50%	None								
Packaged Terminal Air Conditioners and Heat Pumps													
HCFC-22					R-410A	2006	2009	10%	None				0.8%
					R-410A	2009	2010	90%	None				
Positive Displacement Chillers													
HCFC-22	HCFC-22	1996	1996	100%	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	0.5%
									R-410A	2010	2020	40%	
					R-407C	2000	2009	1%	None				

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
CFC-12	HCFC-22	1993	1993	100%	HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	0.2%
									R-410A	2010	2020	40%	
					R-407C	2009	2010	9%	None				
					HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	
									R-410A	2010	2020	40%	
					R-407C	2000	2009	1%	None				
					HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	
									R-410A	2010	2020	40%	
					R-407C	2009	2010	9%	None				
Refrigerated Appliances													
CFC-12	HFC-134a	1994	1995	100%	HFC-134a	2005	2005	100%	None				0.5%
Residential Unitary Air Conditioners													
HCFC-22	HCFC-22	2006	2006	70%	R-410A	2007	2010	29%	None				0.8%
					R-407C	2010	2010	14%	R-410A	2011	2015	100%	
					R-410A	2010	2010	57%	None				
	R-410A	2000	2005	5%	R-410A	2006	2006	100%	None				
	R-410A	2000	2006	5%	None								
	R-410A	2006	2006	20%	None								
Retail Food (Large)													
CFC-12	R-502	1988	1990	100%	HCFC-22	1991	1993	100%	R-404A	1995	2000	17.5%	1.7%
									R-507	1995	2000	7.5%	
									R-404A	2000	2005	31.5%	
									R-507	2000	2005	13.5%	
									R-404A	2005	2010	18%	
									R-507	2005	2010	12%	
R-502	HCFC-22	1990	1993	100%	R-404A	1995	2000	17.5%	None				1.7%
					R-507	1995	2000	7.5%	None				
					R-404A	2000	2005	31.5%	None				
					R-507	2000	2005	13.5%	None				
					R-404A	2005	2010	18%	None				
					R-507	2005	2010	12%	None				
Retail Food (Medium)													
HCFC-22	R-404A	1995	2000	17.5%	None								1.7%
	R-507	1995	2000	7.5%	None								
	R-404A	2000	2005	31.5%	None								
	R-507	2000	2005	13.5%	None								
	R-404A	2005	2010	18%	None								
	R-507	2005	2010	12%	None								
Retail Food (Small)													
CFC-12	HCFC-22	1990	1993	90%	HFC-134a	1993	1995	90%	CO_2	2010	2010	5%	1.7%

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
					R-404A	2000	2009	7.5%	None				
					R-507	2000	2009	2.5%	None				
	R-404A	1993	1996	7.5%	None								
	R-507	1993	1996	2.5%	None								
Transport Refrigeration													
CFC-12	HFC-134a	1993	1995	98%	None								2.5%
	HCFC-22	1993	1995	2%	HFC-134a	1995	1999	100%	None				
R-502	HFC-134a	1993	1995	55%	None								2.5%
	R-404A	1993	1995	45%	None								
Water-Source and Ground-Source Heat Pumps													
HCFC-22	R-407C	2000	2006	5%					None				0.8%
	R-410A	2000	2006	5%					None				
	HFC-134a	2000	2009	2%					None				
	R-407C	2006	2009	2.5%					None				
	R-410A	2006	2009	4.5%					None				
	HFC-134a	2009	2010	18%					None				
	R-407C	2009	2010	22.5%					None				
	R-410A	2009	2010	40.5%					None				
Window Units													
HCFC-22	R-407C	2003	2009	3%	None								5.0%
	R-407C	2009	2010	35%	None								
	R-410A	2003	2009	7%	None								
	R-410A	2009	2010	55%	None								

Table A- 158 presents the average equipment lifetimes and annual HFC emission rates (for servicing and leaks) for each end-use assumed by the Vintaging Model.

Table A- 158. Refrigeration and Air-conditioning Lifetime Assumptions

End-Use	Lifetime (Years)	HFC Emission Rates (%)
Centrifugal Chillers	20 – 27	2.0 – 10.9
Cold Storage	20 – 25	15.0
Commercial Unitary A/C	15	7.9 – 8.6
Dehumidifiers	11	0.5
Ice Makers	20	3.0
Industrial Process Refrigeration	25	3.6 – 12.3
Mobile Air Conditioners	5 –12	2.3 – 18.0
Positive Displacement Chillers	20	0.5 – 1.5
PTAC/PTHP	12	3.9
Retail Food	15 – 20	7.8 – 29.9
Refrigerated Appliances	14	0.6
Residential Unitary A/C	15	7.2 – 8.3
Transport Refrigeration	12	20.6 – 27.9
Water & Ground Source Heat Pumps	20	3.9
Window Units	12	0.6

Aerosols

ODSs, HFCs and many other chemicals are used as propellant aerosols. Pressurized within a container, a nozzle releases the chemical, which allows the product within the can to also be released. Two types of aerosol products are modeled: metered dose inhalers (MDI) and consumer aerosols. In the United States, the use of CFCs in consumer aerosols was banned in 1978, and many products transitioned to hydrocarbons or "not-in-kind" technologies, such as solid deodorants and finger-pump hair sprays. However, MDIs can continue to use CFCs as propellants because their use has been deemed essential. Essential use exemptions granted to the United States under the Montreal Protocol for CFC use in MDIs are limited to the treatment of asthma and chronic obstructive pulmonary disease.

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.

j = Year of emission.

Transition Assumptions

Transition assumptions and growth rates for those items that use ODSs or HFCs as propellants, including vital medical devices and specialty consumer products, are presented in Table A- 159.

Table A-159. Aerosol Product Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
MDIs									
CFC Mix*	HFC-134a	1997	1997	6%	None				0.8%
	Non-ODP/GWP	1998	2007	7%	None				
	CFC Mix*	2000	2000	87%	HFC-134a	2002	2002	34%	
					HFC-134a	2003	2009	47%	
					HFC-227ea	2006	2009	5%	
					HFC-134a	2010	2011	6%	
					HFC-227ea	2010	2011	1%	
					HFC-134a	2011	2012	3%	
					HFC-227ea	2011	2012	0.3%	
					HFC-134a	2014	2014	3%	
					HFC-227ea	2014	2014	0.3%	
Consumer Aerosols (Non-MDIs)									
NA**	HFC-152a	1990	1991	50%	None				2.0%
	HFC-134a	1995	1995	50%	HFC-152a	1997	1998	44%	
					HFC-152a	2001	2005	36%	

*CFC Mix consists of CFC-11, CFC-12 and CFC-114 and represents the weighted average of several CFCs consumed for essential use in MDIs from 1993 to 2008.

**Consumer Aerosols transitioned away from ODS prior to 1985, the year in which the Vintaging Model begins. The portion of the market that is now using HFC propellants is modeled.

Solvents

ODSs, HFCs, PFCs and other chemicals are used as solvents to clean items. For example, electronics may need to be cleaned after production to remove any manufacturing process oils or residues left. Solvents are applied by moving the item to be cleaned within a bath or stream of the solvent. 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, assumed to be 90 percent.

Qc = Quantity of Chemical. Total quantity of a specific chemical sold for use in solvent applications in the year j, by weight.

j = Year of emission.

Transition Assumptions

The transition assumptions and growth rates used within the Vintaging Model for electronics cleaning, metals cleaning, precision cleaning, and adhesives, coatings and inks, are presented in Table A-160.

Table A- 160. Solvent Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
Adhesives									
CH$_3$CCI$_3$	Non-ODP/GWP	1994	1995	100%	None				2.0%
Electronics									
CFC-113	Semi-Aqueous	1994	1995	52%	None				2.0%
	HCFC-225ca/cb	1994	1995	0.2%	Unknown				
	HFC-4310mee	1995	1996	0.7%	None				
	HFE-7100	1994	1995	0.7%	None				
	nPB	1992	1996	5%	None				
	Methyl Siloxanes	1992	1996	0.8%	None				
	No-Clean	1992	1996	40%	None				
CH$_3$CCI$_3$	Non-ODP/GWP	1996	1997	99.8%	None				2.0%
	PFC/PFPE	1996	1997	0.2%	Non-ODP/GWP	2000	2003	90%	
					Non-ODP/GWP	2005	2009	10%	
Metals									
CH$_3$CCI$_3$	Non-ODP/GWP	1992	1996	100%	None				2.0%
CFC-113	Non-ODP/GWP	1992	1996	100%	None				2.0%
CCI$_4$	Non-ODP/GWP	1992	1996	100%	None				2.0%
Precision									
CH$_3$CCI$_3$	Non-ODP/GWP	1995	1996	99.3%	None				2.0%
	HFC-4310mee	1995	1996	0.6%	None				
	PFC/PFPE	1995	1996	0.1%	Non-ODP/GWP	2000	2003	90%	
					Non-ODP/GWP	2005	2009	10%	
CFC-113	Non-ODP/GWP	1995	1996	96%	None				2.0%
	HCFC-225ca/cb	1995	1996	1%	Unknown				
	HFE-7100	1995	1996	3%	None				

Non-ODP/GWP includes chemicals with 0 ODP and low GWP, such as hydrocarbons and ammonia, as well as not-in-kind alternatives such as "no clean" technologies.

Fire Extinguishing

ODSs, HFCs, PFCs and other chemicals are used as fire-extinguishing agents, in both hand-held "streaming" applications as well as in built-up "flooding" equipment similar to water sprinkler systems. Although these systems are generally built to be leak-tight, some leaks do occur and of course emissions occur when the agent is released. 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, as shown in the equation below. In streaming systems, non-halon emissions are assumed to be 3.5 percent of all chemical in use in each year, while in flooding systems 2.5 percent of the installed base of chemical is assumed to leak annually. Halon systems are assumed to leak at higher rates. The equation is applied for a single year, accounting for all fire protection equipment in operation in that year. Each fire protection agent is modeled separately. In the Vintaging Model, streaming applications have a 12-year lifetime and flooding applications have a 20-year lifetime.

$$E_j = r \times \sum Qc_{j-i+1} \quad for\ i=1 \rightarrow k$$

Where:

E = Emissions. Total emissions of a specific chemical in year j for streaming fire extinguishing equipment, by weight.

r = Percent Released. The percentage of the total chemical in operation that is released to the atmosphere.

Qc = Quantity of Chemical. Total amount of a specific chemical used in new fire extinguishing equipment in a given year, $j-i+1$, by weight.

i = Counter, runs from 1 to lifetime (k).

j = Year of emission.

k = Lifetime. The average lifetime of the equipment.

Transition Assumptions

Transition assumptions and growth rates for these two fire extinguishing types are presented in Table A- 161.

Table A- 161. Fire Extinguishing Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
Flooding Agents									
Halon-1301	Halon-1301*	1994	1994	4%	Unknown				2.2%
	HFC-23	1994	1999	0.2%	None				
	HFC-227ea	1994	1999	18%	FK-5-1-12	2003	2010	10%	
					HFC-125	2001	2008	10%	
	Non-ODP/GWP	1994	1994	46%	FK-5-1-12	2003	2010	7%	
	Non-ODP/GWP	1995	2034	10%	None				
	Non-ODP/GWP	1998	2027	10%	None				
	C_4F_{10}	1994	1999	1%	FK-5-1-12	2003	2003	100%	
	HFC-125	1997	2006	11%	None				
Streaming Agents									
Halon-1211	Halon-1211*	1992	1992	5%	Unknown				3.0%
	HFC-236fa	1997	1999	3%	None				
	Halotron	1994	1997	4%	Non-ODP/GWP	2015	2015	25%	
					HFC-236fa	2015	2015	75%	
	Non-ODP/GWP	1993	1994	58%	None				
	Non-ODP/GWP	1995	2024	20%	None				
	Non-ODP/GWP	1999	2018	10%	None				

*Despite the 1994 consumption ban, a small percentage of new halon systems are assumed to continue to be built and filled with stockpiled or recovered supplies.

Foam Blowing

ODSs, HFCs, and other chemicals are used to produce foams, including such items as the foam insulation panels around refrigerators, insulation sprayed on buildings, etc. The chemical is used to create pockets of gas within a substrate, increasing the insulating properties of the item. 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 content upon manufacture, a portion at a constant rate over the lifetime of the foam, a portion at disposal, and a portion after disposal; these portions vary by end-use.

Step 1: Calculate manufacturing emissions (open-cell and closed-cell foams)

Manufacturing emissions occur in the year of foam manufacture, and are calculated as presented in the following equation.

$$Em_j = lm \times Qc_j$$

Where:

Em_j = Emissions from manufacturing. Total emissions of a specific chemical in year j due to manufacturing losses, by weight.

lm = Loss Rate. Percent of original blowing agent emitted during foam manufacture. For open-cell foams, lm is 100%.

Qc = Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.

j = Year of emission.

Step 2: Calculate lifetime emissions (closed-cell foams)

Lifetime emissions occur annually from closed-cell foams throughout the lifetime of the foam, as calculated as presented in the following equation.

$$Eu_j = lu \times \sum Qc_{j-i+1} \quad for \ i=1 \rightarrow k$$

Where:

Eu_j = Emissions from Lifetime Losses. Total emissions of a specific chemical in year j due to lifetime losses during use, by weight.

lu = Leak Rate. Percent of original blowing agent emitted each year during lifetime use.

Qc = Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.

i = Counter, runs from 1 to lifetime (k).

j = Year of emission.

k = Lifetime. The average lifetime of foam product.

Step 3: Calculate disposal emissions (closed-cell foams)

Disposal emissions occur in the year the foam is disposed, and are calculated as presented in the following equation.

$$Ed_j = ld \times Qc_{j-k}$$

Where:

Ed_j = Emissions from disposal. Total emissions of a specific chemical in year j at disposal, by weight.

ld = Loss Rate. Percent of original blowing agent emitted at disposal.

Qc = Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.

j = Year of emission.

k = Lifetime. The average lifetime of foam product.

Step 4: Calculate post-disposal emissions (closed-cell foams)

Post-Disposal emissions occur in the years after the foam is disposed; for example, emissions might occur while the disposed foam is in a landfill. Currently, the only foam type assumed to have post-disposal emissions is polyurethane foam used as domestic refrigerator and freezer insulation, which is expected to continue to emit for 26 years post-disposal, calculated as presented in the following equation.

$$Ep_j = lp \times \sum Qc_{j-m} \quad for \ m=k \rightarrow k + 32$$

Where:

Ep_j = Emissions from post disposal. Total post-disposal emissions of a specific chemical in year j, by weight.

lp = Leak Rate. Percent of original blowing agent emitted post disposal.

Qc = Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.

k = Lifetime. The average lifetime of foam product.

m = Counter. Runs from lifetime (k) to (k+26).

j = Year of emission.

Step 5: Calculate total emissions (open-cell and closed-cell foams)

To calculate total emissions from foams in any given year, emissions from all foam stages must be summed, as presented in the following equation.

$$E_j = Em_j + Eu_j + Ed_j + Ep_j$$

Where:

E_j = Total Emissions. Total emissions of a specific chemical in year j, by weight.

Em = Emissions from manufacturing. Total emissions of a specific chemical in year j due to manufacturing losses, by weight.

Eu_j = Emissions from Lifetime Losses. Total emissions of a specific chemical in year j due to lifetime losses during use, by weight.

Ed_j = Emissions from disposal. Total emissions of a specific chemical in year j at disposal, by weight.

Ep_j = Emissions from post disposal. Total post-disposal emissions of a specific chemical in year j, by weight.

Assumptions

The Vintaging Model contains 13 foam types, whose transition assumptions away from ODS and growth rates are presented in Table A- 162. The emission profiles of these 13 foam types are shown in Table A- 163.

Table A- 162. Foam Blowing Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
Commercial Refrigeration Foam													
CFC-11	HCFC-141b	1989	1996	40%	HFC-245fa	2002	2003	80%	None				6.0%
					Non-ODP/GWP	2002	2003	20%	None				
	HCFC-142b	1989	1996	8%	Non-ODP/GWP	2009	2010	80%	None				
					HFC-245fa	2009	2010	20%	None				
	HCFC-22	1989	1996	52%	Non-ODP/GWP	2009	2010	80%	None				
					HFC-245fa	2009	2010	20%	None				
Flexible PU Foam: Integral Skin Foam													
CFC-11	HCFC-141b	1989	1990	100%	HFC-134a	1993	1996	25%	None				2.0%
					HFC-134a	1994	1996	25%	None				
					CO$_2$	1993	1996	25%	None				
					CO$_2$	1994	1996	25%	None				
Flexible PU Foam: Slabstock Foam, Moulded Foam													
CFC-11	Non-ODP/GWP	1992	1992	100%	None								2.0%
Phenolic Foam													
CFC-11	HCFC-141b	1989	1990	100%	Non-ODP/GWP	1992	1992	100%	None				2.0%
Polyolefin Foam													
CFC-114	HFC-152a	1989	1993	10%	Non-ODP/GWP	2005	2010	100%	None				2.0%
	HCFC-142b	1989	1993	90%	Non-ODP/GWP	1994	1996	100%	None				
PU and PIR Rigid: Boardstock													
CFC-11	HCFC-141b	1993	1996	100%	Non-ODP/GWP	2000	2003	95%	None				6.0%
					HC/HFC-245fa Blend	2000	2003	5%	None				
PU Rigid: Domestic Refrigerator and Freezer Insulation													
CFC-11	HCFC-141b	1993	1995	100%	HFC-134a	1996	2001	7%	Non-ODP/GWP	2002	2003	100%	0.8%
					HFC-245fa	2001	2003	50%	Non-ODP/GWP	2015	2029	100%	
					HFC-245fa	2006	2009	10%	Non-ODP/GWP	2015	2029	100%	
					Non-ODP/GWP	2002	2005	10%	None				
					Non-ODP/GWP	2006	2009	3%	None				
					Non-ODP/GWP	2009	2014	20%	None				
PU Rigid: One Component Foam													
CFC-12	HCFC-142b/22 Blend	1989	1996	70%	Non-ODP/GWP	2009	2010	80%	None				4.0%
					HFC-134a	2009	2010	10%	None				
					HFC-152a	2009	2010	10%	None				

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
	HCFC-22	1989	1996	30%	Non-ODP/GWP	2009	2010	80%	None				
					HFC-134a	2009	2010	10%	None				
					HFC-152a	2009	2010	10%	None				
PU Rigid: Other: Slabstock Foam													
CFC-11	HCFC-141b	1989	1996	100%	CO_2	1999	2003	45%	None				2.0%
					Non-ODP/GWP	2001	2003	45%	None				
					HCFC-22	2003	2003	10%	Non-ODP/GWP	2009	2010	100%	
PU Rigid: Sandwich Panels: Continuous and Discontinuous													
CFC-11	HCFC-141b	1989	1996	82%	HCFC-22/Water Blend	2001	2003	20%	HFC Blend	2009	2010	50%	6.0%
									Non-ODP/GWP	2009	2010	50%	
					HFC-245fa/CO_2 Blend	2002	2004	20%	None				
					Non-ODP/GWP	2001	2004	40%	None				
					HFC-134a	2002	2004	20%	None				
	HCFC-22	1989	1996	18%	HFC-245fa/CO_2 Blend	2009	2010	40%	None				
					Non-ODP/GWP	2009	2010	20%	None				
					CO_2	2009	2010	20%	None				
					HFC-134a	2009	2010	20%	None				
PU Rigid: Spray Foam													
CFC-11	HCFC-141b	1989	1996	100%	HFC-245fa	2002	2003	30%	None				6.0%
					HFC-245fa/CO_2 Blend	2002	2003	60%	None				
					Non-ODP/GWP	2001	2003	10%	None				
XPS: Boardstock Foam													
CFC-12	HCFC-142b/22 Blend	1989	1994	10%	HFC-134a	2009	2010	70%	None				2.5%
					HFC-152a	2009	2010	10%	None				
					CO_2	2009	2010	10%	None				
					Non-ODP/GWP	2009	2010	10%	None				
	HCFC-142b	1989	1994	90%	HFC-134a	2009	2010	70%	None				
					HFC-152a	2009	2010	10%	None				
					CO_2	2009	2010	10%	None				
					Non-ODP/GWP	2009	2010	10%	None				
XPS: Sheet Foam													
CFC-12	CO_2	1989	1994	1%	None								2.0%
	Non-ODP/GWP	1989	1994	99%	CO_2	1995	1999	9%	None				
					HFC-152a	1995	1999	10%	None				

Table A- 163. Emission profile for the foam end-uses

Foam End-Use	Loss at Manufacturing (%)	Annual Leakage Rate (%)	Leakage Lifetime (years)	Loss at Disposal (%)	Total* (%)
Flexible PU Foam: Slabstock Foam, Moulded Foam	100	0	1	0	100
Commercial Refrigeration	6	0.25	15	90.25	100
Rigid PU: Spray Foam	15	1.5	56	1	100
Rigid PU: Slabstock and Other	37.5	0.75	15	51.25	100
Phenolic Foam	23	0.875	32	49	100
Polyolefin Foam	95	2.5	2	0	100
Rigid PU: One Component Foam	100	0	1	0	100
XPS: Sheet Foam*	40	2	25	0	90
XPS: Boardstock Foam	25	0.75	50	37.5	100
Flexible PU Foam: Integral Skin Foam	95	2.5	2	0	100
Rigid PU: Domestic Refrigerator and Freezer Insulation*	4	0.25	14	40.0	47.5
PU and PIR Rigid: Boardstock	6	1	50	44	100
PU Sandwich Panels: Continuous and Discontinuous	5.5	0.5	50	69.5	100

PIR (Polyisicyanurate)
PU (Polyurethane)
XPS (Extruded Polystyrene)
*In general, total emissions from foam end-uses are assumed to be 100 percent, although work is underway to investigate that assumption. In the XPS Sheet/Insulation Board end-use, the source of emission rates and lifetimes did not yield 100 percent emission; it is unclear at this time whether that was intentional. In the Rigid PU Appliance Foam end-use, the source of emission rates and lifetimes did not yield 100 percent emission; the remainder is anticipated to be emitted at a rate of 2.0%/year post-disposal for the next 26 years.

Sterilization

Sterilants kill microorganisms on medical equipment and devices. The principal ODS used in this sector was a blend of 12% ethylene oxide (EtO) and 88% CFC-12, known as "12/88." In that blend, ethylene oxide sterilizes the equipment and CFC-12 is a dilutent solvent to form a non-flammable blend. The sterilization sector is modeled as a single end-use. 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.

j = Year of emission.

Assumptions

The Vintaging Model contains 1 sterilization end-use, whose transition assumptions away from ODS and growth rates are presented in Table A- 164.

Table A- 164. Sterilization Market Transition Assumptions

Initial Market Segment	Primary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
12/88	EtO	1994	1995	95%	2.0%
	Non-ODP/GWP	1994	1995	1%	
	HCFC/EtO Blends	1993	1994	4%	

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 or sector basis. Values for use and emissions are calculated both in metric tons and in teragrams of CO_2 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.

Bank of ODS and ODS Substitutes

The bank of an ODS or an ODS substitute is "the cumulative difference between the chemical that has been consumed in an application or sub-application and that which has already been released" (IPCC 2006). For any given year, the bank is equal to the previous year's bank, less the chemical in equipment disposed of during the year, plus chemical in new equipment entering the market during that year, less the amount emitted but not replaced, plus the amount added to replace chemical emitted prior to the given year, as shown in the following equation:

$$Bc_j = Bc_{j-1} - Qd_j + Qp_j + E_e - Q_r$$

Where:

Bc_j = Bank of Chemical. Total bank of a specific chemical in year j, by weight.

Qd_j = Quantity of Chemical in Equipment Disposed. Total quantity of a specific chemical in equipment disposed of in year j, by weight.

Qp_j = Quantity of Chemical Penetrating the Market. Total quantity of a specific chemical that is entering the market in year j, by weight.

E_e = Emissions of Chemical Not Replaced. Total quantity of a specific chemical that is emitted during year j but is not replaced in that year. The Vintaging Model assumes all chemical emitted from refrigeration, air conditioning and fire extinguishing equipment is replaced in the year it is emitted, hence this term is zero for all sectors except foam blowing.

Q_r = Chemical Replacing Previous Year's Emissions. Total quantity of a specific chemical that is used to replace emissions that occurred prior to year j. The Vintaging Model assumes all chemical emitted from refrigeration, air conditioning and fire extinguishing equipment is replaced in the year it is emitted, hence this term is zero for all sectors.

j = Year of emission.

Table A-165 provides the bank for ODS and ODS substitutes by chemical grouping in metric tons (MT) for 1990-2009.

Table A- 165. Banks of ODS and ODS Substitutes, 1990-2009 (MT)

	CFC	HCFC	HFC
1990	653,338	235,625	868
1995	757,485	454,719	50,761
2000	628,584	878,343	181,693
2001	602,580	947,180	210,207
2002	578,017	999,467	241,960
2003	554,078	1,033,925	280,053
2004	531,714	1,067,106	318,505
2005	513,896	1,103,085	354,544
2006	500,430	1,135,099	390,237
2007	489,582	1,160,421	425,719
2008	482,541	1,174,094	457,860
2009	479,890	1,165,278	498,695

References

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

3.9. 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 from enteric fermentation; consequently, the more detailed IPCC Tier 2 methodology was used to estimate emissions from all cattle (except for bulls). The IPCC Tier 1 methodology was used to estimate emissions from bulls and the other types of livestock.

Estimate Methane Emissions from Cattle

This section describes the process used to estimate methane emissions from cattle enteric fermentation using the Cattle Enteric Fermentation Model (CEFM).[51]   The CEFM, based on recommendations provided in IPCC/UNEP/OECD/IEA (1997), IPCC (2000) and IPCC (2006), uses information on population, energy requirements, digestible energy, and methane conversion rates to estimate methane emissions.[52] The emission methodology consists of the following three steps: (1) characterize the cattle population to account for animal population categories with different emission profiles; (2) characterize cattle diets to generate information needed to estimate emission factors; and (3) estimate emissions using these data and the IPCC Tier 2 equations.

Step 1: Characterize U.S. Cattle Population

The national cattle population estimates in the inventory submission are based on data obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service Quick Stats database (USDA 2010). A summary of the annual average populations upon which all livestock-related emissions are based is provided in Table A-166. Cattle populations used in the Enteric Fermentation sector were estimated using the cattle transition matrix in the CEFM, which uses January 1 USDA population estimates and weight data to simulate the population of U.S. cattle from birth to slaughter, and results in an estimate of the number of animals in a particular cattle grouping while taking into account the monthly rate of weight gain, the average weight of the animals, and the death and calving rates. The use of supplemental USDA data and the cattle transition matrix in the CEFM results in the cattle population estimates for this sector differing slightly from the January 1 or July 1 USDA point estimates and the cattle population data obtained from the Food and Agriculture Organization of the United Nations (FAO).

Table A-166: Cattle Population Estimates from the CEFM Transition Matrix for 1990-2009

Livestock Type	1990	1995	2000	2005	2006	2007	2008	2009
Calves 0-6 months	22,561	23,499	22,569	21,678	21,621	21,483	21,155	20,940
Dairy								
Dairy Cows	10,015	9,482	9,183	9,004	9,104	9,145	9,257	9,333
Dairy Replacements 7-11 months	1,214	1,216	1,196	1,257	1,277	1,299	1,304	1,325
Dairy Replacements 12-23 months	2,915	2,892	2,812	2,905	3,017	3,043	3,097	3,101
Beef								
Bulls	2,160	2,385	2,293	2,214	2,258	2,214	2,207	2,184
Beef Cows	32,455	35,190	33,575	32,674	32,703	32,644	32,435	31,712
Beef Replacements 7-11 months	1,269	1,493	1,313	1,363	1,380	1,349	1,312	1,287
Beef Replacements 12-23 months	2,967	3,637	3,097	3,171	3,294	3,276	3,169	3,098
Steer Stockers	10,321	11,716	8,724	8,185	8,248	8,302	8,233	8,501
Heifer Stockers	5,946	6,699	5,371	5,015	5,041	4,966	4,868	5,051
Feedlot Cattle	9,549	11,064	13,006	12,652	13,526	13,404	13,070	12,964

Note: Mature animal populations are not assumed to have significant monthly fluctuations, and therefore the populations utilized are the January estimates downloaded from USDA (2010).

The population transition matrix in the CEFM simulates the U.S. cattle population over time and provides an estimate of the population age and weight structure by cattle type on a monthly basis. Since cattle often do not remain in a single population type for an entire year (e.g., calves become stockers, stockers become feedlot animals), and emission

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[51] Emissions from bulls are estimated in the CEFM using a Tier 1 approach based on published population statistics and national average emission factors because the variation in diets and within year population is assumed to be minimal. The IPCC recommends the use of a methane conversion factor of zero for calves, because they consume mainly milk, therefore this results in no methane emissions from calves through 6 months.

[52] Additional information on the Cattle Enteric Fermentation Model can be found in ICF (2006).

profiles vary both between and within each cattle type, these monthly age groups are tracked in the enteric fermentation model to obtain more accurate emission estimates than would be available from annual point estimates of population (such as available from USDA statistics) and weight for each cattle type.

The transition matrix tracks both dairy and beef populations, and divides the populations into males and females, and subdivides the population further into specific cattle groupings for replacement, stocker, feedlot, and mature animals. The matrix is based primarily on two types of data: population statistics and weight statistics (including target weights, slaughter weights, and weight gain). Using the weight data, the transition matrix simulates the growth of animals over time by month. The matrix also relies on supplementary data, such as feedlot placement statistics, slaughter statistics, death rates, and calving rates.

The basic method for tracking population of animals per category is based on the number of births (or graduates) into the monthly age group minus those animals that die or are slaughtered and those that graduate to the next category (such as stockers to feedlot placements).

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 CH_4 emissions associated with each life stage. Given that a stage can last less than one year (e.g., beef calves are weaned at 7 months), each is modeled on a per-month basis. The type of cattle also impacts CH_4 emissions (e.g., beef versus dairy). Consequently, there is an independent transition matrix for each of three separate lifecycle phases, 1) calves, 2) replacements and stockers, and 3) feedlot animals. In addition, the number of mature cows is tracked for both dairy and beef stock. Each lifecycle is discussed separately below, and the categories tracked are listed in Table A-167.

Table A-167: Cattle Population Categories Used for Estimating CH₄ Emissions

Dairy Cattle	Beef Cattle
Calves	Calves
Heifer Replacements	Heifer Replacements
Cows	Heifer and Steer Stockers
	Animals in Feedlots (Heifers & Steers)
	Cows
	Bulls*

* Bulls (beef and dairy) are accounted for in a single category.

The key variables tracked for each of these cattle population categories (except bulls) are as follows:

Calves. 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 for each year was taken from USDA (2010). For dairy cows, the number of births is assumed to be distributed equally throughout the year (approximately 8.3 percent per month), beef births are distributed according to Table A-168, based on estimates from the National Animal Health Monitoring System (NAHMS) (USDA/APHIS/VS 1998, 1994, 1993). To determine whether calves were born to dairy or beef cows, the dairy cow calving rate (USDA/APHIS/VS 2002, USDA/APHIS/VS 1996) was multiplied by the total dairy cow population to determine the number of births attributable to dairy cows, with the remainder assumed to be attributable to beef cows. Total annual calf births are obtained from USDA, and distributed into monthly cohorts by cattle type (beef or dairy). Calf growth is modeled by month, based on estimated monthly weight gain for each cohort (approximatey 61 pounds per month). Total calf population is modified through time to account for veal calf slaughter at 4 months and a calf death loss of 0.35 percent annually (distributed across age cohorts up to six months of age). An example of a transition matrix for calves is shown in Table A-169. Note that calves age one through six months available in January have been tracked through the model based on births and death loss from the previous year.

Table A-168: Estimated Beef Cow Births by Month

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
7%	15%	28%	22%	9%	3%	2%	2%	3%	4%	3%	3%

Table A-169: Example of Monthly Average Populations from Calf Transition Matrix

Age (month)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6	1,207	1,199	1,494	1,751	1,684	1,666	2,665	5,005	8,720	7,062	3,279	1,631
5	1,199	1,494	1,751	1,684	1,666	2,665	5,005	8,720	7,062	3,279	1,631	1,212
4	1,494	1,751	1,684	1,666	2,665	5,005	8,720	7,062	3,279	1,631	1,212	1,202
3	1,751	1,684	1,666	2,665	5,005	8,720	7,062	3,279	1,631	1,212	1,202	1,495
2	1,684	1,666	2,665	5,005	8,720	7,062	3,279	1,631	1,212	1,202	1,495	1,748
1	1,666	2,665	5,005	8,720	7,062	3,279	1,631	1,212	1,202	1,495	1,748	1,680
0	2,665	5,005	8,720	7,062	3,279	1,631	1,212	1,202	1,495	1,748	1,680	1,661

Replacements and Stockers. At seven months of age, calves 'graduate' and are separated into the applicable cattle types. First the number of replacements required for beef and dairy cattle are calculated based on estimated death losses and population changes between beginning and end of year population estimates. All steer, and remaining heifers (after subtracting required replacements), are considered 'stockers,' that is backgrounding animals that are eligible for placement into feedlots as they reach the appropriate weight class. During the stocker phase animals are subtracted out of the transition matrix for placement into feedlots based on feedlot placement statistics from USDA (2010).

The data and calculations that occur for the stocker category include matrices that estimate the population of backgrounding heifers and steer, as well as a matrix for total combined stockers. The matrices start with the beginning of year populations in January and model the progression of each cohort. The age structure of the January population is based on estimated births by month from the previous two years, although in order to balance the population properly, an adjustment is added that slightly reduces population percentages in the older populations. The populations are modified through addition of graduating calves (month 7, bottom row of Table A-170) and subtraction through death loss and animals placed in feedlots. Eventually, an entire cohort population of stockers may be zero, indicating that the complete cohort has been transitioned into feedlots. An example of the transition matrix for stockers is shown in Table A-170.

Table A-170: Example of Monthly Average Populations from Stocker Transition Matrix

Age (month)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
23	202	214	126	47	20	12	10	11	9	7	5	51
22	353	174	59	23	15	12	13	13	9	7	103	311
21	286	81	29	17	15	15	15	12	9	153	421	559
20	133	40	22	17	18	18	14	12	197	526	765	457
19	66	30	22	21	21	17	14	273	620	965	629	212
18	49	30	27	25	20	17	321	779	1,141	795	291	305
17	49	37	31	24	20	379	882	1,442	942	368	546	49
16	60	43	30	24	453	1,004	1,636	1,193	435	779	49	49
15	71	41	30	531	1,160	1,867	1,355	551	985	49	49	61
14	68	41	669	1,324	2,162	1,547	625	1,337	49	49	61	71
13	67	918	1,607	2,471	1,796	716	1,669	49	49	61	71	68
12	1,076	1,774	2,813	2,017	857	2,242	282	49	61	71	68	67
11	2,027	3,105	2,297	962	2,765	365	179	82	91	76	72	1,094
10	3,532	2,542	1,082	3,229	507	253	209	261	213	128	1,151	2,683
9	2,860	1,204	3,588	607	451	425	504	464	429	1,353	2,916	6,195
8	1,328	4,083	770	617	664	915	782	831	1,682	3,596	6,832	5,605
7	4,450	878	871	1,060	1,295	1,232	1,230	2,114	4,188	7,484	6,012	2,665

In order to ensure a balanced population of both stockers and placements, additional data tables are utilized in the stocker matrix calculations. The tables summarize the placement data by weight class and month, and is based on the total number of animals within the population that are available to be placed in feedlots and the actual feedlot placement statistics provided by USDA (2010). In cases where there are discrepancies between the USDA estimated placements by weight class and the calculated animals available by weight, the model pulls available stockers from one higher weight category if available. If there are still not enough animals to fulfill requirements the model pulls animals from the next lower category. Note that in the current time series, this method was able to ensure that total placement data matched USDA estimates, and no shortfalls have occurred.

In addition, 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 animals. Weaning weights were estimated at 515 lbs. Other reported target weights

were available for 12, 15, 24, and 36 month-old animals, depending on the animal type. Beef cow mature weight was taken from measurements provided by a major British Bos taurus breed (Enns 2008). Beef replacement weight was calculated as 70 percent of mature weight at 15 months and 85 percent of mature weight at 24 months. As dairy weights are not a trait that is typically tracked, mature weight for dairy cows was estimated at 1,500 for all years, based on a personal communication with Kris Johnson (2010) and an estimate from Holstein Association USA (2010). Dairy replacement at 15 months was assumed to be 875 lbs and replacement at 24 months is 1,300 lbs. Live slaughter weights were derived from dressed slaughter weight data for each year (USDA 2010). The annual typical animal mass for each livestock type are presented in Table A- 171

Weight gain for stocker animals was based on monthly gain estimates from Johnson (1999) for 1989, and from average daily estimates from Lippke et al. 2000, Pinchack et al., 2004, Platter et al., 2003, and Skogerboe et al., 2000 for 2000 through 2007. Interim years were calculated linearly, as shown in Table A-172, and weight gain was held constant starting in 2008. Live slaughter weight was estimated as dressed weight divided by 0.63. This ratio represents the dressed weight (i.e. weight of the carcass after removal of the internal organs), to the live weight (i.e. weight taken immediately before slaughter). Table A-172 provides weights and weight gains that vary by year in the CEFM.

Table A- 171: Typical Animal Mass that Varies by Year (lbs)

Year/Cattle Type	Dairy Cows	Dairy Replacements	Beef Cows	Beef Replacements	Steer Stockers	Heifer Stockers	Steer Feedlot	Heifer Feedlot
1990	1,500	900	1,221	820	692	652	923	846
1991	1,500	898	1,225	822	695	656	975	867
1992	1,500	897	1,263	841	714	673	984	878
1993	1,500	899	1,280	852	721	683	930	864
1994	1,500	898	1,280	854	721	689	944	876
1995	1,500	898	1,282	858	735	701	947	880
1996	1,500	898	1,285	859	739	707	940	878
1997	1,500	900	1,286	861	737	708	939	877
1998	1,500	897	1,296	866	736	710	957	892
1999	1,500	899	1,292	862	731	709	960	895
2000	1,500	897	1,272	849	720	702	961	899
2001	1,500	898	1,272	850	726	707	963	901
2002	1,500	897	1,276	852	726	708	982	915
2003	1,500	900	1,308	872	719	702	973	905
2004	1,500	897	1,323	878	719	702	967	905
2005	1,500	895	1,327	880	718	706	975	917
2006	1,500	898	1,341	890	725	713	984	925
2007	1,500	897	1,348	895	721	707	992	928
2008	1,500	898	1,348	895	721	705	1,000	939
2009	1,500	897	1,348	895	731	715	1,007	948

Table A-172: Weight Gains that Vary by Year (lbs)

Year/Cattle Type	Steer Stockers to 12 months(lbs/day)	Steer Stockers to 24 months (lbs/day)	Heifer Stockers to 12 months(lbs/day)	Heifer Stockers to 24 months(lbs/day)
1990	1.53	1.23	1.23	1.08
1991	1.56	1.29	1.29	1.15
1992	1.59	1.35	1.35	1.23
1993	1.62	1.41	1.41	1.30
1994	1.65	1.47	1.47	1.38
1995	1.68	1.53	1.53	1.45
1996	1.71	1.59	1.59	1.53
1997	1.74	1.65	1.65	1.60
1998	1.77	1.71	1.71	1.68
1999	1.80	1.77	1.77	1.75
2000	1.83	1.83	1.83	1.83
2001	1.83	1.83	1.83	1.83
2002	1.83	1.83	1.83	1.83
2003	1.83	1.83	1.83	1.83
2004	1.83	1.83	1.83	1.83
2005	1.83	1.83	1.83	1.83
2006	1.83	1.83	1.83	1.83
2007	1.83	1.83	1.83	1.83
2008	1.83	1.83	1.83	1.83
2009	1.83	1.83	1.83	1.83

Sources: Enns (2008), Johnson (1999), Lippke et al. (2000), NRC (1999), Pinchack et al. (2004), Platter et al. (2003), Skogerboe et al. (2000)

Feedlot Animals. Feedlot placement statistics from USDA provide data on the placement of animals from the stocker population into feedlots on a monthly basis by weight class. The model uses these data to shift a sufficient number of animals from the stocker cohorts into the feedlot populations to match the reported placement data. After animals are placed in feedlots they progress through two steps. First, animals spend 25 days on a step-up diet to become acclimated to the new feed type, during this time weight gain is estimated to be 2.8 to 3 pounds per day (Johnson 1999). Animals are then switched to a finishing diet for a period of time before they are slaughtered. Weight gain during finishing diets is estimated to be 3 to 3.3 pounds per day (Johnson 1999). 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 target weight (as determined by weights at slaughter). Additionally, animals remaining in feedlots at the end of the year are tracked for inclusion in the following year's emission and population counts. For 1990 to 1995, only the total placement data were available, therefore placements for each weight category (displayed in Table A-173) for those years are based on the average of monthly placements from the 1996 to 1998 reported figures. Placement data is available by weight class for all years from 1996 onward. Table A-173 provides a summary of the reported feedlot placement statistics for 2009.

Table A-173: Feedlot Placements in the United States for 2009 (Number of animals placed in Thousand Head)

Weight Placed	When:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
< 600 lbs		380	320	305	355	395	315	455	435	490	615	510	430
600 – 700 lbs		505	385	340	315	305	290	365	395	450	645	565	420
700 – 800 lbs		553	538	593	405	433	371	458	514	593	579	394	401
> 800 lbs		420	435	570	525	505	415	585	775	855	635	375	295
Total		**1,858**	**1,678**	**1,808**	**1,600**	**1,638**	**1,391**	**1,863**	**2,119**	**2,388**	**2,474**	**1,844**	**1,546**

Source: USDA (2010).
Note: Totals may not sum due to independent rounding.

Mature Animals. 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 CH_4 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 process results in a range of weighted monthly lactation estimates expressed as lbs/animal/month. The monthly estimates from January to December are 3.3, 5.1, 8.7, 12.0, 13.6, 13.3, 11.7, 9.3, 6.9, 4.4, 3.0, and 2.8 lbs milk/animal/day. Annual estimates for dairy cattle were taken from USDA milk production statistics. Dairy lactation estimates for 1990 through 2009 are shown in

Table A-174. Beef and dairy cow and bull populations are assumed to remain relatively static throughout the year, as large fluctuations in population size are assumed to not occur. These estimates are taken from the USDA beginning and end of year population datasets.

Table A-174: Dairy Lactation by State (lbs/ year/cow)*

State/Year	1990	1995	2000	2005	2006	2007	2008	2009
Alabama	12,214	14,176	13,920	14,000	14,500	15,154	15,333	14,909
Alaska	13,300	17,000	14,500	12,273	12,250	14,667	12,000	10,000
Arizona	17,500	19,735	21,820	22,679	22,855	23,260	23,382	23,028
Arkansas	11,841	12,150	12,436	13,545	12,900	12,941	12,400	12,615
California	18,456	19,573	21,130	21,404	21,815	22,440	22,344	22,000
Colorado	17,182	18,687	21,618	22,577	23,155	22,932	22,930	23,089
Connecticut	15,606	16,438	17,778	19,200	19,316	19,211	19,158	18,684
Delaware	13,667	14,500	14,747	16,622	16,286	16,618	16,923	17,000
Florida	14,033	14,698	15,688	16,591	16,447	16,832	17,167	18,061
Georgia	12,973	15,550	16,284	17,259	18,234	18,169	17,829	18,600
Hawaii	13,604	13,654	14,358	12,889	13,256	12,241	10,882	14,200
Idaho	16,475	18,147	20,816	22,332	22,346	22,513	22,432	22,091
Illinois	14,707	15,887	17,450	18,827	19,252	18,612	18,569	18,873
Indiana	14,590	15,375	16,568	20,295	19,861	20,307	19,683	20,137
Iowa	15,118	16,124	18,298	20,641	20,127	20,085	19,995	20,367
Kansas	12,576	14,390	16,923	20,505	20,938	19,882	20,641	21,085
Kentucky	10,947	12,469	12,841	12,896	13,296	13,889	13,444	14,190
Louisiana	11,605	11,908	12,034	12,400	12,375	12,034	12,269	11,870
Maine	14,619	16,025	17,128	18,030	17,938	17,788	18,273	18,061
Maryland	13,461	14,725	16,083	16,099	17,281	18,121	18,375	18,255
Massachusetts	14,871	16,000	17,091	17,059	17,375	17,000	16,933	17,571
Michigan	15,394	17,071	19,017	21,635	22,234	22,761	22,180	22,445
Minnesota	14,127	15,894	17,777	18,091	18,598	18,817	18,927	19,230
Mississippi	12,081	12,909	15,028	15,280	14,957	15,429	14,550	13,889
Missouri	13,632	14,158	14,662	16,026	16,000	14,982	14,682	14,654
Montana	13,542	15,000	17,789	19,579	18,632	18,500	18,412	19,933
Nebraska	13,866	14,797	16,513	17,950	18,328	18,220	18,672	19,721
Nevada	16,400	18,128	19,000	21,680	20,148	20,481	20,704	21,821
New Hampshire	15,100	16,300	17,333	18,875	19,533	19,333	19,933	19,533
New Jersey	13,538	13,913	15,250	16,000	16,182	16,800	16,900	17,889
New Mexico	18,815	18,969	20,944	21,192	21,853	21,958	23,269	24,320
New York	14,658	16,501	17,378	18,639	18,879	19,303	19,859	20,071
North Carolina	15,220	16,314	16,746	18,741	18,510	19,188	18,979	19,644
North Dakota	12,624	13,094	14,292	14,182	14,688	15,310	16,077	16,739
Ohio	13,767	15,917	17,027	17,567	17,737	18,109	18,321	18,744
Oklahoma	12,327	13,611	14,440	16,480	16,630	16,580	16,578	16,983
Oregon	16,273	17,289	18,222	18,876	19,000	19,417	19,772	19,719
Pennsylvania	14,726	16,492	18,081	18,722	19,390	19,422	19,262	19,360
Rhode Island	14,250	14,773	15,667	17,000	17,273	16,455	18,091	17,818
South Carolina	12,771	14,481	16,087	16,000	16,294	17,889	17,889	18,765
South Dakota	12,257	13,398	15,516	17,741	18,580	19,306	19,956	20,128
Tennessee	11,825	13,740	14,789	15,743	15,657	15,857	16,068	16,232
Texas	14,350	15,244	16,503	19,646	19,501	18,982	20,134	20,898
Utah	15,838	16,739	17,573	18,875	20,314	20,376	20,894	20,988
Vermont	14,528	16,210	17,199	18,469	18,383	18,079	18,400	18,289
Virginia	14,213	15,116	15,833	16,990	17,363	17,530	17,612	18,083
Washington	18,532	20,091	22,644	23,270	23,055	23,239	23,344	23,171
West Virginia	11,250	12,667	15,588	14,923	15,385	15,000	15,083	14,727
Wisconsin	13,973	15,397	17,306	18,500	18,824	19,310	19,546	20,079
Wyoming	12,337	13,197	13,571	14,878	17,612	18,831	19,386	18,811

Source: USDA (2010).
* Beef lactation data were developed using the methodology described in Step 1.

Step 2: Characterize U.S. Cattle Population Diets

To support development of digestible energy (DE, the percent of gross energy intake digested by the animal) and CH_4 conversion rate (Y_m, the fraction of gross energy converted to CH_4) 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 (1996). The data for each of the diets (e.g., proportions of different feed constituents, such as hay or grains) were used to determine feed chemical composition for use in estimating digestible energy and Y_m for each animal type.

DE and Y_m vary by diet and animal type. The IPCC recommends Y_m values of 3.0±1.0 percent for feedlot cattle and 6.5±1.0 percent for all other cattle (IPCC 2006). Given the availability of detailed diet information for different regions and animal types in the United States, digestible energy and Y_m values unique to the United States[53] were developed. Digestible energy and Y_m values were estimated for each cattle population category, for each year in the time series based on physiological modeling, published values, and/or expert opinion.

For dairy cows, ruminant digestion models were used to estimate Y_m. The three major categories of input required by the models 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 Y_m values were estimated for 1990 using the Donovan and Baldwin model (1999) that represents physiological processes in the ruminant animals and diet characteristics from USDA (1996). The Donovan and Baldwin model accounts for differing diets (i.e., grain-based or forage-based), so that Y_m values for the variable feeding characteristics within the U.S. cattle population can be estimated. Subsequently, a literature review of dairy diets was conducted and nearly 250 diets were analyzed from 1990 through 2008 across 23 states. Kebreab et al (2008). conducted an evaluation of models and found that the COWPOLL model was the best model for estimating Y_m for dairy. Therefore, the COWPOLL model was used to estimate Y_m values for each of the diets. Due to the variability associated with cattle diets, a function based on the national trend observed from the analysis of the diary diets was used to calculate 1991 and beyond values based on the regional 1990 Y_m values from Donovan and Baldwin.. The resulting scaling factor is shown below:

$$Y_m = Ym(1990)EXP\left(\frac{1.22}{(Year-1980)}\right) / EXP\left(\frac{1.22}{(1990-1980)}\right)$$

DE values for dairy cows were estimated from the literature search based on the on annual trends observed in the recent data collection effort. The regional variability observed in the literature search was not statistically significant, and therefore DE was not varied by region.

Considerably less data was available for dairy heifers, so assumptions were based on the relationship of the collected data literature on dairy heifers to the data on dairy cow diets. From this relationship, DE was estimated as the mature cow DE minus three percent, and Y_m was estimated as that of the mature dairy cow plus 0.1 percent.

To calculate the DE values for grazing beef cattle, diet composition assumptions were used to estimate weighted DE values for a combination of forage and supplemental diets. Where DE values were not available for specific feed types, total digestible nutrients (TDN) as a percent of dry matter (DM) intake was used as a proxy for DE, as listed in NRC (2000). Forage diets make up the majority of beef cattle diets, and two separate regional DE values were used to account for the generally lower forage quality in the western United States. For all non-western beef cattle, the forage DE was an average of the seasonal values for Grass Pasture diets listed in Appendix Table 1 of the NRC (2000). This resulted in a DE of 64.7 percent for the forage portion of the diet for all beef cattle in regions other than the west. For beef cattle in the west, the forage DE was calculated as the seasonal average for meadow and range diets listed in Appendix Table 1 of the NRC (2000). This resulted in a DE for the forage portion of the western region diet of 58.5 percent. In addition, it was assumed that each region fed a supplemental diet, as shown in Table A- 175. By weighting the calculated DE values from the forage and supplemental diets, the DE values for the composite diet were calculated.[54] The percent of each diet that is assumed to be supplemental and the forage DE values used for each region, and the resulting weighted DE values are

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[53] 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 research conducted to characterize the diets of U.S. cattle and assess the Y_m values associated with different animal performance and feed characteristics in the United States.

[54] For example, in California the forage DE of 64.7 was used for 95 percent of the grazing cattle diet and a supplemented diet DE of 69.3 percent was used for five percent of the diet, for a total weighted DE of 64.9 percent, as shown in Table A-176.

shown in Table A-176. These values are used for steer and heifer stockers and beef replacements. Finally, for beef cows, the DE value was adjusted downward by two percent to reflect the lower digestibility diets of the mature beef cow based on Johnson (2002). Y_m values for all grazing beef cattle were set at 6.5 percent based on Johnson (2002).

For feedlot animals, DE and Y_m values for 1990 were taken from Johnson (1999). . In the CEFM, values for 1991 through 1999 were linearly extrapolated based on values for 1990 and 2000. DE and Y_m values for 2000 onwards were estimated using the MOLLY model as described in Kebreab et al (2008). In addition, feedlot animals are assumed to spend the first 25 days in the feedlot on a "step-up" diet to become accustomed to the higher quality feedlot diets. The step-up DE and Y_m are calculated as the average of all state forage and feedlot diet DE and Y_m values.

Table A-177 shows the regional DE and Y_m for U.S. cattle in each region for 2009.

Table A- 175: DE Values and Representative Regional Diets (Percent of Diet for each Region) for the Supplemental Diet of Grazing Beef Cattle

Feed	Source of TDN (NRC 2000)	Unweighted TDN or DE	California [a]	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Alfalfa Hay	Table 11-1, feed #4	59.6%	65%	30%	30%	29%	12%	30%	
Barley	Table 11-1, feed #12	86.3%	10%	15%					
Bermuda	Table 11-1, feed #17	48.5%							35%
Bermuda Hay	Table 11-1, feed #17	48.5%				40%			
Corn	Table 11-1, feed #38	88.1%	10%	10%	25%	11%	13%	13%	
Corn Silage	Table 11-1, feed #39	71.2%			25%		20%	20%	
Cotton Seed Meal	Table 11-1, feed #42	74.4%				7%			
Grass Hay	Table 1a, feed #129, 147, 148	53.7%		40%				30%	
Orchard	Table 11-1, feed #61	53.5%							40%
Soybean Meal Supplement	Table 11-1, feed #70	83.1%		5%	5%				5%
Sorghum	Table 11-1, feed #67	81.3%							20%
Soybean Hulls	Table 11-1, feed #69	76.4%						7%	
Timothy Hay	Table 11-1, feed #77	55.5%					50%		
Whole Cotton Seed	Table 11-1, feed #41	89.2%	5%				5%		
Wheat Middlings	Table 1a, feed #433	83.0%			15%	13%			
Wheat	Table 11-1, feed #83	87.2%	10%						
Weighted Total			**69%**	**65%**	**74%**	**62%**	**65%**	**65%**	**59%**

Source of representative regional diets: Donovan (1999).
[a] Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above. The Western region includes AK, WA, OR, ID, NV, UT, AZ, HI, and NM; the Northeastern region includes PA, NY, MD, DE, NJ, CT, RI, MA, VT, NH, ME, and WV; the Southcentral region includes AR, LA, OK, and TX; the Midwestern region includes MO, IL, IN, OH, MN, WI, MI, and IA; the Northern Great Plains include MT, WY, ND, SD, NE, KS, and CO; and the Southeastern region includes VA, NC, KY, TN, MS, AL, GA, SC, and FL.

Table A-176: Percent of Each Diet that is Supplemental and the Resulting DE Values for Each Region

Region[a]	Percent Supplement	Percent Forage	Forage DE Used	Calculated Weighted Average DE
West	10	90	59	59
Northeast	15	85	65	65
Southcentral	10	90	65	64
Midwest	15	85	65	65
Northern Great Plains	15	85	65	66
Southeast	5	95	65	64
California	5	95	65	65

Sources: Percent of total diet that is supplemental diet, Donovan (1999); Forage DE, NRC (2000).
[a] Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above. The Western region includes AK, WA, OR, ID, NV, UT, AZ, HI, and NM; the Northeastern region includes PA, NY, MD, DE, NJ, CT, RI, MA, VT, NH, ME, and WV; the Southcentral region includes AR, LA, OK, and TX; the Midwestern region includes MO, IL, IN, OH, MN, WI, MI, and IA; the Northern Great Plains include MT, WY, ND, SD, NE, KS, and CO; and the Southeastern region includes VA, NC, KY, TN, MS, AL, GA, SC, and FL.

Table A-177: Regional Digestible Energy (DE) and CH₄ Conversion Rates (Yₘ) for Cattle in 2009

Animal Type	Data	California [c]	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Beef Repl. Heif.	DE[a]	65	59	66	64	65	65	64
	Y_m [b]	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Dairy Repl. Heif.	DE	64	64	64	64	64	64	64
	Y_m	6.0%	6.0%	5.7%	6.5%	6.4%	5.7%	7.0%
Steer Stockers	DE	65	59	66	64	65	65	64
	Y_m	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Heifer Stockers	DE	65	59	66	64	65	65	64
	Y_m	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Steer Feedlot	DE	83	83	83	83	83	83	83
	Y_m	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%
Heifer Feedlot	DE	83	83	83	83	83	83	83
	Y_m	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%
Beef Cows	DE	63	57	64	62	63	63	62
	Y_m	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Dairy Cows	DE	67	67	67	67	67	67	67
	Y_m	5.9%	5.9%	5.6%	6.4%	6.3%	5.6%	6.9%
Steer Step-Up	DE	72	72	72	72	72	72	72
	Y_m	5.2%	5.2%	5.2%	5.2%	5.2%	5.2%	5.2%
Heifer Step-Up	DE	72	72	72	72	72	72	72
	Y_m	5.2%	5.2%	5.2%	5.2%	5.2%	5.2%	5.2%

[a] Digestible Energy in units of percent of GE (MJ/Day).
[b] Methane Conversion Rate is the fraction of GE in feed converted to methane.
[c] Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above. The Western region includes AK, WA, OR, ID, NV, UT, AZ, HI, and NM; the Northeastern region includes PA, NY, MD, DE, NJ, CT, RI, MA, VT, NH, ME, and WV; the Southcentral region includes AR, LA, OK, and TX; the Midwestern region includes MO, IL, IN, OH, MN, WI, MI, and IA; the Northern Great Plains include MT, WY, ND, SD, NE, KS, and CO; and the Southeastern region includes VA, NC, KY, TN, MS, AL, GA, SC, and FL.

Step 3: Estimate CH₄ Emissions from Cattle

Emissions by state were estimated in three steps: a) determine gross energy (GE) intake using the IPCC (2006) equations, b) determine an emission factor using the GE values and other factors, and c) sum the daily emissions for each animal type. Finally, the state emissions were aggregated to obtain the national emissions estimate. The necessary data values for each state and animal type include:

- Body Weight (kg)
- Weight Gain (kg/day)
- Net Energy for Activity (C_a, MJ/day)[55]
- Standard Reference Weight (kg)[56]
- 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 CH₄)
- Population

Step 3a: Determine 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 (2006).

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[55] Zero for feedlot conditions, 0.17 for high quality confined pasture conditions, and 0.36 for extensive open range or hilly terrain 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.
[56] Standard Reference Weight is the mature weight of a female animal of the animal type being estimated, used in the model to account for breed potential.

$$GE = \left[\frac{\left(\dfrac{NE_m + NE_a + NE_l + NE_{work} + NE_p}{REM} \right) + \left(\dfrac{NE_g}{REG} \right)}{\dfrac{DE\%}{100}} \right]$$

Where,

GE	= Gross energy (MJ/day)
NE_m	= Net energy required by the animal for maintenance (MJ/day)
NE_a	= Net energy for animal activity (MJ/day)
NE_l	= Net energy for lactation (MJ/day)
NE_{work}	= Net energy for work (MJ/day)
NE_p	= Net energy required for pregnancy (MJ/day)
REM	= Ratio of net energy available in a diet for maintenance to digestible energy consumed
NE_g	= Net energy needed for growth (MJ/day)
REG	= Ratio of net energy available for growth in a diet to digestible energy consumed
DE	= Digestible energy expressed as a percent of gross energy (percent)

Step 3b: Determine Emission Factor

The emission factor (DayEmit) was determined using the gross energy value and the methane conversion factor (Y_m) for each category. This relationship is shown in the following equation:

$$DayEmit = \frac{GE \times Y_m}{55.65}$$

Where,

DayEmit	= Emission factor (kg CH_4/head/day)
GE	= Gross energy intake (MJ/head/day)
Y_m	= CH_4 conversion rate, which is the fraction of gross energy in feed converted to CH_4 (%)
55.65	= A factor for the energy content of methane (MJ/kg CH_4)

The daily emission factors were estimated for each animal type and state, calculated national emission factors are shown by animal type in Table A-178.

Table A-178: Calculated National Emission Factors for Cattle by Animal Type (kg CH₄/head/year)

Cattle Type	1990	1995	2000	2005	2006	2007	2008	2009
Dairy								
Cows	124	125	132	133	134	139	139	140
Replacements 7-11 months	48	46	46	45	45	46	46	46
Replacements 12-23 months	73	69	70	67	67	70	69	70
Beef								
Bulls	53	53	53	53	53	53	53	53
Cows	89	92	91	94	94	94	94	94
Replacements 7-11 months	54	57	57	59	60	60	60	60
Replacements 12-23 months	63	66	66	68	69	69	69	69
Steer Stockers	55	56	58	58	58	58	57	57
Heifer Stockers	51	56	60	59	59	59	59	59
Feedlot Cattle	39	38	39	39	39	42	42	43

Note: To convert to a daily emission factor, the yearly emission factor can be divided by 365 (the number of days in a year).

Step 3c: Estimate Total Emissions

Emissions were summed for each month and for each state population category using the daily emission factor for a representative animal and the number of animals in the category. The following equation was used:

$$\text{Emissions}_{state} = \text{DayEmit}_{state} \times \text{Days/Month} \times \text{SubPop}_{state}$$

Where,

DayEmit_{State} = The emission factor for the subcategory and state (kg CH_4/head/day)
Days/Month = The number of days in the month
SubPop_{State} = The number of animals in the subcategory and state during the month

This process was repeated for each month, and the totals for each state subcategory were summed to achieve an emission estimate for a state for the entire year and state estimates were summed to obtain the national total. The estimates for each of the 10 subcategories of cattle are listed in Table A-179. The emissions for each subcategory were then summed to estimate total emissions from beef cattle and dairy cattle for the entire year.

Table A-179: CH₄ Emissions from Cattle (Gg)

Cattle Type	1990	1995	2000	2005	2006	2007	2008	2009
Dairy	**1,513**	**1,440**	**1,460**	**1,449**	**1,479**	**1,544**	**1,564**	**1,581**
Cows	1,242	1,183	1,209	1,197	1,219	1,271	1,289	1,304
Replacements 7-11 months	58	56	55	56	57	60	60	61
Replacements 12-23 months	212	201	196	196	203	213	214	216
Beef	**4,502**	**5,128**	**4,790**	**4,731**	**4,803**	**4,837**	**4,796**	**4,742**
Bulls	114	126	122	117	120	117	117	116
Cows	2,887	3,223	3,059	3,056	3,079	3,083	3,065	2,995
Replacements 7-11 months	69	85	74	80	82	81	79	77
Replacements 12-23 months	188	241	204	217	228	228	220	215
Steer Stockers	563	661	508	472	475	478	473	489
Heifer Stockers	305	374	322	298	298	294	288	298
Feedlot Cattle	375	416	502	489	521	556	554	553
Total	**6,015**	**6,567**	**6,251**	**6,180**	**6,282**	**6,381**	**6,374**	**6,323**

Notes: Totals may not sum due to independent rounding. Because calves younger than 7 months consume mainly milk the IPCC recommends the use of methane conversion factor of zero, resulting in no methane emissions from this subcategory of cattle.

Emission Estimates from Other Livestock

All livestock population data, except for horses, were taken from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) agricultural statistics database (USDA 2009). Table A- 183of the Manure Management Annex shows the population data for all livestock species that were used for estimating all livestock-related emissions. For each animal category, the USDA publishes monthly, annual, and multi-year livestock population and production estimates. All data were downloaded from the USDA-NASS agricultural database (USDA 2010). The Food and Agriculture Organization (FAO) publishes horse population data. These data were accessed from the FAOSTAT database (FAO 2010). Methane emissions from sheep, goats, swine, and horses were estimated by multiplying published national population estimates by the IPCC emission factor for each year. Table A-180 shows the emission factors used for these other livestock.

Enteric fermentation emissions from all livestock types are shown in Table A-181 and Table A-182.

Table A-180: Emission Factors for Other Livestock (kg CH₄/head/year)

Livestock Type	Emission Factor
Sheep	8
Goats	5
Horses	18
Swine	1.5

Source: IPCC (2006)

Table A-181: CH$_4$ Emissions from Enteric Fermentation (Tg CO$_2$ Eq.)

Livestock Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Beef Cattle	94.5	107.7	100.6	99.9	100.0	100.0	98.3	99.3	100.9	101.6	100.7	99.6
Dairy Cattle	31.8	30.2	30.7	30.5	30.6	28.4	29.9	30.4	31.1	32.4	32.9	33.2
Horses	1.9	1.9	2.0	2.1	2.3	2.6	3.0	3.5	3.6	3.6	3.6	3.6
Sheep	1.9	1.5	1.2	1.2	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0
Swine	1.7	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	2.1	2.1	2.1
Goats	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Total	**132.1**	**143.5**	**136.5**	**135.7**	**136.1**	**134.4**	**134.4**	**136.5**	**138.8**	**141.0**	**140.6**	**139.8**

Note: Totals may not sum due to independent rounding.

Table A-182: CH$_4$ Emissions from Enteric Fermentation (Gg)

Livestock Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Beef Cattle	4,502	5,128	4,790	4,757	4,761	4,762	4,680	4,731	4,803	4,837	4,796	4,742
Dairy Cattle	1,513	1,440	1,460	1,453	1,457	1,354	1,422	1,449	1,479	1,544	1,564	1,581
Horses	91	92	94	99	108	126	144	166	171	171	171	171
Sheep	91	72	56	55	53	51	49	49	50	49	48	46
Swine	81	88	88	88	90	90	91	92	93	98	101	99
Goats	13	12	12	12	13	13	14	15	15	16	16	16
Total	**6,290**	**6,832**	**6,502**	**6,464**	**6,481**	**6,396**	**6,400**	**6,500**	**6,611**	**6,715**	**6,696**	**6,655**

Note: Totals may not sum due to independent rounding.

3.10. Methodology for Estimating CH₄ and N₂O Emissions from Manure Management

The following steps were used to estimate methane (CH_4) and nitrous oxide (N_2O) 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 emission estimates for Agricultural Soil Management (see the Agricultural Soils Management Annex).

Step 1: Livestock Population Characterization Data

Annual animal population data for 1990 through 2009 for all livestock types, except horses and goats were obtained from the USDA National Agricultural Statistics Service (NASS). The population data used in the emissions calculations for cattle, swine, and sheep were downloaded from the USDA NASS Population Estimates Database (USDA 2009a). Poultry population data were obtained from USDA NASS reports (USDA 1995a, 1995b, 1998a, 1999, 2004a, 2004b, 2010a, and 2010b). Horse population data were obtained from the Food and Agriculture Organization (FAO) FAOSTAT database (FAO 2010). Goat population data for 1992, 1997, 2002, and 2007 were obtained from the Census of Agriculture (USDA 2009a). Additional data sources used and adjustments to these data sets are described below.

Cattle: For all cattle groups (cows, heifers, steers, bulls, and calves), the USDA data provide cattle inventories from January (for each state) and July (as a U.S. total only) of each year. Cattle inventories change over the course of the year, sometimes significantly, as new calves are born and as cattle are moved into feedlots and subsequently slaughtered; therefore, to develop the best estimate for the annual animal population, the populations and the individual characteristics, such as weight and weight gain, pregnancy, and lactation of each animal type were tracked in the Cattle Enteric Fermentation Model (CEFM). For animals that have relatively static populations throughout the year, such as mature cows and bulls, the January 1 values were used. For animals that have flucatuating populations throughout the year, such as calves and growing heifers and steer, the populations are modeled based on a transition matrix that uses annual population data from USDA along with USDA data on animal births, placement into feedlots, and slaughter statistics.

Swine: The USDA provides quarterly data for each swine subcategory: breeding, market under 50 pounds (under 23 kg), market 50 to 119 pounds (23 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.

Sheep: Population data for lamb and sheep on feed are not available after 1993 (USDA 1994). The number of lamb and sheep on feed for 1994 through 2009 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 in feedlots versus pasture/crop residue were provided only for lamb in 1993. To calculate the populations of sheep and lamb in feedlots for all years, it was assumed that the percentage of sheep and lamb on feed that are in 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 1992, 1997, 2002, and 2007 (USDA 2009a). The data for 1992 were used for 1990 through 1992 and the data for 2007 were used for 2007 through 2009. Data for 1993 through 1996, 1998 through 2001, and 2003 through 2006 were extrapolated based on the 1992, 1997, and 2002 Census data.

Poultry: The USDA provides population data for hens (one year old or older), pullets (hens younger than one year old), broilers, other chickens, and turkeys (USDA 1995a, 1995b, 1998a, 1999, 2004a, 2004b, 2010a, and 2010b). The annual population data for boilers and turkeys were adjusted for the turnover (i.e., slaughter) rate (Lange 2000). All poultry population data were adjusted to account for states that report non-disclosed populations to USDA NASS. The combined populations of the states reporting non-disclosed populations are reported as "other" states. State populations for the non-disclosed states were estimated by equally distributing the population attributed to "other" states to each of the non-disclosed states.

Horses: The FAO publishes annual total U.S. horse population, which were accessed from the FAOSTAT database (FAO 2010). State horse population data were estimated using state population distributions from the 1992, 1997, and 2002 Census of Agriculture and the FAO national population data. A summary of the livestock population characterization data used to calculate CH4 and N2O emissions is presented in Table A- 183.

Step 2: Waste Characteristics Data

Methane and N$_2$O emissions calculations are based on the following animal characteristics for each relevant livestock population:

- Volatile solids (VS) excretion rate;
- Maximum methane producing capacity (B$_o$) for U.S. animal waste;
- Nitrogen excretion rate (Nex); and
- Typical animal mass (TAM).

Table A-184 presents a summary of the waste characteristics used in the emissions estimates. 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. The USDA's Agricultural Waste Management Field Handbook (AWMFH; USDA 1996a, 2008) is one of the primary sources of waste characteristics. Data from the 1996 and 2008 USDA AWMFH were used to estimate VS and Nex for most animal groups across the time series of the inventory, as shown in Table A-3. In some cases, data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) were used to supplement the USDA data. The VS and Nex data for breeding swine are from 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). Due to the change in USDA reporting of hens and pullets, new nitrogen and VS excretion rates were calculated for the combined population of hens and pullets; a weighted average rate was calculated based on hen and pullet population data from 1990 to 2004.

The method for calculating VS excretion and Nex from beef and dairy cows, heifers, and steers is based on the relationship between animal performance characteristics such as diet, lactation, and weight gain and energy utilization. The method used is outlined by the IPCC Tier II methodology, and is modeled in the enteric fermentation portion of the inventory in order to take advantage of the detailed diet and animal performance data assembled as part of the Tier II analysis for cattle.

Volatile solids content of manure is the fraction of the diet consumed by cattle that is not digested and thus excreted as fecal material; fecal material combined with urinary excretions constitutes manure. The enteric fermentation model requires the estimation of gross energy intake and its fractional digestibility to estimate enteric CH4 emissions (see the Enteric Fermentation Annex for details on the enteric energy model). These two inputs are used to calculate the indigestible energy per animal unit as gross energy minus digestible energy plus the amount of gross energy for urinary energy excretion per animal unit (2 or 4 percent). This value is then converted to VS production per animal unit using the typical conversion of dietary gross energy to dry organic matter of 18.45 MJ/kg, after subtracting out the ash content of manure. The current equation recommended by the 2006 IPCC Guidelines is:

$$VS\,production\,(kg) = \left[(GE - DE) + (UE \times GE)\right] \times \frac{1 - ASH}{18.45}$$

Where,

GE	= Gross energy intake (MJ)
DE	= Digestible energy (MJ)
(UE × GE)	= Urinary energy expressed as fraction of GE, assumed to be 0.04 except for feedlots which are reduced 0.02 as a result of the high grain content of their diet.
ASH	= Ash content of manure calculated as a fraction of the dry matter feed intake (assumed to be 0.08).
18.45	= Conversion factor for dietary GE per kg of dry matter (MJ per kg). This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock.

Nitrogen uptake in cattle is carried out through dietary protein intake. However, when feed intake of protein exceeds the nutrient requirements of the animal, the excess nitrogen is excreted, primarily through the urine. To calculate the nitrogen excreted by each animal type, the cattle enteric fermentation model (CEFM) utilizes the energy balance calculations recommended by the IPCC (2006) for gross energy and the energy required for growth along with inputs of weight gain, milk production, and the percent of crude protein in the diets. The total nitrogen excreted is measured in the CEFM as nitrogen consumed minus nitrogen retained by the animal for growth and in milk. The basic equation for calculating Nex is shown below, followed by the equations for each of the constituent parts.

$$N_{excreted} = N_{consumed} - \left(N_{growth} + N_{milk}\right)$$

Where,

N $_{excreted}$ = Daily N excreted per animal, kg per animal per day.
N $_{consumed}$ = Daily N intake per animal, kg per animal per day
N $_{growth}$ = Nitrogen retained by the animal for growth, kg per animal per day
N $_{milk}$ = Nitrogen retained in milk, kg per animal per day

The equation for nitrogen consumed is based on the 2006 IPCC Guidelines, and is estimated as:

$$N_{consumed} = \left[\frac{GE}{18.45} * \left(\frac{\frac{CP\%}{100}}{6.25}\right)\right]$$

Where:

N $_{consumed}$ = Daily N intake per animal, kg per animal per day
GE = Gross energy intake, as calculated in the CEFM, MJ per animal per day
18.45 = Conversion factor for dietary GE per kg of dry matter, MJ per kg.
CP% = Percent crude protein in diet, input into the CEFM
6.25 = Conversion from kg of dietary protein to kg of dietary N, kg feed per kg N

The portion of consumed nitrogen that is retained as product equals the nitrogen required for weight gain plus that in milk. The nitrogen retained in body weight gain by stockers, replacements, or feedlot animals is calculated using the net energy for growth (NEg), weight gain (WG), and other conversion factors and constants. The equation matches current 2006 IPCC Guidelines recommendations, and is as follows:

$$N_{growth} = \frac{\left\{WG * \left[268 - \frac{(7.03 * NEg)}{WG}\right]\right\}}{1000}{6.25}$$

Where,

N $_{growth}$ = Nitrogen retained by the animal for growth, kg per animal per day
WG = Daily weight gain of the animal, kg per day
268 = Constant from 2006 IPCC Guidelines
7.03 = Constant from 2006 IPCC Guidelines
NEg = Net energy required for growth, MJ per animal per day
1,000 = Conversion from grams to kilograms
6.25 = Conversion from kg of dietary protein to kg of dietary N, kg feed per kg N

The N content of milk produced also currently matches the 2006 IPCC Guidelines. Milk nitrogen retained as product is calculated using the following equation:

$$N_{milk} = \frac{milk * \left(\frac{pr\%}{100}\right)}{6.38}$$

Where,

N $_{milk}$	= Nitrogen retained in milk, kg per animal per day
milk	= Milk production, kg per day
pr%	= Percent protein in milk, estimated from the fat content as 1.9 + 0.4 * %Fat
100	= Conversion from percent to value (e.g., 4% to 0.04)
6.38	= Conversion from kg Protein to kg N

The VS and N equations above were used to calculate VS and Nex rates for each state, cattle type, and year. Table A- 186 presents the state-specific VS and Nex production rates used for cattle in 2009.

Step 3: Waste Management System Usage Data

Table A- 187 summarizes 2009 manure distribution data among waste management systems (WMS) at beef feedlots, dairies, dairy heifer facilities, and swine, layer, broiler, and turkey operations. Manure from the remaining animal types (beef cattle not on feed, sheep, horses, and goats) is managed on pasture, range, or paddocks, on drylot, or with solids storage systems. Additional information on the development of the manure distribution estimates for each animal type is presented below. Definitions of each WMS type are presented in Table A- 188.

Beef Cattle and Dairy Heifers: The beef feedlot and dairy heifer WMS data were developed using information from EPA's Office of Water's engineering cost analyses conducted to support the development of effluent limitations guidelines for Concentrated Animal Feeding Operations (EPA 2002b). Based on EPA site visits and state contacts supporting this work and additional contacts with the national USDA office to estimate the percent of beef steers and heifers in feedlots (Milton 2000), feedlot manure is almost exclusively managed in drylots. Therefore, for these animal groups, the percent of manure deposited in drylots is assumed to be 100 percent. In addition, there is a small amount of manure contained in runoff, which may or may not be collected in runoff ponds. The runoff from feedlots was calculated by region in *Calculations: Percent Distribution of Manure for Waste Management Systems* (ERG 2000b) and was used to estimate the percentage of manure managed in runoff ponds in addition to drylots; this percentage ranges from 0.4 to 1.3 percent. The percentage of manure generating emissions from beef feedlots is therefore greater than 100 percent. The remaining population categories of beef cattle outside of feedlots are managed through pasture, range, or paddock systems, which are utilized for the majority of the population of beef cattle in the country.

Dairy Cows: The WMS data for dairy cows were developed using data from the Census of Agriculture, EPA's Office of Water, USDA, and expert sources. Farm-size distribution data are reported in the 1992, 1997, and 2002 Census of Agriculture (USDA 2009a). It was assumed that the data provided for 1992 were the same as that for 1990 and 1991, and data provided for 2002 were the same as that for 2003 through 2009. Data for 1993 through 1996 and 1998 through 2001 were extrapolated using the 1992, 1997, and 2002 data. The percent of waste by system was estimated using the USDA data broken out by geographic region and farm size.

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 waste managed in lagoons (flush systems), liquid/slurry systems (scrape systems), and solid storage (separated solids) (EPA 2002b). Manure management system data for small (fewer than 200 head) dairies were obtained from USDA (2000a). 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 (includes slurry tank, slurry earth-basin, and aerated lagoon), anaerobic lagoon, and solid storage (includes manure pack, outside storage, and inside storage).

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 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 et al. 1999). Census of Agriculture population data for 1992, 1997, and 2002 (USDA 2009a) were used in conjunction with the state data obtained from personal communications to determine regional percentages of total dairy cattle and dairy waste that are managed using these systems. These percentages were applied to the total annual dairy cow and heifer state population data for 1990 through 2009, which were obtained from the USDA NASS (USDA 2009b).

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. Due to limitations in how USDA reports the manure management data, the total percent of systems for a region and farm size is greater than 100 percent. However, manure is typically partitioned to use only one manure management system, rather than transferred between several different systems. Emissions estimates are only calculated for the final manure management system used for each portion of manure. 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. 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 2000a).

Swine: The distribution of manure managed in each WMS was estimated using data from a USDA report and EPA's Office of Water site visits (USDA 1998, ERG 2000a). For operations with less than 200 head, manure management system data were obtained from USDA (USDA 1998). It was assumed that those operations use pasture, range, or paddock systems. For swine operations with greater than 200 head, the percent of waste managed in each system was estimated using the EPA and USDA data broken out by geographic region and farm size. Farm-size distribution data reported in the 1992, 1997, and 2002 Census of Agriculture (USDA 2009a) were used to determine the percentage of all swine utilizing the various manure management systems. It was assumed that the swine farm size data provided for 1992 were the same as that for 1990 and 1991, and data provided for 2002 were the same as that for 2003 through 2009. Data for 1993 through 1996 and 1998 through 2001 were extrapolated using the 1992, 1997, and 2002 data. The reported manure management systems were deep pit, liquid/slurry (includes above- and below-ground slurry), anaerobic lagoon, and solid storage (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 was greater than 100 percent. Typically, this means that a portion of the manure at a swine operation is handled in one system (e.g., liquid system), and a separate portion 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, which could result in increased emissions, so reported systems data were normalized to 100 percent for incorporation into the WMS distribution, using the same method as described above for dairy operations.

Sheep: Waste management system data for sheep were obtained from USDA NASS sheep report for years 1990 through 1993 (USDA 1994). Data for 2001 are obtained from USDA APHIS sheep report (USDA 2003). The data for years 1994-2000 are calculated assuming a linear progression from 1993 to 2001. Due to lack of additional data, data for years 2002 and beyond are assumed to be the same as 2001. It was assumed that all sheep manure not deposited in feedlots was deposited on pasture, range, or paddock lands (Anderson 2000).

Goats and Horses: Waste management system data for 1990 to 2009 were obtained from Appendix H of *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). It was assumed that all manure not deposited in pasture, range, or paddock lands was managed in dry systems.

Poultry—Hens (one year old or older), Pullets (hens less than one year old), and Other Chickens: Waste management system data for 1992 were obtained from *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). These data were also used to represent 1990 and 1991. 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 a United Egg Producers voluntary survey (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 2000b). 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 through 2009 was equal to that estimated for 1999. Data collected for EPA's Office of Water, including information collected during site visits (EPA 2002b), were used to estimate the distribution of waste by management system and animal type.

Poultry—Broilers and Turkeys: The percentage of turkeys and broilers on pasture was obtained from *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). It was assumed that one percent of poultry waste is deposited in pastures, ranges, and paddocks (EPA 1992). The remainder of waste is assumed to be deposited in operations with bedding management.

Step 4: Emission Factor Calculations

Methane conversion factors (MCFs) and N_2O emission factors (EFs) used in the emission calculations were determined using the methodologies presented below.

Methane Conversion Factors (MCFs)

Climate-based IPCC default MCFs (IPCC 2006) were used for all dry systems; these factors are presented in Table A- 189. A U.S.-specific methodology was used to develop MCFs for all lagoon and liquid systems.

For animal waste managed in dry systems, the appropriate IPCC default MCF was applied based on annual average temperature data. Each state and year in the inventory was assigned a climate classification of cool, temperate or warm.

For anaerobic lagoons and other liquid systems a climate-based approach based on the van't Hoff-Arrhenius equation was developed to estimate MCFs that reflects the seasonal changes in temperatures, and also accounts for long-term retention time. This approach is consistent with the recently revised guidelines from IPCC (IPCC 2006). The van't Hoff-Arrhenius equation, with a base temperature of 30°C, is 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	= 303.15K
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 VS that are biologically available for conversion to CH_4 based on the temperature of the system. For those animal populations using liquid manure management systems or manure runoff ponds (i.e., dairy cow, dairy heifer, layers, beef in 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 2009). County population data were calculated from state-level population data from NASS and county-state distribution data from the 1992, 1997, and 2002 Census data (USDA 2009a). County population distribution data for 1990 and 1991 were assumed to be the same as 1992; county population distribution data for 1993 through 1996 were extrapolated based on 1992 and 1997 data; county population data for 1998 through 2001 were extrapolated based on 1997 and 2002 data; and county population data for 2003 to 2009 were assumed to be the same as 2002.

Annual MCFs for liquid systems are calculated as follows for each animal type, state, and year of the inventory:

- The weighted-average temperature for a state is calculated using the population estimates and average monthly temperature in each county.

- 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 uncovered anaerobic lagoons and 7.5°C is used for liquid/slurry and deep pit systems.

- Monthly production of VS added to the system is estimated based on the number of animals present.

- For lagoon systems, the calculation of methane includes a management and design practices (MDP) factor. This factor, equal to 0.8, was developed based on model comparisons to empirical CH_4 measurement data from anaerobic lagoon systems in the United States (ERG 2001). The MDP factor represents a variety of factors that may affect methane production in lagoon systems.

- The amount of VS available for conversion to CH_4 is assumed to be equal to the amount of VS produced during the month (from Step 3). For anaerobic lagoons, the amount of VS available also includes VS that may remain in the system from previous months.

- The amount of VS consumed during the month is equal to the amount available for conversion multiplied by the "f" factor.

- For anaerobic lagoons, the amount of VS carried over from one month to the next is equal to the amount available for conversion minus the amount consumed. Lagoons are also modeled to have a solids clean-out once per year, occurring after the month of September.

- The estimated amount of CH_4 generated during the month is equal to the monthly VS consumed multiplied by the maximum CH_4 potential of the waste (B_o).

The annual MCF is then calculated as:

$$MCF_{annual} = \frac{CH_4 \text{ generated}_{annual}}{VS \text{ produced}_{annual} \times B_o}$$

Where,

MCF_{annual}	= Methane conversion factor
$VS \text{ produced}_{annual}$	= Volatile solids excreted annually
B_o	= Maximum CH_4 producing potential of the waste

In order to account for the carry-over of VS from one year to the next, it is assumed that a portion of the VS from the previous year are available in the lagoon system in the next year. For example, the VS from October, November, and December of 2005 are available in the lagoon system starting January of 2006 in the MCF calculation for lagoons in 2006. Following this procedure, the resulting MCF for lagoons accounts for temperature variation throughout the year, residual VS in a system (carry-over), and management and design practices that may reduce the VS available for conversion to CH_4. It is assumed that liquid-slurry systems have a retention time less than 30 days, so the liquid-slurry MCF calculation doesn't reflect the VS carry-over.

The liquid system MCFs are presented in Table A-8 by state, WMS, and animal group for 2009.

Nitrous Oxide Emission Factors

Direct N_2O emission factors for manure management systems (kg N_2O-N/kg excreted N) were set equal to the most recent default IPCC factors (IPCC 2006), presented in Table A- 191.

Indirect N_2O emission factors account for two fractions of nitrogen losses: volatilization of ammonia (NH_3) and NO_X ($Frac_{gas}$) and runoff/leaching ($Frac_{runoff/leach}$). IPCC default indirect N_2O emission factors were used to estimate indirect N_2O emissions. These factors are 0.010 kg N_2O-N/kg N for volatilization and 0.0075 kg N_2O/kg N for runoff/leaching.

EPA developed country-specific estimates of nitrogen losses for $Frac_{gas}$ and $Frac_{runoff/leach}$ for the U.S. The vast majority of volatilization losses are NH_3. Although there are also some small losses of NO_X, no quantified estimates were available for use and those losses are believed to be small (about 1 percent) in comparison to the NH_3 losses. Therefore, $Frac_{gas}$ values were based on WMS-specific volatilization values estimated from U.S. EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). To estimate $Frac_{runoff/leach}$, EPA used data from EPA's Office of Water that estimate the amount of runoff from beef, dairy, and heifer operations in five geographic regions of the country (EPA 2002b). These estimates were used to develop U.S. runoff factors by animal type, WMS, and region. Nitrogen losses from leaching are believed to be small in comparison to the runoff losses; therefore, $Frac_{runoff/leach}$ was set equal to the runoff loss factor. Nitrogen losses from volatilization and runoff/leaching are presented in Table A-192.

Step 5: CH_4 and N_2O Emission Calculations

To calculate methane emissions for animals other than cattle, EPA first estimated the amount of volatile solids excreted in manure that is managed in each WMS:

$$VS \text{ excreted}_{State, Animal, WMS} = Population_{State, Animal} \times \frac{TAM}{1000} \times VS \times WMS \times 365.25$$

Where,

$VS \text{ excreted}_{State, Animal, WMS} =$	Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)

Population $_{\text{State, Animal}}$	=	Annual average state animal population by animal type (head)
TAM	=	Typical animal mass (kg)
VS	=	Volatile solids production rate (kg VS/1000 kg animal mass/day)
WMS	=	Distribution of manure by WMS for each animal type in a state (percent)
365.25	=	Days per year

Using the CEFM VS data for cattle, the amount of VS excreted was calculated using the following equation:

$$VS \text{ excreted}_{\text{State, Animal, WMS}} = Population_{\text{State, Animal}} \times VS \times WMS$$

Where,

VS excreted $_{\text{State, Animal, WMS}}$ =		Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
Population $_{\text{State, Animal}}$	=	Annual average state animal population by animal type (head)
VS	=	Volatile solids production rate (kg VS/animal/year)
WMS	=	Distribution of manure by WMS for each animal type in a state (percent)

For all animals, the estimated amount of VS was used to calculate methane emissions using the following equation:

$$CH_4 = \sum_{\text{State, Animal, WMS}} \left(VS \text{ excreted}_{\text{State, Animal, WMS}} \times B_o \times MCF \times 0.662 \right)$$

Where,

CH_4	=	CH_4 emissions (kg CH_4/yr)
VS excreted $_{\text{WMS, State}}$	=	Amount of VS excreted in manure managed in each WMS (kg/yr)
B_o	=	Maximum CH_4 producing capacity (m^3 CH_4/kg VS)
MCF $_{\text{animal, state, WMS}}$	=	MCF for the animal group, state and WMS (percent)
0.662	=	Density of methane at 25° C (kg CH_4/m^3 CH_4)

EPA developed a calculation to estimate the amount of CH_4 emitted from anaerobic digestion (AD) systems utilizing CH_4 capture and combustion technology. First, EPA assumed that AD systems produce 90 percent of the maximum CH_4 producing capacity. This value is applied for all climate regions and AD system types. However, EPA realizes that the actual amount of CH_4 produced by each AD system is very variable and will change based on operational and climate conditions and an assumption of 90 percent is likely overestimating CH_4 production from some systems and underestimating CH_4 production in other systems. The CH_4 production of AD systems is calculated using the equation below:

$$CH_4 \text{ Production AD}_{\text{AD System}} = Population \text{ AD}_{\text{AD System}} \times \frac{TAM}{1000} \times VS \times B_o \times 0.662 \times 365.25 \times 0.90$$

Where,

CH_4 Production AD$_{\text{AD system}}$=		CH_4 production from a particular AD system, (kg/yr)
Population AD $_{\text{state}}$	=	Number of animals on a particular AD system
VS	=	Volatile solids production rate (kg VS/1000 kg animal mass-day)
TAM	=	Typical Animal Mass (kg/head)
B_o	=	Maximum CH_4 producing capacity (CH4 m^3/kg VS)
0.662	=	Density of methane at 25° C (kg CH_4/m^3 CH_4)
365.25	=	Days/year
0.90	=	CH_4 production factor for AD systems

Next, EPA considered the collection efficiency (CE) and destruction efficiency (DE) of the AD system. The CE of covered lagoon systems was assumed to be 75 percent, and the CE of complete mix and plug flow AD systems was assumed to be 99 percent (EPA 2008). The CH_4 DE from flaring or burning in an engine was assumed to be 98 percent;

therefore, the amount of CH_4 that would not be flared or combusted was assumed to be 2 percent (EPA 2008). The amount of CH_4 produced by systems with anaerobic digestion was calculated with the following equation:

$$CH_4 \text{ Emissions AD} = \sum_{\text{State, Animal, AD Systems}} \left(\begin{array}{c} \left[CH_4 \text{ Production AD}_{\text{AD system}} \times CE_{\text{AD system}} \times (1-DE)\right] \\ + \left[CH_4 \text{ Production AD}_{\text{AD system}} \times (1-CE_{\text{AD system}})\right] \end{array} \right)$$

Where:

CH_4 Emissions AD	=	CH_4 emissions from AD systems, (kg/yr)
CH_4 Production $AD_{\text{AD system}}$ =		CH_4 production from a particular AD system, (kg/yr)
$CE_{\text{AD system}}$	=	Collection efficiency of the AD system, varies by AD system type
DE	=	Destruction efficiency of the AD system, 0.98 for all systems

In addition to methane emissions, EPA also estimated total N_2O emissions from manure management systems. Total N_2O emissions were calculated by summing direct and indirect N_2O emissions. The first step in estimating direct and indirect N_2O emissions was calculating the amount of nitrogen excreted in manure and managed in each WMS for animals other than cattle using the following equation:

$$N \text{ excreted }_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \text{WMS} \times \frac{\text{TAM}}{1000} \times \text{Nex} \times 365.25$$

Where,

N excreted $_{\text{State, Animal, WMS}}$	=	Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
Population $_{\text{state}}$	=	Annual average state animal population by animal type (head)
WMS	=	Distribution of manure by waste management system for each animal type in a state (percent)
TAM	=	Typical animal mass (kg)
Nex	=	Total Kjeldahl nitrogen excretion rate (kg N/1000 kg animal mass/day)
365.25	=	Days per year

Using the CEFM Nex data for cattle, the amount of N excreted was calculated using the following equation:

$$N \text{ excreted }_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \text{WMS} \times \text{Nex}$$

Where,

N excreted $_{\text{State, Animal, WMS}}$	=	Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
Population $_{\text{state}}$	=	Annual average state animal population by animal type (head)
WMS	=	Distribution of manure by waste management system for each animal type in a state (percent)
Nex	=	Total Kjeldahl nitrogen excretion rate (kg N/animal/year)

For all animals, direct N_2O emissions were calculated as follows:

$$\text{Direct N2O} = \sum_{\text{State, Animal, WMS}} \left(N \text{ excreted}_{\text{State, Animal, WMS}} \times EF_{\text{WMS}} \times \frac{44}{28} \right)$$

Where,

Direct N_2O	=	Direct N_2O emissions (kg N_2O/yr)
N excreted $_{\text{State, Animal, WMS}}$	=	Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
EF_{WMS}	=	Direct N_2O emission factor from IPCC guidelines (kg N_2O-N /kg N)
44/28	=	Conversion factor of N_2O-N to N_2O

Indirect N_2O emissions were calculated for all animals with the following equation:

$$\text{Indirect N}_2\text{O} = \sum_{\text{State, Animal, WMS}} \left(\begin{bmatrix} \text{N excreted}_{\text{State, Animal, WMS}} \times \dfrac{\text{Frac}_{\text{gas, WMS}}}{100} \times \text{EF}_{\text{volatilization}} \times \dfrac{44}{28} \end{bmatrix} + \\ \begin{bmatrix} \text{N excreted}_{\text{State, Animal, WMS}} \times \dfrac{\text{Frac}_{\text{runoff/leach, WMS}}}{100} \times \text{EF}_{\text{runnoff/leach}} \times \dfrac{44}{28} \end{bmatrix} \right)$$

Where,

Indirect N_2O	=	Indirect N_2O emissions (kg N_2O/yr)
N excreted $_{\text{State, Animal, WMS}}$	=	Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
$\text{Frac}_{\text{gas,WMS}}$	=	Nitrogen lost through volatilization in each WMS
$\text{Frac}_{\text{runoff/leach,WMS}}$	=	Nitrogen lost through runoff and leaching in each WMS; data were not available for leaching so the value reflects only runoff
$\text{EF}_{\text{volatilization}}$	=	Emission factor for volatilization (0.010 kg N_2O-N/kg N)
$\text{EF}_{\text{runoff/leach}}$	=	Emission factor for runoff/leaching (0.0075 kg N_2O-N/kg N)
44/28	=	Conversion factor of N_2O-N to N_2O

Emission estimates of CH_4 and N_2O by animal type are presented for all years of the inventory in Table A- 193 and Table A- 194, respectively. Emission estimates for 2009 are presented by animal type and state in Table A- 195 and Table A- 196, respectively.

Table A- 183: Livestock Population (1,000 Head)

Animal Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Dairy Cattle	14,144	13,590	13,191	13,217	13,165	13,215	13,021	13,165	13,398	13,487	13,658	13,759
Dairy Cows	10,015	9,482	9,183	9,172	9,106	9,142	8,988	9,004	9,104	9,145	9,257	9,333
Dairy Heifer	4,129	4,108	4,008	4,045	4,060	4,073	4,033	4,162	4,294	4,343	4,401	4,426
Swine[1]	53,941	58,899	58,864	58,913	60,028	59,827	60,735	61,073	61,887	65,417	67,408	66,142
Market <50 lb.	18,359	19,656	19,574	19,659	19,863	19,929	20,222	20,228	20,514	21,812	19,964	19,559
Market 50-119 lb.	11,734	12,836	12,926	12,900	13,284	13,138	13,400	13,519	13,727	14,557	17,219	17,077
Market 120-179 lb.	9,440	10,545	10,748	10,708	11,013	11,050	11,227	11,336	11,443	12,185	12,931	12,517
Market >180 lb.	7,510	8,937	9,385	9,465	9,738	9,701	9,922	9,997	10,113	10,673	11,193	11,084
Breeding	6,899	6,926	6,231	6,181	6,129	6,011	5,963	5,993	6,090	6,190	6,102	5,905
Beef Cattle[2]	87,228	95,683	89,948	89,118	89,102	88,232	86,441	86,954	88,070	87,639	86,450	85,736
Feedlot Steers	6,357	7,233	8,304	7,932	8,116	8,416	8,018	8,116	8,724	8,674	8,481	8,450
Feedlot Heifers	3,192	3,831	4,702	4,569	4,557	4,676	4,521	4,536	4,801	4,730	4,589	4,514
NOF Bulls	2,160	2,385	2,293	2,274	2,244	2,248	2,201	2,214	2,258	2,214	2,207	2,184
NOF Calves	22,561	23,499	22,569	22,389	22,325	21,997	21,781	21,678	21,621	21,483	21,155	20,940
NOF Heifers	10,182	11,829	9,781	9,832	9,843	9,564	9,321	9,550	9,716	9,592	9,350	9,436
NOF Steers	10,321	11,716	8,724	8,724	8,883	8,347	8,067	8,185	8,248	8,302	8,233	8,501
NOF Cows	32,455	35,190	33,575	33,398	33,134	32,983	32,531	32,674	32,703	32,644	32,435	31,712
Sheep	11,358	8,989	7,036	6,908	6,623	6,321	6,105	6,135	6,230	6,120	5,950	5,747
Sheep On Feed	1,180	1,771	2,963	3,256	3,143	3,049	2,943	2,982	3,043	3,000	2,911	2,805
Sheep NOF	10,178	7,218	4,073	3,652	3,480	3,272	3,162	3,153	3,187	3,120	3,039	2,942
Goats	2,516	2,357	2,419	2,475	2,530	2,652	2,774	2,897	3,019	3,141	3,141	3,141
Poultry[3]	1,537,074	1,826,977	2,033,123	2,060,398	2,097,691	2,085,268	2,130,877	2,150,410	2,154,236	2,166,936	2,175,990	2,086,699
Hens >1 yr.	273,467	299,071	333,593	340,317	340,209	340,979	343,922	348,203	349,888	346,613	339,859	339,526
Pullets	73,167	81,369	95,159	95,656	95,289	100,346	101,429	96,809	96,596	103,816	99,458	101,588
Chickens	6,545	7,637	8,088	8,126	8,353	8,439	8,248	8,289	7,938	8,164	7,589	8,496
Broilers	1,066,209	1,331,940	1,506,127	1,525,413	1,562,015	1,544,155	1,589,209	1,613,091	1,612,327	1,619,400	1,638,055	1,554,636
Turkeys	117,685	106,960	90,155	90,887	91,826	91,349	88,069	84,018	87,487	88,943	91,029	82,453
Horses	5,069	5,130	5,240	5,500	6,000	7,000	8,000	9,200	9,500	9,500	9,500	9,500

Note: Totals may not sum due to independent rounding.

[1] Prior to 2008, the Market <50 lbs category was <60 lbs and the Market 50-119 lbs category was Market 60-119 lbs; USDA updated the categories to be more consistent with international animal categories.

[2] NOF = Not on Feed

[3] Pullets includes laying pullets, pullets younger than 3 months, and pullets older than 3 months.

Table A- 184: Waste Characteristics Data

Animal Group	TAM (kg)	TAM Source	Total Kjeldahl Nitrogen, N_{ex} (kg/day per 1,000 kg mass)	N_{ex} Source	Maximum Methane Generation Potential, B_o (m^3 CH4/kg VS added)	B_o Source	Volatile Solids, VS (kg/day per 1,000 kg mass)	VS Source
Dairy Cows	680	Enteric Fermentation Table A- 171	Table A- 185	Moffroid and Pape, 2010	0.24	Morris 1976	Table A- 185	Moffroid and Pape, 2010
Dairy Heifers	406-408	Enteric Fermentation Table A- 171	Table A- 185	Moffroid and Pape, 2010	0.17	Bryant et. al. 1976	Table A- 185	Moffroid and Pape, 2010
Feedlot Steers	419-457	Enteric Fermentation Table A- 171	Table A- 185	Moffroid and Pape, 2010	0.33	Hashimoto 1981	Table A- 185	Moffroid and Pape, 2010
Feedlot Heifers	384-430	Enteric Fermentation Table A- 171	Table A- 185	Moffroid and Pape, 2010	0.33	Hashimoto 1981	Table A- 185	Moffroid and Pape, 2010
NOF Bulls	750	Shuyler 2000	Table A- 186	USDA 1996a	0.17	Hashimoto 1981	Table A- 186	USDA 1996a
NOF Calves	118	USDA 1996a	Table A- 186	USDA 1996a, 2008	0.17	Hashimoto 1981	Table A- 186	USDA 1996a, 2008
NOF Heifers	296-406	Enteric Fermentation Table A- 171	Table A- 185	Moffroid and Pape, 2010	0.17	Hashimoto 1981	Table A- 185	Moffroid and Pape, 2010
NOF Steers	314-335	Enteric Fermentation Table A- 171	Table A- 185	Moffroid and Pape, 2010	0.17	Hashimoto 1981	Table A- 185	Moffroid and Pape, 2010
NOF Cows	554-611	Enteric Fermentation Table A- 171	Table A- 185	Moffroid and Pape, 2010	0.17	Hashimoto 1981	Table A- 185	Moffroid and Pape, 2010
Market Swine <50 lbs.	13	ERG 2010a	Table A- 186	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 186	USDA 1996a, 2008
Market Swine <60 lbs.	16	Safley 2000	Table A- 186	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 186	USDA 1996a, 2008
Market Swine 50-119 lbs.	39	ERG 2010a	Table A- 186	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 186	USDA 1996a, 2008
Market Swine 60-119 lbs.	41	Safley 2000	Table A- 186	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 186	USDA 1996a, 2008
Market Swine 120-179 lbs.	68	Safley 2000	Table A- 186	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 186	USDA 1996a, 2008
Market Swine >180 lbs.	91	Safley 2000	Table A- 186	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 186	USDA 1996a, 2008
Breeding Swine	198	Safley 2000	Table A- 186	USDA 1996a, 2008	0.48	Hashimoto 1984	Table A- 186	USDA 1996a, 2008
Feedlot Sheep	25	EPA 1992	Table A- 186	ASAE 1998, USDA 2008	0.36	EPA 1992	Table A- 186	ASAE 1998, USDA 2008
NOF Sheep	80	EPA 1992	Table A- 186	ASAE 1998, USDA 2008	0.19	EPA 1992	Table A- 186	ASAE 1998, USDA 2008
Goats	64	ASAE 1999	Table A- 186	ASAE 1998	0.17	EPA 1992	Table A- 186	ASAE 1998
Horses	450	ASAE 1999	Table A- 186	ASAE 1998, USDA 2008	0.33	EPA 1992	Table A- 186	ASAE 1998, USDA 2008
Hens >/= 1 yr	1.8	ASAE 1999	Table A- 186	USDA 1996a, 2008	0.39	Hill 1982	Table A- 186	USDA 1996a, 2008
Pullets	1.8	ASAE 1999	Table A- 186	USDA 1996a, 2008	0.39	Hill 1982	Table A- 186	USDA 1996a, 2008
Other Chickens	1.8	ASAE 1999	Table A- 186	USDA 1996a, 2008	0.39	Hill 1982	Table A- 186	USDA 1996a, 2008

| Broilers | 0.9 | ASAE 1999 | Table A- 186 | USDA 1996a, 2008 | 0.36 | Hill 1984 | Table A- 186 | USDA 1996a, 2008 |
| Turkeys | 6.8 | ASAE 1999 | Table A- 186 | USDA 1996a, 2008 | 0.36 | Hill 1984 | Table A- 186 | USDA 1996a, 2008 |

Table A-185: Estimated Volatile Solids and Nitrogen Excreted Production Rate by year for Animals Other Than Cattle (kg/day/1000 kg animal mass)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
VS																				
Market Swine <50 lb.	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8
Market Swine 50-119 lb.	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Market Swine 120-179 lb.	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Market Swine >180 lb.	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Breeding Swine	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.611	2.623	2.634	2.645	2.656	2.668	2.679	2.69	2.701	2.713	2.724	2.735	2.735
NOF Bulls	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04	6.04
NOF Calves	6.41	6.41	6.41	6.41	6.41	6.41	6.41	6.5175	6.625	6.733	6.84	6.948	7.055	7.163	7.27	7.378	7.485	7.593	7.7	7.7
Sheep	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.11	9.02	8.93	8.84	8.75	8.66	8.57	8.48	8.39	8.3	8.3
Goats	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Hens >1 yr.	10.091	10.091	10.091	10.091	10.091	10.091	10.091	10.097	10.103	10.109	10.115	10.121	10.1265	10.132	10.138	10.144	10.150	10.156	10.162	10.162
Pullets	10.091	10.091	10.091	10.091	10.091	10.091	10.091	10.097	10.103	10.109	10.115	10.121	10.1265	10.132	10.138	10.144	10.150	10.156	10.162	10.162
Chickens	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.817	10.833	10.85	10.867	10.883	10.9	10.917	10.933	10.95	10.967	10.983	11	11
Broilers	15	15	15	15	15	15	15	15.167	15.333	15.5	15.667	15.833	16	16.167	16.333	16.5	16.667	16.833	17	17
Turkeys	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.596	9.492	9.388	9.283	9.179	9.075	8.971	8.867	8.7625	8.658	8.554	8.45	8.45
Horses	10	10	10	10	10	10	10	10	10	9.61	9.22	8.83	8.44	8.05	7.66	7.27	6.88	6.49	6.1	6.1
Nex																				
Market Swine <50 lb.	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.627	0.653	0.68	0.707	0.733	0.76	0.787	0.813	0.84	0.867	0.893	0.92	0.92
Market Swine 50-119 lb.	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.44	0.45	0.46	0.47	0.48	0.49	0.5	0.51	0.52	0.53	0.54	0.54
Market Swine 120-179 lb.	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.44	0.45	0.46	0.47	0.48	0.49	0.5	0.51	0.52	0.53	0.54	0.54
Market Swine >180 lb.	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.44	0.45	0.46	0.47	0.48	0.49	0.5	0.51	0.52	0.53	0.54	0.54
Breeding Swine	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.232	0.230	0.227	0.224	0.221	0.219	0.216	0.213	0.211	0.208	0.205	0.203	0.203
NOF Bulls	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
NOF Calves	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.313	0.325	0.338	0.35	0.363	0.375	0.388	0.4	0.413	0.425	0.438	0.45	0.45
Sheep	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.423	0.426	0.429	0.432	0.435	0.438	0.441	0.444	0.447	0.45	0.45
Goats	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Hens >1 yr.	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.703	0.711	0.719	0.727	0.735	0.743	0.750	0.758	0.766	0.774	0.782	0.79	0.79
Pullets	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.703	0.711	0.719	0.727	0.735	0.743	0.750	0.758	0.766	0.774	0.782	0.79	0.79
Chickens	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.853	0.875	0.898	0.92	0.943	0.965	0.988	1.01	1.033	1.055	1.078	1.1	1.1
Broilers	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.088	1.077	1.065	1.053	1.042	1.03	1.018	1.007	0.995	0.983	0.972	0.96	0.96
Turkeys	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.730	0.721	0.711	0.702	0.692	0.683	0.673	0.663	0.654	0.644	0.635	0.625	0.625
Horses	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.295	0.289	0.284	0.278	0.273	0.267	0.262	0.256	0.251	0.245	0.245

Table A- 186: Estimated Volatile Solids and Nitrogen Excreted Production Rate by State for Cattle for 2009 (kg/animal/year)

State	Volatile Solids							Nitrogen Excreted						
	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer
Alabama	2,267.41	1,251.47	1,680.43	1,103.73	979.63	673.81	656.14	135.78	68.85	70.16	48.18	40.04	53.69	55.01
Alaska	1,846.07	1,251.47	2,158.74	1,475.35	1,287.98	758.17	723.58	115.86	68.85	84.14	60.31	49.59	61.06	61.25
Arizona	2,819.52	1,251.47	2,158.74	1,440.02	1,287.98	674.59	656.77	157.68	68.85	84.14	58.35	49.59	53.76	55.07
Arkansas	2,046.05	1,251.47	1,675.36	1,093.22	976.43	731.19	702.01	124.61	68.85	72.93	49.63	41.72	58.70	59.26
California	2,723.70	1,251.47	1,638.85	1,042.04	953.48	688.37	667.78	152.93	68.85	71.23	46.75	40.63	54.96	56.09
Colorado	2,824.09	1,251.47	1,546.94	951.51	896.01	685.35	665.37	157.87	68.85	71.65	44.97	40.74	54.70	55.87
Connecticut	2,494.94	1,251.47	1,652.50	1,093.00	962.06	674.37	656.59	143.73	68.85	68.93	47.85	39.24	53.74	55.06
Delaware	2,369.10	1,251.47	1,652.50	1,062.76	962.06	740.93	709.80	138.33	68.85	68.93	45.95	39.24	59.55	59.98
Florida	2,502.90	1,251.47	1,680.43	1,117.18	979.63	723.70	696.02	145.89	68.85	70.16	49.02	40.04	58.05	58.70
Georgia	2,543.18	1,251.47	1,680.43	1,103.56	979.63	706.46	682.24	147.62	68.85	70.16	48.17	40.04	56.54	57.43
Hawaii	2,159.89	1,251.47	2,158.74	1,450.79	1,287.98	706.46	682.24	129.34	68.85	84.14	58.95	49.59	56.54	57.43
Idaho	2,749.48	1,251.47	2,158.74	1,392.62	1,287.98	679.06	660.34	154.67	68.85	84.14	55.73	49.59	54.15	55.40
Illinois	2,509.01	1,251.47	1,653.05	1,037.84	962.40	664.58	648.76	144.34	68.85	70.73	45.55	40.34	52.88	54.33
Indiana	2,603.48	1,251.47	1,653.05	1,050.80	962.40	661.25	646.10	148.40	68.85	70.73	46.38	40.34	52.59	54.09
Iowa	2,620.71	1,251.47	1,653.05	1,022.85	962.40	675.86	657.78	149.14	68.85	70.73	44.59	40.34	53.87	55.17
Kansas	2,674.30	1,251.47	1,546.94	945.66	896.01	684.40	664.60	151.44	68.85	71.65	44.57	40.74	54.61	55.80
Kentucky	2,213.71	1,251.47	1,680.43	1,092.37	979.63	731.19	702.01	133.47	68.85	70.16	47.47	40.04	58.70	59.26
Louisiana	1,990.33	1,251.47	1,675.36	1,112.51	976.43	714.03	688.29	122.21	68.85	72.93	50.88	41.72	57.20	57.99
Maine	2,448.34	1,251.47	1,652.50	1,080.42	962.06	692.36	670.97	141.73	68.85	68.93	47.06	39.24	55.31	56.39
Maryland	2,462.83	1,251.47	1,652.50	1,066.48	962.06	641.27	630.13	142.36	68.85	68.93	46.18	39.24	50.85	52.61
Massachusetts	2,411.79	1,251.47	1,652.50	1,080.42	962.06	706.46	682.24	140.16	68.85	68.93	47.06	39.24	56.54	57.43
Michigan	2,775.94	1,251.47	1,653.05	1,045.14	962.40	674.88	656.99	155.80	68.85	70.73	46.02	40.34	53.78	55.09
Minnesota	2,535.74	1,251.47	1,653.05	1,047.02	962.40	690.51	669.49	145.49	68.85	70.73	46.14	40.34	55.15	56.25
Mississippi	2,191.18	1,251.47	1,680.43	1,103.12	979.63	680.89	661.80	132.50	68.85	70.16	48.14	40.04	54.31	55.54
Missouri	2,193.82	1,251.47	1,653.05	1,067.85	962.40	681.24	662.08	130.80	68.85	70.73	47.47	40.34	54.34	55.56
Montana	2,588.27	1,251.47	1,546.94	1,003.22	896.01	657.92	643.44	147.74	68.85	71.65	48.53	40.74	52.30	53.84
Nebraska	2,572.43	1,251.47	1,546.94	950.97	896.01	680.84	661.76	147.06	68.85	71.65	44.93	40.74	54.30	55.53
Nevada	2,729.35	1,251.47	2,158.74	1,428.01	1,287.98	691.23	670.06	153.80	68.85	84.14	57.69	49.59	55.21	56.30
New Hampshire	2,558.38	1,251.47	1,652.50	1,073.63	962.06	706.46	682.24	146.46	68.85	68.93	46.63	39.24	56.54	57.43
New Jersey	2,435.51	1,251.47	1,652.50	1,068.91	962.06	745.24	713.24	141.18	68.85	68.93	46.34	39.24	59.93	60.30
New Mexico	2,916.03	1,251.47	2,158.74	1,417.32	1,287.98	667.61	651.18	161.82	68.85	84.14	57.10	49.59	53.15	54.56
New York	2,598.56	1,251.47	1,652.50	1,050.97	962.06	675.38	657.39	148.18	68.85	68.93	45.21	39.24	53.83	55.13
North Carolina	2,621.22	1,251.47	1,680.43	1,103.07	979.63	731.19	702.01	150.97	68.85	70.16	48.14	40.04	58.70	59.26
North Dakota	2,349.60	1,251.47	1,546.94	985.19	896.01	671.24	654.09	137.49	68.85	71.65	47.29	40.74	53.46	54.83
Ohio	2,499.38	1,251.47	1,653.05	1,061.17	962.40	668.17	651.63	143.92	68.85	70.73	47.04	40.34	53.20	54.60
Oklahoma	2,372.40	1,251.47	1,675.36	1,066.91	976.43	672.96	655.46	138.62	68.85	72.93	47.94	41.72	53.61	54.95
Oregon	2,572.28	1,251.47	2,158.74	1,414.00	1,287.98	671.24	654.09	147.06	68.85	84.14	56.91	49.59	53.46	54.83
Pennsylvania	2,545.40	1,251.47	1,652.50	1,050.97	962.06	671.24	654.09	145.90	68.85	68.93	45.21	39.24	53.46	54.83
Rhode Island	2,430.23	1,251.47	1,652.50	1,095.96	962.06	675.44	657.44	140.95	68.85	68.93	48.03	39.24	53.83	55.14
South Carolina	2,555.49	1,251.47	1,680.43	1,107.64	979.63	688.56	667.94	148.15	68.85	70.16	48.42	40.04	54.98	56.11
South Dakota	2,602.79	1,251.47	1,546.94	970.02	896.01	674.32	656.55	148.37	68.85	71.65	46.25	40.74	53.73	55.05
Tennessee	2,366.26	1,251.47	1,680.43	1,100.05	979.63	671.24	654.09	140.02	68.85	70.16	47.95	40.04	53.46	54.83
Texas	2,664.94	1,251.47	1,675.36	1,058.67	976.43	678.95	660.25	151.19	68.85	72.93	47.41	41.72	54.14	55.40
Utah	2,667.08	1,251.47	2,158.74	1,424.78	1,287.98	719.20	692.43	151.13	68.85	84.14	57.51	49.59	57.66	58.37
Vermont	2,465.40	1,251.47	1,652.50	1,055.51	962.06	727.14	698.78	142.47	68.85	68.93	45.49	39.24	58.35	58.96
Virginia	2,504.58	1,251.47	1,680.43	1,097.87	979.63	675.38	657.39	145.96	68.85	70.16	47.81	40.04	53.83	55.13
Washington	2,830.17	1,251.47	2,158.74	1,401.02	1,287.98	674.99	657.08	158.13	68.85	84.14	56.19	49.59	53.79	55.10
West Virginia	2,199.28	1,251.47	1,652.50	1,071.08	962.06	617.96	611.49	131.04	68.85	68.93	46.47	39.24	48.81	50.89
Wisconsin	2,599.14	1,251.47	1,653.05	1,067.78	962.40	676.24	658.08	148.21	68.85	70.73	47.46	40.34	53.90	55.19
Wyoming	2,504.44	1,251.47	1,546.94	989.11	896.01	671.24	654.09	144.14	68.85	71.65	47.56	40.74	53.46	54.83

Source: Moffroid and Pape, 2010.

Table A-187: 2009 Manure Distribution Among Waste Management Systems by Operation (Percent)

State	Beef Feedlots Dry Lot[2]	Beef Feedlots Liquid/ Slurry[2]	Dairies[1] Pasture	Dairies[1] Daily Spread	Dairies[1] Solid Storage	Dairies[1] Liquid/ Slurry	Dairies[1] Anaerobic Lagoon	Dairies[1] Deep Pit	Dairy Heifer Facilities Daily Spread[2]	Dairy Heifer Facilities Dry Lot[2]	Dairy Heifer Facilities Liquid/ Slurry[2]	Dairy Heifer Facilities Pasture[2]	Swine Operations[1] Pasture	Swine Operations[1] Solid Storage	Swine Operations[1] Liquid/ Slurry	Swine Operations[1] Anaerobic Lagoon	Swine Operations[1] Deep Pit	Layer Operations Anaerobic Lagoon	Layer Operations Poultry without Litter	Broiler and Turkey Operations Pasture	Broiler and Turkey Operations Poultry with Litter
Alabama	100	1.3	45	17	11	10	17	0	17	38	0	45	5	4	8	51	32	41.9	58.1	1	99
Alaska	100	1.3	4	6	28	24	30	8	6	90	1	4	53	2	13	10	22	25	75	1	99
Arizona	100	0.4	0	10	9	20	61	0	10	90	0	0	14	3	5	50	27	60	40	1	99
Arkansas	100	1.3	57	15	11	7	10	1	15	28	0	57	4	4	12	46	35	0	100	1	99
California	100	1.3	1	11	9	21	58	0	11	88	1	1	13	3	8	47	29	12	88	1	99
Colorado	100	0.4	1	1	12	24	62	1	1	98	0	1	2	5	26	17	50	60	40	1	99
Connecticut	100	1	6	43	17	20	12	2	43	51	0	6	57	2	12	9	20	5	95	1	99
Delaware	100	1	6	44	19	19	10	2	44	50	0	6	12	4	24	18	42	5	95	1	99
Florida	100	1.3	17	22	8	15	39	0	22	61	1	17	71	1	8	6	14	41.9	58.1	1	99
Georgia	100	1.3	40	18	10	11	21	0	18	42	0	40	8	4	10	47	32	41.9	58.1	1	99
Hawaii	100	1.3	1	0	11	21	67	0	0	99	1	1	23	3	18	21	34	25	75	1	99
Idaho	100	0.4	0	1	12	23	63	1	1	99	0	0	46	3	15	10	26	60	40	1	99
Illinois	100	0.6	5	8	43	26	13	5	8	87	0	5	2	5	28	15	50	2	98	1	99
Indiana	100	0.6	8	13	35	24	16	3	13	79	0	8	3	5	28	15	50	0	100	1	99
Iowa	100	0.6	6	10	41	25	14	4	10	83	0	6	1	4	12	48	35	0	100	1	99
Kansas	100	0.6	3	5	28	33	29	3	5	92	0	3	2	5	28	13	51	2	98	1	99
Kentucky	100	1	61	14	14	6	2	2	14	24	0	61	5	4	12	45	34	5	95	1	99
Louisiana	100	1.3	60	14	10	6	9	1	14	26	0	60	54	2	13	10	22	60	40	1	99
Maine	100	1	7	45	20	17	9	2	45	48	0	7	73	1	7	6	13	5	95	1	99
Maryland	100	1	7	44	23	15	8	3	44	49	0	7	21	4	21	16	38	5	95	1	99
Massachusetts	100	1	7	45	24	15	6	3	45	47	0	7	31	3	19	14	32	5	95	1	99
Michigan	100	0.6	3	6	32	33	22	4	6	91	0	3	5	5	25	17	48	2	98	1	99
Minnesota	100	0.6	6	10	44	24	12	5	10	84	0	6	2	5	26	18	49	0	100	1	99
Mississippi	100	1.3	57	15	10	7	10	0	15	28	0	57	2	4	6	57	31	60	40	1	99
Missouri	100	0.6	8	14	48	18	6	5	14	77	0	8	3	5	28	14	51	0	100	1	99
Montana	100	0.4	3	4	25	26	36	6	4	93	0	3	6	5	25	17	47	60	40	1	99
Nebraska	100	0.6	4	6	35	30	21	4	6	90	0	4	3	5	28	15	50	2	98	1	99
Nevada	100	0.4	0	0	11	24	64	0	0	99	0	0	35	2	4	39	20	0	100	1	99
New Hampshire	100	1	7	44	21	16	9	3	44	49	0	7	57	2	12	9	20	5	95	1	99
New Jersey	100	1	8	45	24	14	6	3	45	47	0	8	31	3	19	14	33	5	95	1	99
New Mexico	100	0.4	0	10	9	19	61	0	10	90	0	0	92	0	2	2	4	60	40	1	99
New York	100	1	7	45	20	16	10	2	45	48	0	7	20	4	21	15	40	5	95	1	99
North Carolina	100	1	54	15	12	11	6	1	15	31	0	54	0	4	6	58	31	41.9	58.1	1	99
North Dakota	100	0.6	6	11	45	22	12	4	11	83	0	6	9	5	24	17	45	2	98	1	99
Ohio	100	0.6	8	14	41	23	11	4	14	78	0	8	7	4	27	15	47	0	100	1	99
Oklahoma	100	0.4	0	6	25	23	40	6	6	94	0	0	1	4	6	58	31	60	40	1	99
Oregon	100	1.3	20	0	13	21	44	2	0	80	1	20	58	2	12	9	20	25	75	1	99
Pennsylvania	100	1	9	47	25	12	5	2	47	44	0	9	5	5	25	18	47	0	100	1	99

State	Beef Feedlots		Dairies[1]						Dairy Heifer Facilities				Swine Operations[1]					Layer Operations		Broiler and Turkey Operations	
	Dry Lot[2]	Liquid/ Slurry[2]	Pasture	Daily Spread	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[2]	Dry Lot[2]	Liquid/ Slurry[2]	Pasture[2]	Pasture	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Anaerobic Lagoon	Poultry without Litter	Pasture	Poultry with Litter
Rhode Island	100	1	9	47	26	12	4	3	47	44	0	9	56	2	12	9	21	5	95	1	99
South Carolina	100	1.3	54	15	8	9	13	0	15	31	0	54	6	4	9	50	32	60	40	1	99
South Dakota	100	0.6	5	8	38	28	18	4	8	87	0	5	3	5	26	18	48	2	98	1	99
Tennessee	100	1	59	15	12	9	4	2	15	26	0	59	10	4	12	41	33	5	95	1	99
Texas	100	0.4	0	8	13	24	53	2	8	92	0	0	7	3	6	54	29	12	88	1	99
Utah	100	0.4	1	1	17	26	51	3	1	98	0	1	1	6	26	17	51	60	40	1	99
Vermont	100	1	7	44	19	17	10	2	44	49	0	7	86	1	4	3	7	5	95	1	99
Virginia	100	1	57	15	12	9	4	2	15	28	0	57	3	4	7	55	31	5	95	1	99
Washington	100	1.3	17	0	11	22	49	1	0	83	1	17	37	3	17	12	31	12	88	1	99
West Virginia	100	1	7	45	23	16	7	3	45	48	0	7	58	2	11	8	21	5	95	1	99
Wisconsin	100	0.6	7	12	42	24	12	4	12	82	0	7	13	4	24	17	42	2	98	1	99
Wyoming	100	0.4	7	12	22	23	30	6	12	81	0	7	3	5	26	17	49	60	40	1	99

[1] In the methane inventory for manure management, the percent of dairy cows and swine with anaerobic digestion systems is estimated using data from EPA's AgSTAR Program.

[2] Because manure from beef feedlots and dairy heifers may be managed for long periods of time in multiple systems (i.e., both drylot and runoff collection pond), the percent of manure that generates emissions is greater than 100 percent.

Table A-188: Manure Management System Descriptions

Manure Management System	Description[1]
Pasture	The manure from pasture and range grazing animals is allowed to lie as is, and is not managed. N_2O emissions from deposited manure are covered under the N_2O from Agricultural Soils category.
Daily Spread	Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion. N_2O emissions during storage and treatment are assumed to be zero. N_2O emissions from land application are covered under the Agricultural Soils category.
Solid Storage	The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked due to the presence of a sufficient amount of bedding material or loss of moisture by evaporation.
Dry Lot	A paved or unpaved open confinement area without any significant vegetative cover where accumulating manure may be removed periodically. Dry lots are most typically found in dry climates but also are used in humid climates.
Liquid/ Slurry	Manure is stored as excreted or with some minimal addition of water to facilitate handling and is stored in either tanks or earthen ponds, usually for periods less than one year.
Anaerobic Lagoon	Uncovered anaerobic lagoons are designed and operated to combine waste stabilization and storage. Lagoon supernatant is usually used to remove manure from the associated confinement facilities to the lagoon. Anaerobic lagoons are designed with varying lengths of storage (up to a year or greater), depending on the climate region, the volatile solids loading rate, and other operational factors. Anaerobic lagoons accumulate sludge over time, diminishing treatment capacity. Lagoons must be cleaned out once every 5 to 15 years, and the sludge is typically applied to agricultural lands. The water from the lagoon may be recycled as flush water or used to irrigate and fertilize fields. Lagoons are sometimes used in combination with a solids separator, typically for dairy waste. Solids separators help control the buildup of nondegradable material such as straw or other bedding materials.
Anaerobic Digester	Animal excreta with or without straw are collected and anaerobically digested in a large containment vessel or covered lagoon. Digesters are designed and operated for waste stabilization by the microbial reduction of complex organic compounds to CO2 and CH4, which is captured and flared or used as a fuel.
Deep Pit	Collection and storage of manure usually with little or no added water typically below a slatted floor in an enclosed animal confinement facility. Typical storage periods range from 5 to 12 months, after which manure is removed from the pit and transferred to a treatment system or applied to land.
Poultry with Litter	Enclosed poultry houses use bedding derived from wood shavings, rice hulls, chopped straw, peanut hulls, or other products, depending on availability. The bedding absorbs moisture and dilutes the manure produced by the birds. Litter is typically cleaned out completely once a year. These manure systems are typically used for all poultry breeder flocks and for the production of meat type chickens (broilers) and other fowl.
Poultry without Litter	In high-rise cages or scrape-out/belt systems, manure is excreted onto the floor below with no bedding to absorb moisture. The ventilation system dries the manure as it is stored. When designed and operated properly, this high-rise system is a form of passive windrow composting.

[1] Manure management system descriptions are from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Volume 4: Agriculture, Forestry and Other Land Use, Chapter 10: Emissions from Livestock and Manure Management, Tables 10.18 and 10.21) and the *Development Document for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations* (EPA-821-R-03-001, December 2002).

Table A-189: Methane Conversion Factors (percent) for Dry Systems

Waste Management System	Cool Climate MCF	Temperate Climate MCF	Warm Climate MCF
Aerobic Treatment	0	0	0
Cattle Deep Litter (<1 month)	0.03	0.03	0.3
Cattle Deep Litter (>1 month)	0.21	0.44	0.76
Composting - In Vessel	0.005	0.005	0.005
Composting - Static Pile	0.005	0.005	0.005
Composting-Extensive/ Passive	0.005	0.01	0.015
Composting-Intensive	0.005	0.01	0.015
Daily Spread	0.001	0.005	0.01
Dry Lot	0.01	0.015	0.05
Fuel	0.1	0.1	0.1

Waste Management System	Cool Climate MCF	Temperate Climate MCF	Warm Climate MCF
Pasture	0.01	0.015	0.02
Poultry with bedding	0.015	0.015	0.015
Poultry without bedding	0.015	0.015	0.015
Solid Storage	0.02	0.04	0.05

Table A-190: Methane Conversion Factors by State for Liquid Systems for 2009 (percent)

State	Dairy		Swine		Beef	Poultry
	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Liquid/Slurry	Anaerobic Lagoon
Alabama	0.76	0.39	0.76	0.38	0.40	0.76
Alaska	0.46	0.14	0.46	0.14	0.14	0.46
Arizona	0.80	0.62	0.75	0.37	0.48	0.76
Arkansas	0.74	0.34	0.75	0.36	0.34	0.74
California	0.75	0.35	0.74	0.32	0.42	0.75
Colorado	0.63	0.21	0.67	0.24	0.22	0.63
Connecticut	0.68	0.24	0.68	0.24	0.25	0.69
Delaware	0.74	0.31	0.74	0.31	0.31	0.74
Florida	0.78	0.52	0.78	0.50	0.51	0.78
Georgia	0.76	0.39	0.76	0.38	0.38	0.75
Hawaii	0.77	0.58	0.77	0.58	0.58	0.77
Idaho	0.67	0.23	0.65	0.22	0.22	0.65
Illinois	0.71	0.28	0.71	0.28	0.27	0.71
Indiana	0.70	0.27	0.71	0.27	0.27	0.71
Iowa	0.68	0.24	0.69	0.25	0.25	0.69
Kansas	0.73	0.30	0.73	0.30	0.30	0.73
Kentucky	0.74	0.31	0.74	0.31	0.31	0.74
Louisiana	0.77	0.46	0.77	0.46	0.47	0.77
Maine	0.63	0.20	0.63	0.20	0.20	0.63
Maryland	0.72	0.29	0.73	0.30	0.30	0.73
Massachusetts	0.67	0.23	0.68	0.24	0.24	0.67
Michigan	0.67	0.23	0.68	0.24	0.23	0.68
Minnesota	0.66	0.23	0.67	0.23	0.23	0.66
Mississippi	0.76	0.41	0.76	0.39	0.41	0.76
Missouri	0.73	0.30	0.72	0.30	0.30	0.73
Montana	0.59	0.19	0.61	0.20	0.20	0.61
Nebraska	0.70	0.26	0.70	0.26	0.25	0.70
Nevada	0.71	0.26	0.71	0.27	0.26	0.71
New Hampshire	0.63	0.20	0.65	0.22	0.20	0.64
New Jersey	0.72	0.28	0.72	0.29	0.28	0.72
New Mexico	0.72	0.30	0.71	0.28	0.28	0.68
New York	0.65	0.22	0.66	0.22	0.22	0.67
North Carolina	0.73	0.31	0.75	0.37	0.32	0.73
North Dakota	0.65	0.21	0.65	0.21	0.21	0.64
Ohio	0.70	0.26	0.71	0.27	0.26	0.71
Oklahoma	0.75	0.37	0.74	0.35	0.34	0.75
Oregon	0.62	0.20	0.63	0.21	0.22	0.64
Pennsylvania	0.69	0.25	0.70	0.26	0.26	0.71
Rhode Island	0.69	0.26	0.69	0.26	0.26	0.69
South Carolina	0.76	0.38	0.76	0.39	0.39	0.76
South Dakota	0.68	0.24	0.68	0.24	0.24	0.68
Tennessee	0.74	0.31	0.75	0.34	0.32	0.74
Texas	0.76	0.44	0.76	0.43	0.37	0.77
Utah	0.67	0.23	0.66	0.22	0.23	0.66
Vermont	0.63	0.21	0.63	0.21	0.21	0.63
Virginia	0.71	0.28	0.73	0.31	0.28	0.72
Washington	0.62	0.20	0.64	0.21	0.22	0.63
West Virginia	0.69	0.26	0.70	0.26	0.26	0.69
Wisconsin	0.66	0.22	0.67	0.23	0.23	0.67
Wyoming	0.59	0.18	0.64	0.21	0.21	0.62

Table A-191: Direct Nitrous Oxide Emission Factors for 2009 (kg N_2O-N/kg KjdI N)

Waste Management System	Direct N_2O Emission Factor
Aerobic Treatment (forced aeration)	0.005
Aerobic Treatment (natural aeration)	0.01
Anaerobic Digester	0
Anaerobic Lagoon	0
Cattle Deep Bed (active mix)	0.07
Cattle Deep Bed (no mix)	0.01
Composting_in vessel	0.006
Composting_intensive	0.1
Composting_passive	0.01
Composting_static	0.006
Daily Spread	0
Deep Pit	0.002
Dry Lot	0.02
Fuel	0
Liquid/Slurry	0.005
Pasture	0
Poultry with bedding	0.001
Poultry without bedding	0.001
Solid Storage	0.005

Table A-192: Indirect Nitrous Oxide Loss Factors (percent)

Animal Type	Waste Management System	Volatilization Nitrogen Loss	Runoff/Leaching Nitrogen Loss[1]				
			Central	Pacific	Mid-Atlantic	Midwest	South
Beef Cattle	Dry Lot	23	1.1	3.9	3.6	1.9	4.3
Beef Cattle	Liquid/Slurry	26	0	0	0	0	0
Beef Cattle	Pasture	0	0	0	0	0	0
Dairy Cattle	Anaerobic Lagoon	43	0.2	0.8	0.7	0.4	0.9
Dairy Cattle	Daily Spread	10	0	0	0	0	0
Dairy Cattle	Deep Pit	24	0	0	0	0	0
Dairy Cattle	Dry Lot	15	0.6	2	1.8	0.9	2.2
Dairy Cattle	Liquid/Slurry	26	0.2	0.8	0.7	0.4	0.9
Dairy Cattle	Pasture	0	0	0	0	0	0
Dairy Cattle	Solid Storage	27	0.2	0	0	0	0
Goats	Dry Lot	23	1.1	3.9	3.6	1.9	4.3
Goats	Pasture	0	0	0	0	0	0
Horses	Dry Lot	23	0	0	0	0	0
Horses	Pasture	0	0	0	0	0	0
Poultry	Anaerobic Lagoon	54	0.2	0.8	0.7	0.4	0.9
Poultry	Liquid/Slurry	26	0.2	0.8	0.7	0.4	0.9
Poultry	Pasture	0	0	0	0	0	0
Poultry	Poultry with bedding	26	0	0	0	0	0
Poultry	Poultry without bedding	34	0	0	0	0	0
Poultry	Solid Storage	8	0	0	0	0	0
Sheep	Dry Lot	23	1.1	3.9	3.6	1.9	4.3
Sheep	Pasture	0	0	0	0	0	0
Swine	Anaerobic Lagoon	58	0.2	0.8	0.7	0.4	0.9
Swine	Deep Pit	34	0	0	0	0	0
Swine	Liquid/Slurry	26	0.2	0.8	0.7	0.4	0.9
Swine	Pasture	0	0	0	0	0	0
Swine	Solid Storage	45	0	0	0	0	0

[1] Data for nitrogen losses due to leaching were not available, so the values represent only nitrogen losses due to runoff.

Table A- 193: Methane Emissions from Livestock Manure Management (Gg) [a]

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Dairy Cattle	599	615	598	623	663	693	702	734	781	854	900	960	997	856	969	1018	1034	1151	1147	1168
Dairy Cows	592	608	591	616	656	686	695	727	774	846	893	952	990	850	962	1011	1027	1143	1139	1159
Dairy Heifer	7	7	7	7	7	7	7	7	7	7	7	7	7	6	7	7	7	7	8	8	8
Swine	624	676	639	680	741	764	730	783	892	849	834	854	879	857	851	905	889	965	918	903
Market Swine	484	524	500	534	585	608	582	626	720	692	680	696	720	703	701	745	730	798	763	753
Market <50 lbs.	102	110	104	109	119	121	116	125	141	133	131	134	137	135	134	141	139	152	107	105
Market 50-119 lbs.	101	111	105	110	120	124	117	127	144	138	136	138	144	140	140	148	146	159	170	169
Market 120-179 lbs.	136	147	140	151	164	170	163	175	201	193	189	192	199	196	194	208	203	223	223	218
Market >180 lbs.	145	156	152	165	182	194	185	198	235	229	225	232	240	233	233	248	243	264	262	260
Breeding Swine	140	152	139	146	156	155	148	157	172	157	155	158	158	154	150	160	159	166	155	150
Beef Cattle	128	128	131	131	137	140	139	136	139	139	133	135	133	133	130	132	139	136	131	130
Feedlot Steers	14	14	14	13	14	14	14	13	13	14	15	15	15	16	15	15	16	16	16	16
Feedlot Heifers	7	7	7	7	8	8	8	8	8	8	9	9	9	9	9	9	9	9	9	9
NOF Bulls	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
NOF Calves	8	8	8	8	9	9	8	8	9	9	9	9	9	9	9	9	10	10	9	9
NOF Heifers	12	12	13	14	14	15	15	14	14	14	13	13	13	13	12	13	13	13	12	12
NOF Steers	12	12	13	14	13	14	14	13	13	12	11	11	11	10	10	10	10	10	10	10
NOF Cows	69	69	70	71	74	76	76	74	76	76	71	73	71	71	71	71	74	73	70	69
Sheep	7	7	7	6	6	5	5	5	5	4	4	4	4	4	3	3	3	3	3	3
Goats	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Poultry	131	132	127	131	131	128	126	128	130	126	127	131	130	130	129	129	131	134	129	127
Hens >1 yr.	73	72	70	73	72	69	68	67	70	66	67	70	67	68	66	66	66	67	64	64
Total Pullets	25	26	23	23	23	22	21	23	23	21	22	22	22	22	23	22	23	25	23	23
Chickens	4	4	4	4	4	4	3	3	4	4	3	3	4	4	3	3	3	3	3	4
Broilers	19	20	20	21	22	23	24	25	26	27	28	28	29	29	30	31	32	32	33	31
Turkeys	10	10	10	10	9	9	9	9	8	7	7	7	7	7	7	7	7	7	7	6
Horses	22	22	21	21	21	21	21	21	22	21	20	20	21	24	26	28	28	27	24	24

[a] Accounts for CH$_4$ reductions due to capture and destruction of CH$_4$ at facilities using anaerobic digesters.

Table A- 194: Total (Direct and Indirect) Nitrous Oxide Emissions from Livestock Manure Management (Gg)

Animal Type	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Dairy Cattle	17.1	17.01	17.03	17.27	17.4	17.7	17.7	17.9	18.0	17.6	17.9	18.2	18.5	16.5	17.8	18.2	18.7	18.8	18.5	18.7
Dairy Cows	10.0	10.07	9.97	10.05	10.1	10.3	10.3	10.4	10.5	10.2	10.5	10.5	10.6	9.6	10.2	10.4	10.7	10.7	10.5	10.7
Dairy Heifer	7.0	6.93	7.06	7.22	7.3	7.4	7.4	7.4	7.5	7.4	7.5	7.7	7.8	7.0	7.5	7.8	8.1	8.1	8.0	8.0
Swine	4.0	4.18	4.33	4.37	4.6	4.5	4.4	4.7	5.1	5.0	5.0	5.1	5.3	5.4	5.6	5.7	5.9	6.3	6.4	6.3
Market Swine	3.0	3.11	3.26	3.29	3.5	3.5	3.3	3.6	4.0	4.1	4.1	4.2	4.4	4.5	4.7	4.8	5.0	5.4	5.6	5.5
Market <50 lbs.	0.6	0.59	0.61	0.60	0.6	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.1	0.8	0.8
Market 50-119 lbs.	0.6	0.67	0.70	0.70	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.0	1.1	1.3	1.2
Market 120-179 lbs.	0.9	0.90	0.94	0.95	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.5	1.6	1.6
Market >180 lbs.	0.9	0.95	1.02	1.04	1.1	1.1	1.1	1.2	1.3	1.3	1.3	1.4	1.5	1.5	1.5	1.6	1.6	1.8	1.9	1.9
Breeding Swine	1.0	1.07	1.08	1.07	1.1	1.1	1.0	1.1	1.1	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8
Beef Cattle	19.8	20.33	20.15	19.10	21.0	21.8	21.5	21.5	21.7	24.1	25.0	24.1	24.8	25.1	23.7	24.1	25.8	25.6	25.2	25.2
Feedlot Steers	13.4	13.67	13.56	12.83	13.9	14.4	14.0	13.9	14.1	15.5	16.1	15.4	16.1	16.3	15.3	15.5	16.8	16.7	16.5	16.5

Feedlot Heifers	6.4	6.65	6.60	6.27	7.0	7.4	7.4	7.6	7.6	8.5	8.9	8.7	8.8	8.8	8.4	8.5	9.0	8.9	8.7	8.6
Sheep	0.4	0.41	0.44	0.44	0.6	0.7	0.8	0.9	0.9	1.0	1.1	1.2	1.2	1.2	1.1	1.2	1.2	1.2	1.2	1.1
Goats	0.1	0.07	0.07	0.07	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Poultry	4.7	4.79	4.88	4.96	5.1	5.1	5.3	5.3	5.3	5.3	5.3	5.3	5.4	5.3	5.4	5.4	5.4	5.4	5.4	5.1
Hens >1 yr.	1.0	1.02	1.02	1.03	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.3
Total Pullets	0.3	0.29	0.29	0.29	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Chickens	0.0	0.03	0.03	0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Broilers	2.2	2.26	2.36	2.46	2.6	2.7	2.8	2.8	2.9	2.9	2.9	2.9	3.0	2.9	2.9	3.0	2.9	2.9	2.9	2.7
Turkeys	1.2	1.19	1.18	1.14	1.1	1.1	1.1	1.1	1.0	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.7
Horses	0.7	0.70	0.71	0.71	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.9	1.0	1.1	1.1	1.1	1.1	1.1

Table A- 195: Methane Emissions by State from Livestock Manure Management for 2009 (Gg) [a]

State	Beef on Feedlots	Beef Not on Feed	Dairy Cow	Dairy Heifer	Swine—Market	Swine—Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses
Alabama	0.0091	2.5130	0.7878	0.0133	1.8870	0.5402	8.8601	3.6406	0.0528	0.0090	0.0302	0.6750
Alaska	0.0001	0.0214	0.0336	0.0003	0.0036	0.0019	0.1801	0.0000	0.0526	0.0060	0.0001	0.0096
Arizona	0.8202	1.3914	52.2827	0.1192	2.2931	0.6103	0.6572	0.0000	0.0528	0.1057	0.0158	0.5327
Arkansas	0.0042	2.3427	0.4741	0.0095	1.5543	2.1073	0.5189	3.8171	0.7252	0.0090	0.0190	0.6119
California	1.3793	3.5354	401.7280	2.0424	1.5433	0.2113	4.2273	0.2654	0.3751	0.4652	0.0490	1.4005
Colorado	1.5272	2.2547	25.9551	0.0901	4.7356	2.7422	3.1055	+	0.0526	0.1927	0.0122	0.6150
Connecticut	0.0002	0.0214	0.9206	0.0186	0.0086	0.0054	0.2664	0.2645	0.0526	0.0038	0.0011	0.0595
Delaware	0.0002	0.0127	0.3593	0.0041	0.0533	0.0427	0.0727	0.8381	0.0526	0.0060	0.0009	0.0205
Florida	0.0049	3.3731	17.9106	0.0998	0.0643	0.0530	6.8326	0.1526	0.0528	0.0090	0.0216	0.9338
Georgia	0.0078	2.0242	6.0643	0.0614	2.6177	1.0343	15.2216	4.8018	0.0528	0.0090	0.0315	0.5944
Hawaii	0.0014	0.3871	0.3521	0.0029	0.1295	0.0854	0.1325	+	0.0528	0.0090	0.0034	0.0507
Idaho	0.3405	1.7547	113.6925	0.4155	0.1240	0.0714	0.5614	+	0.0526	0.0987	0.0044	0.3824
Illinois	0.2797	1.1587	7.1004	0.0951	36.9889	9.7843	0.2512	+	0.0526	0.0273	0.0084	0.4106
Indiana	0.1859	0.6572	9.9651	0.1057	31.3953	5.4684	0.8165	0.2645	0.3739	0.0235	0.0118	0.4193
Iowa	2.0285	3.3553	15.5070	0.2062	264.5844	28.7171	1.7071	0.2645	0.0526	0.0940	0.0140	0.3719
Kansas	3.8479	5.2668	17.1442	0.1058	18.8129	3.5728	0.0416	+	0.0526	0.0376	0.0124	0.4644
Kentucky	0.0190	2.8498	1.5234	0.0881	5.0055	1.0488	0.5920	1.1114	0.0526	0.0188	0.0245	0.9063
Louisiana	0.0043	1.8598	0.8950	0.0194	0.0565	0.0306	2.1219	0.2654	0.0528	0.0090	0.0081	0.4687
Maine	0.0003	0.0387	1.3237	0.0296	0.0078	0.0058	0.3816	+	0.0526	0.0038	0.0015	0.0628
Maryland	0.0202	0.1159	2.5013	0.0453	0.2579	0.0736	0.2180	1.0567	0.0526	0.0060	0.0042	0.1588
Massachusetts	0.0002	0.0237	0.4876	0.0117	0.0643	0.0141	0.0106	+	0.0526	0.0038	0.0021	0.1062
Michigan	0.2544	0.4613	34.7198	0.2332	8.3149	1.9980	0.6120	0.2645	0.0526	0.0367	0.0070	0.5225
Minnesota	0.4411	1.5054	28.1062	0.4485	58.7581	10.6826	0.3644	0.1622	0.0526	0.0658	0.0092	0.4657
Mississippi	0.0088	1.8861	0.8255	0.0190	5.8277	1.2846	8.2188	2.8818	0.0528	0.0090	0.0115	0.5058
Missouri	0.0965	5.1365	4.7540	0.0650	25.0029	7.4122	0.2482	0.2645	0.4611	0.0390	0.0241	0.7706
Montana	0.0645	3.4419	1.6729	0.0149	1.1172	0.3543	0.3486	+	0.0526	0.1198	0.0031	0.5437
Nebraska	3.9357	5.7938	5.8908	0.0319	25.5224	7.3081	0.5819	0.2645	0.0526	0.0334	0.0086	0.3390
Nevada	0.0092	0.7279	6.3173	0.0153	0.0285	0.0121	0.0214	+	0.0526	0.0315	0.0030	0.0950
New Hampshire	0.0001	0.0181	0.6294	0.0123	0.0107	0.0034	0.0659	+	0.0526	0.0038	0.0010	0.0511
New Jersey	0.0003	0.0283	0.3514	0.0087	0.0531	0.0160	0.0715	+	0.0526	0.0060	0.0027	0.1549
New Mexico	0.2468	1.6482	77.4893	0.2155	0.0015	0.0010	0.5920	+	0.0526	0.0564	0.0089	0.2770
New York	0.0481	0.3778	27.1686	0.5322	0.4586	0.1625	0.4220	0.2645	0.0526	0.0291	0.0100	0.4391
North Carolina	0.0038	1.0137	1.7797	0.0354	151.1504	35.4253	11.0133	2.7590	0.8878	0.0197	0.0369	0.6074
North Dakota	0.1065	2.1409	1.3253	0.0313	0.8294	0.6165	0.0390	+	0.0526	0.0413	0.0011	0.2312
Ohio	0.3035	0.9541	16.8066	0.1837	16.4061	3.1993	0.9148	0.2042	0.1296	0.0611	0.0174	0.6158
Oklahoma	0.5381	6.0089	9.8078	0.0684	32.2081	14.2156	3.5948	0.8181	0.0526	0.0376	0.0313	0.8553
Oregon	0.1395	1.7579	13.5532	0.0933	0.0571	0.0239	0.8226	0.2645	0.0526	0.1034	0.0095	0.4620
Pennsylvania	0.1272	0.6633	15.4864	0.4585	10.2107	1.8110	0.7260	0.5557	0.2243	0.0470	0.0148	0.6010
Rhode Island	+	0.0042	0.0310	0.0009	0.0049	0.0039	0.0696	+	0.0526	0.0038	0.0002	0.0180
South Carolina	0.0025	0.7246	1.0262	0.0186	4.2497	0.4742	5.0711	0.8637	0.2976	0.0090	0.0163	0.3354
South Dakota	0.6037	4.0757	7.4168	0.0632	10.1931	2.8293	0.1373	+	0.1122	0.1433	0.0027	0.3628
Tennessee	0.0071	2.4632	1.5864	0.0796	2.6957	0.4871	0.2492	0.6867	0.0526	0.0160	0.0327	0.7329
Texas	6.2856	22.3466	93.4873	0.5075	14.7215	2.4491	4.3726	2.4289	0.0528	0.6132	0.4273	3.4006
Utah	0.0392	1.1290	14.7238	0.0679	4.0454	1.0264	2.7412	+	0.0798	0.1363	0.0043	0.3088
Vermont	0.0005	0.0547	5.2580	0.1005	0.0032	0.0018	0.0188	+	0.0526	0.0038	0.0016	0.0686
Virginia	0.0505	1.6854	2.7183	0.0776	5.7130	0.8152	0.4380	0.8717	0.4237	0.0352	0.0158	0.4668
Washington	0.2798	1.0249	37.9185	0.1870	0.0989	0.0570	1.1358	0.2645	0.0526	0.0249	0.0082	0.4636
West Virginia	0.0142	0.5231	0.3899	0.0051	0.0223	0.0137	0.0971	0.2994	0.0823	0.0155	0.0070	0.1949
Wisconsin	0.3705	1.1936	70.4229	1.0204	2.4065	0.8365	0.2969	0.1658	0.0526	0.0399	0.0140	0.6197
Wyoming	0.1025	1.6831	0.6483	0.0075	0.2398	0.2827	0.0085	+	0.0526	0.1973	0.0021	0.4158

+ Emission estimate is less than 0.00005 Gg.

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

Table A- 196: Total (Direct and Indirect) Nitrous Oxide Emissions by State from Livestock Manure Management for 2009 (Gg)

State	Beef Feedlot-Heifer	Beef Feedlot-Steers	Dairy Cow	Dairy Heifer	Swine—Market	Swine—Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses
Alabama	0.0021	0.0040	0.0060	0.0045	0.0099	0.0021	0.0639	0.3221	0.0061	0.0049	0.0024	0.0232
Alaska	+	+	0.0006	0.0004	0.0001	+	0.0031	+	0.0061	0.0016	+	0.0005
Arizona	0.2208	0.4235	0.2285	0.1056	0.0116	0.0024	0.0034	+	0.0061	0.0165	0.0012	0.0183
Arkansas	0.0014	0.0026	0.0050	0.0033	0.0088	0.0087	0.0736	0.3377	0.0840	0.0042	0.0015	0.0210
California	0.3129	0.5977	2.1407	1.6247	0.0085	0.0008	0.0873	0.0235	0.0435	0.0822	0.0039	0.0481
Colorado	0.6402	1.2240	0.1751	0.1381	0.0493	0.0212	0.0192	+	0.0061	0.0452	0.0014	0.0317
Connecticut	0.0001	0.0001	0.0149	0.0133	0.0001	+	0.0116	0.0235	0.0061	0.0030	0.0001	0.0031
Delaware	0.0001	0.0002	0.0049	0.0027	0.0004	0.0003	0.0030	0.0744	0.0061	0.0049	0.0001	0.0011
Florida	0.0011	0.0020	0.0924	0.0506	0.0004	0.0002	0.0469	0.0135	0.0061	0.0049	0.0017	0.0321
Georgia	0.0018	0.0035	0.0434	0.0228	0.0141	0.0041	0.1106	0.4248	0.0061	0.0049	0.0025	0.0204
Hawaii	0.0003	0.0006	0.0018	0.0023	0.0007	0.0003	0.0014	+	0.0061	0.0016	0.0003	0.0017
Idaho	0.1429	0.2737	0.7334	0.6375	0.0013	0.0005	0.0034	+	0.0061	0.0232	0.0005	0.0197
Illinois	0.1096	0.2108	0.1408	0.1205	0.3498	0.0678	0.0181	+	0.0061	0.0190	0.0010	0.0212
Indiana	0.0727	0.1399	0.2096	0.1218	0.3033	0.0388	0.1134	0.0235	0.0435	0.0164	0.0014	0.0216
Iowa	0.8062	1.5456	0.2924	0.2542	1.7628	0.1407	0.2370	0.0235	0.0061	0.0656	0.0017	0.0192
Kansas	1.4902	2.8499	0.1782	0.1401	0.1705	0.0239	0.0030	+	0.0061	0.0262	0.0015	0.0239
Kentucky	0.0068	0.0129	0.0316	0.0288	0.0299	0.0046	0.0246	0.0987	0.0061	0.0152	0.0029	0.0467
Louisiana	0.0010	0.0018	0.0081	0.0043	0.0003	0.0001	0.0111	0.0235	0.0061	0.0042	0.0006	0.0161
Maine	0.0001	0.0002	0.0244	0.0204	0.0001	+	0.0176	+	0.0061	0.0030	0.0002	0.0032
Maryland	0.0071	0.0137	0.0427	0.0300	0.0022	0.0005	0.0091	0.0938	0.0061	0.0049	0.0005	0.0082
Massachusetts	0.0001	0.0001	0.0107	0.0078	0.0006	0.0001	0.0005	+	0.0061	0.0030	0.0002	0.0055
Michigan	0.1022	0.1959	0.5270	0.3146	0.0858	0.0152	0.0453	0.0235	0.0061	0.0256	0.0008	0.0269
Minnesota	0.1778	0.3394	0.6319	0.5617	0.6070	0.0812	0.0506	0.0144	0.0061	0.0459	0.0011	0.0240
Mississippi	0.0020	0.0039	0.0071	0.0047	0.0291	0.0047	0.0430	0.2550	0.0061	0.0049	0.0009	0.0174
Missouri	0.0375	0.0718	0.1234	0.0724	0.2284	0.0499	0.0346	0.0235	0.0536	0.0272	0.0029	0.0397
Montana	0.0270	0.0520	0.0213	0.0218	0.0134	0.0031	0.0022	+	0.0061	0.0281	0.0004	0.0280
Nebraska	1.5630	2.9921	0.0829	0.0423	0.2541	0.0536	0.0425	0.0235	0.0061	0.0233	0.0010	0.0175
Nevada	0.0038	0.0073	0.0368	0.0233	0.0002	0.0001	0.0030	+	0.0061	0.0074	0.0004	0.0049
New Hampshire	+	0.0001	0.0117	0.0087	0.0001	+	0.0030	+	0.0061	0.0030	0.0001	0.0026
New Jersey	0.0001	0.0002	0.0070	0.0055	0.0005	0.0001	0.0030	+	0.0061	0.0049	0.0003	0.0080
New Mexico	0.1006	0.1934	0.4144	0.2955	+	+	0.0034	+	0.0061	0.0132	0.0011	0.0143
New York	0.0181	0.0347	0.4805	0.3629	0.0049	0.0013	0.0186	0.0235	0.0061	0.0236	0.0012	0.0226
North Carolina	0.0014	0.0026	0.0228	0.0144	0.7694	0.1326	0.0811	0.2441	0.1029	0.0107	0.0029	0.0209
North Dakota	0.0431	0.0827	0.0314	0.0387	0.0092	0.0050	0.0030	+	0.0061	0.0289	0.0001	0.0119
Ohio	0.1194	0.2294	0.3446	0.2115	0.1571	0.0225	0.1270	0.0181	0.0151	0.0493	0.0021	0.0317
Oklahoma	0.2153	0.4131	0.0760	0.0657	0.1696	0.0546	0.0190	0.0726	0.0061	0.0262	0.0037	0.0441
Oregon	0.0497	0.0954	0.1223	0.1036	0.0006	0.0002	0.0106	0.0235	0.0061	0.0274	0.0011	0.0238
Pennsylvania	0.0465	0.0892	0.3984	0.2817	0.0966	0.0127	0.1009	0.0493	0.0261	0.0381	0.0018	0.0310
Rhode Island	+	+	0.0008	0.0005	+	+	0.0030	+	0.0061	0.0030	+	0.0009
South Carolina	0.0006	0.0011	0.0076	0.0051	0.0220	0.0018	0.0265	0.0764	0.0345	0.0049	0.0013	0.0115
South Dakota	0.2413	0.4627	0.1309	0.0819	0.1030	0.0210	0.0101	+	0.0130	0.1001	0.0003	0.0187
Tennessee	0.0025	0.0048	0.0238	0.0279	0.0157	0.0021	0.0105	0.0610	0.0061	0.0130	0.0039	0.0378
Texas	1.7394	3.3315	0.5319	0.4742	0.0833	0.0102	0.0892	0.2149	0.0061	0.0959	0.0337	0.1168
Utah	0.0165	0.0313	0.1145	0.1031	0.0599	0.0109	0.0163	+	0.0093	0.0320	0.0005	0.0159
Vermont	0.0002	0.0003	0.1044	0.0703	+	+	0.0009	+	0.0061	0.0030	0.0002	0.0035
Virginia	0.0181	0.0347	0.0430	0.0295	0.0317	0.0033	0.0186	0.0774	0.0493	0.0286	0.0019	0.0241
Washington	0.1000	0.1917	0.2872	0.2164	0.0011	0.0005	0.0274	0.0235	0.0061	0.0066	0.0010	0.0239
West Virginia	0.0051	0.0099	0.0077	0.0034	0.0002	0.0001	0.0043	0.0266	0.0096	0.0126	0.0008	0.0100
Wisconsin	0.1489	0.2855	1.6751	1.2450	0.0246	0.0063	0.0221	0.0147	0.0061	0.0279	0.0017	0.0319
Wyoming	0.0429	0.0824	0.0079	0.0094	0.0045	0.0039	0.0001	+	0.0061	0.0463	0.0002	0.0214

+ Emission estimate is less than 0.00005 Gg.

3.11. Methodology for Estimating N$_2$O Emissions from Agricultural Soil Management

Nitrous oxide emissions from agricultural soils result from the interaction of the natural processes of denitrification and nitrification with management practices that add or release mineral nitrogen (N) in the soil profile. Emissions can occur directly in the soil where the N is made available or can be transported to another location following volatilization, leaching, or runoff, and then converted into N$_2$O.

A combination of Tier 1 and Tier 3 approaches was used to estimate direct and indirect N$_2$O emissions from agricultural soils. The process-based biogeochemical model DAYCENT (a Tier 3 approach) was used to estimate N$_2$O emissions resulting from croplands on mineral soils that were used to produce major crops, while the IPCC (2006) Tier 1 methodology was applied to estimate N$_2$O emissions for non-major crop types on mineral soils. The Tier 1 method was also used to estimate direct N$_2$O emissions due to drainage and cultivation of organic cropland soils. Direct N$_2$O emissions from grasslands were estimated by using a combination of DAYCENT and IPCC (2006) Tier 1 methods. A combination of DAYCENT and Tier 1 methods was also used to estimate indirect emissions from all managed lands (i.e., croplands, grasslands, forest lands, and settlements). Specifically, the amount of N volatilized from soils, as well as leaching or transport of nitrate (NO$_3^-$) off-site in surface runoff waters was computed by DAYCENT for the direct emission analyses, while IPCC default factors were used to estimate N transport for the analyses using the Tier 1 methodology. The indirect N$_2$O emissions resulting from off-site transport of N were then computed using the IPCC (2006) Tier 1 default emission factor. Overall, the Tier 3 approach is used to estimate approximately 85 percent of direct soil emissions and 70 percent of total soil N$_2$O emissions associated with agricultural soil management in the United States.

DAYCENT (Del Grosso et al. 2001, Parton et al. 1998) simulates biogeochemical N fluxes between the atmosphere, vegetation, and soil, allowing for a more complete estimation of N$_2$O emissions than IPCC Tier 1 methods by accounting for the influence of environmental conditions including soil characteristics and weather patterns, specific crop and forage qualities that influence the N cycle, and management practices at a daily time step. For example, plant growth is controlled by nutrient availability, water, and temperature stress; moreover, growth removes mineral N from the soil before it can potentially be converted into N$_2$O. Nutrient supply is a function of external nutrient additions as well as litter and soil organic matter (SOM) decomposition rates, and increasing decomposition can lead to greater N$_2$O emissions by enhancing mineral N availability in soils. In this model-based assessment framework, daily maximum/minimum temperature and precipitation, timing and description of management events (e.g., fertilization, tillage, harvest), and soil texture data are model inputs to DAYCENT, which form the basis to simulate key processes and generate robust estimates of N$_2$O emissions from soils. Key processes simulated within sub-models of DAYCENT include plant production, organic matter formation and decomposition, soil water and soil temperature regimes by layer, and nitrification and denitrification processes (Figure A- 7). Comparison of model results and plot level data show that DAYCENT reliably simulates crop yields, soil organic matter levels, and trace gas fluxes for a number of native and managed systems (Del Grosso et al. 2001, 2005). Comparisons with measured data showed that DAYCENT estimated emissions more accurately and precisely than the IPCC Tier 1 methodology (Figure A- 8). The linear regression of simulated vs. measured emissions for DAYCENT had higher r^2 and a fitted line closer to a perfect 1:1 relationship between measured and modeled N$_2$O emissions (Del Grosso et al. 2005, 2008). This is not surprising, since DAYCENT includes site-specific factors (climate, soil properties, and previous management) that influence N$_2$O emissions. Furthermore, DAYCENT also simulated NO$_3^-$ leaching (root mean square error = 20 percent) more accurately than IPCC Tier 1 methodology (root mean square error = 69 percent) (Del Grosso et al. 2005). Thus, the Tier 3 approach has reduced uncertainties in the agricultural soil management section relative to earlier Inventory years where the IPCC Tier 1 method was used. The latest operational version of DAYCENT has several improvements, including (1) elimination of the influence of labile (i.e., easily decomposable by microbes) C availability on surface litter denitrification rates, (2) incorporation of precipitation events on surface litter denitrification, and (3) having the wettest soil layer within the rooting zone control plant transpiration.

[Begin Text Box]

Box 1. DAYCENT Model Simulation of Nitrification and Denitrification

The DAYCENT model simulates the two biogeochemical processes, nitrification and denitrification, that result in N$_2$O emissions from soils (Del Grosso et al. 2000, Parton et al. 2001). Nitrification is calculated for the top 15 cm of soil, while denitrification is calculated for the entire soil profile. The equations and key parameters controlling N$_2$O emissions from nitrification and denitrification are described below.

Nitrification is controlled by soil ammonium (NH_4^+) concentration, water filled pore space (WFPS), temperature (t), and pH according to the following equation:

$$Nit = NH_4 \times K_{max} \times F(t) \times F(WFPS) \times F(pH)$$

where,

Nit	=	the soil nitrification rate (g N/m^2/day)
NH_4	=	the model-derived soil ammonium concentration (g N/m^2)
K_{max}	=	the maximum fraction of NH_4^+ nitrified ($K_{max} = 0.10$/day)
F(t)	=	the effect of soil temperature on nitrification (Figure A- 5a)
F(WFPS)	=	the effect of soil water content and soil texture on nitrification (Figure A- 5b)
F(pH)	=	the effect of soil pH on nitrification (Figure A- 5c)

The current parameterization used in the model assumes that 1.2 percent of nitrified N is converted to N_2O.

N_2O emissions from denitrification are a function of soil NO_3^- concentration, WFPS, heterotrophic (i.e., microbial) respiration, and texture. Denitrification is calculated for each soil layer in the profile, and N_2O emissions from each layer are summed to obtain total soil emissions. The model assumes that denitrification rates are controlled by the availability of soil NO_3^- (electron acceptor), labile C compounds (electron donor) and oxygen (competing electron acceptor). Heterotrophic soil respiration is used as a proxy for labile C availability, while oxygen availability is a function of soil physical properties that influence gas diffusivity, soil WFPS, and oxygen demand. The model selects the minimum of the NO_3^- and CO_2 functions to establish a maximum potential denitrification rate for particular levels of electron acceptor and C substrate and accounts for limitations of oxygen availability to estimate daily denitrification rates according to the following equation:

$$Den = min[F(CO_2), F(NO_3)] \times F(WFPS)$$

where,

Den	=	the soil denitrification rate (μg N/g soil/day)
$F(CO_2)$	=	a function relating N gas flux to soil respiration (Figure A- 6a)
$F(NO_3)$	=	a function relating N gas flux to nitrate levels (Figure A- 5b)
F(WFPS)	=	a dimensionless multiplier (Figure A- 6c).

The x inflection point of F(WFPS) is a function of respiration and soil gas diffusivity at field capacity (D_{FC}):

$$x \text{ inflection} = 0.90 - M(CO_2)$$

where,

M	=	a multiplier that is a function of D_{FC}.

Respiration has a much stronger effect on the water curve in clay soils with low D_{FC} than in loam or sandy soils with high D_{FC} (Figure A- 6c). The model assumes that microsites in fine-textured soils can become anaerobic at relatively low water contents when oxygen demand is high.

After calculating total N gas flux, the ratio of N_2/N_2O is estimated so that total N gas emissions can be partitioned between N_2O and N_2:

$$R_{N2/N2O} = F_r(NO_3/CO_2) \times F_r(WFPS).$$

where,

$R_{N2/N2O}$	=	the ratio of N_2/N_2O
$F_r(NO_3/CO_2)$	=	a function estimating the impact of the availability of electron donor relative to substrate
$F_r(WFPS)$	=	a multiplier to account for the effect of soil water on N_2:N_2O.

For $F_r(NO_3/CO_2)$, as the ratio of electron donor to substrate increases, a higher portion of N gas is assumed to be in the form of N_2O. For $F_r(WFPS)$, as WFPS increases, a higher portion of N gas is assumed to be in the form of N_2.

[End Box]

Figure A- 5: Effect of Soil Temperature, Water-Filled Pore Space, and pH on Nitrification Rates

Figure A- 6: Effect of Soil Nitrite Concentration, Heterotrophic Respiration Rates, and Water-Filled Pore Space on Denitrification Rates

There are five steps in estimating direct N_2O emissions from cropland and grassland soils, and indirect N_2O emissions from volatilization, leaching, and runoff from all managed lands (i.e., croplands, grasslands, forest lands, and settlements). First, the activity data are derived from a combination of land-use, livestock, crop, and grassland management surveys, as well as expert knowledge. In the second, third, and fourth steps, direct and indirect N_2O emissions are estimated using DAYCENT and/or the Tier 1 method. In the fifth step, total emissions are computed by summing all components. The remainder of this annex describes the methods underlying each step.

Step 1: Derive Activity Data

The activity data requirements vary for major crops, non-major crops, grasslands, organic cropland soils, settlements and forest lands. Activity data were derived for direct and indirect N_2O emission calculations as described below.

Step 1a: Activity Data for Direct Emissions from Crop Production on Mineral Soils

Nitrous oxide emissions from mineral cropland soils include emissions from both major and non-major cropping systems and were estimated using a Tier 3 and Tier 1 approach, respectively.

Major Crop Types: Tier 3 DAYCENT Simulations

The activity data requirements for estimating N_2O emissions from major crop types (corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton) include the following: (1) crop-specific mineral N fertilizer rates and timing, (2) crop-specific manure amendment N rates and timing, (3) other N inputs, (4) crop-specific land management information, (5) native vegetation, (6) daily weather data for every county, (7) sub-county-level soil texture data, and (8) county-level crop areas. The United States was divided into 63 agricultural regions based on common cropping practices as defined by McCarl et al. (1993), and data were assembled and provided as inputs to the DAYCENT biogeochemical ecosystem model.

Synthetic N Fertilizer Application: Data on N fertilizer rates were obtained primarily from the U.S. Department of Agriculture–Economic Research Service 1995 Cropping Practices Survey (ERS 1997). In this survey, data on inorganic N fertilization rates were collected for major crops (corn, cotton, soybeans, and wheat) in the high production states during 1995. It is assumed that the fertilization rates have not changed much during the Inventory reporting period, which is confirmed by the sales data showing relatively minor change in the amount of fertilizer sold for on-farm use across the time series of this Inventory (Ruddy et al. 2006). The trend and therefore the rates and uncertainties reflected in the 1995 survey data are considered representative for 1990 through 2008 (trends will be re-evaluated when new fertilization data are released by U.S. Department of Agriculture). Note that all wheat data were combined into one category and assumed to represent small grains in aggregate. Estimates for sorghum fertilizer rates were derived from corn fertilizer rates using a ratio of national average corn fertilizer rates to national average sorghum fertilizer rates, which were derived from additional publications (NASS 1992, 1999, 2004; ERS 1988; Grant and Krenz 1985; USDA 1954, 1957, 1966). Alfalfa hay is assumed to not be fertilized, but grass hay is fertilized according to rates from published farm enterprise budgets (NRIAI 2003).

The ERS survey parameter "TOT N" (total amount of N applied per acre), with a small number of records deleted as outliers, was used in determining the fraction of crop acres receiving fertilizer and the average fertilizer rates for each region. Mean fertilizer rates and standard deviations for irrigated and rainfed crops were produced for each state with a minimum of 15 data points for irrigated and rainfed, respectively. If a state was not surveyed for a particular crop or if fewer than 15 data points existed for one of the categories, then data were aggregated to U.S. Department of Agriculture Farm Production Regions in order to estimate a mean and standard deviation for fertilization rates (Farm Production Regions are groups of states in the United States with similar agricultural commodities). If Farm Production Region data were not available, crop data were aggregated to the entire United States (all major states surveyed) to estimate a mean and standard deviation for a particular crop in a state lacking sufficient data. Standard deviations for fertilizer rates were used

to construct probability distribution functions (PDFs) with log-normal densities in order to address uncertainties in application rates (see Step 2a for discussion of uncertainty methods). Total fertilizer application data are found in Table A- 197.

Simulations were conducted for the period prior to 1990 in order to initialize the DAYCENT model (see Step 2a), and estimates for crop-specific regional fertilizer rates prior to 1990 were based largely on extrapolation/interpolation of fertilizer rates from the years with available data. For crops in some agricultural regions, little or no data were available, and, therefore, a geographic regional mean was used to simulate N fertilization rates (e.g., no data were available from Alabama during the 1970s and 1980s for corn fertilization rates; therefore, mean values from the southeastern United States were used to simulate fertilization to corn fields in this state).

Managed Livestock Manure[57] *N Amendment Rates and Timing:* County-level manure addition estimates have been derived from manure N addition rates developed by the Natural Resources Conservation Service (NRCS) (Edmonds et al. 2003). Working with the farm-level crop and animal data from the 1997 Census of Agriculture, NRCS has coupled estimates of manure N produced with estimates of manure N recoverability by animal waste management system to produce county-level estimates of manure N applied to cropland and pasture. Edmonds et al. (2003) defined a hierarchy that included 24 crops, cropland used as pasture, and permanent pasture. They estimated the area amended with manure and application rates in 1997 for both manure-producing farms and manure-receiving farms within a county and for two scenarios—before implementation of Comprehensive Nutrient Management Plans (baseline) and after implementation (Edmonds et al. 2003). The goal of nutrient management plans is to apply manure nutrients at a rate meeting plant demand, thus limiting leaching losses of nutrients to groundwater and waterways. For DAYCENT simulations, the baseline scenario estimates have been used as the basis for manure amendment applications under the assumption that Comprehensive Nutrient Management Plans have not been fully implemented. This is a conservative assumption because it allows for higher leaching rates due to some over-application of manure to soils. The rates for manure-producing farms and manure-receiving farms have been area-weighted and combined to produce a single county-level estimate for the amount of land amended with manure and the manure N application rate for each crop in each county. Several of the crops in Edmonds et al. (2003) have been area-weighted and combined into broader crop categories. For example, all small grain crops have been combined into one category. In order to address uncertainty in these data, uniform probability distributions were constructed based on the proportion of land receiving manure versus the amount not receiving manure for each crop type and pasture. For example, if 20 percent of land producing corn in a county was amended with manure, randomly drawing a value equal to or greater than 0 and less than 20 would lead to a simulation with a manure amendment, while drawing a value greater than or equal to 20 and less than 100 would lead to no amendment in the simulation (see Step 2a for further discussion of uncertainty methods).

Edmonds et al. (2003) only provides manure application rate data for 1997, but the amount of managed manure available for soil application changes annually, so the area amended with manure was adjusted relative to 1997 to account for all the manure available for application in other years. Specifically, the manure N available for application in other years was divided by the manure N available in 1997. If the ratio was greater than 1, there was more manure N available in that county relative to the amount in 1997, and so it was assumed a larger area was amended with manure. In contrast, ratios less than one implied less area was amended with manure because there was a lower amount available in the year compared to 1997. The amendment area in each county for 1997 was multiplied by the ratio to reflect the impact of manure N availability on the area amended. The amount of managed manure N available for application to soils was calculated by determining the populations of animals that were on feedlots or otherwise housed in order to collect and manage the manure, as described in the Manure Management section (Section 6.2) and annex (Annex 3.10).

To estimate C inputs associated with manure N application rates derived from Edmonds et al. (2003), carbon-nitrogen (C:N) ratios for livestock-specific manure types were adapted from the Agricultural Waste Management Field Handbook (USDA 1996), On-Farm Composting Handbook (NRAES 1992), and recoverability factors provided by Edmonds et al (2003). The C:N ratios were applied to county-level estimates of manure N excreted by animal type and management system to produce a weighted county average C:N ratio for manure amendments. The average C:N ratio was used to determine the associated C input for crop amendments derived from Edmonds et al. (2003).

To account for the common practice of reducing inorganic N fertilizer inputs when manure is added to a cropland soil, crop-specific reduction factors were derived from mineral fertilization data for land amended with manure versus land

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[57] For purposes of the Inventory, total livestock manure is divided into two general categories: (1) managed manure, and (2) unmanaged manure. Managed manure includes manure that is stored in manure management systems such as pits and lagoons, as well as manure applied to soils through daily spread manure operations. Unmanaged manure encompasses all manure deposited on soils by animals on PRP.

not amended with manure in the ERS 1995 Cropping Practices Survey (ERS 1997). Mineral N fertilization rates were reduced for crops receiving manure N based on a fraction of the amount of manure N applied, depending on the crop and whether it was irrigated or rainfed. The reduction factors were randomly selected from PDFs with normal densities in order to address uncertainties in the dependence between manure amendments and mineral fertilizer application.

Manure N that was not applied to major crops and grassland was assumed to be applied to non-major crop types. The fate of manure N is summarized in Table A- 198.

Residue N Inputs: Residue N input is estimated as part of the DAYCENT simulation and is not an input to the model. Unlike the Tier 1 approach, N inputs from crop residues are not considered activity data in the DAYCENT simulations because N availability from this source is simulated by the model based on N uptake during crop growth according to environmental and management conditions, such as temperature, precipitation, and edaphic (i.e., soil) characteristics, in combination with the harvest practices. That is, while the model accounts for the contribution of N from crop residues to the soil profile and subsequent N_2O emissions, this source of mineral soil N is not activity data in the sense that it is not a model input. Similarly, N from mineralization of soil organic matter and asymbiotic N fixation are also simulated by the model. The simulated total N inputs of above- and below-ground residue N and fixed N that was not harvested and not burned (the DAYCENT simulations assumed that 3 percent of non-harvested above ground residues for grain crops were burned) are provided in Table A- 199.

Other N Inputs: Other N inputs are estimated within the DAYCENT simulation, and thus input data are not required, including mineralization from decomposition of soil organic matter and asymbiotic fixation of N from the atmosphere. The influence of additional inputs of N are estimated in the simulations so that there is full accounting of all emissions from managed lands, as recommended by IPCC (2006). The simulated total N inputs from other sources are provided in Table A- 199.

Crop Rotation and Land Management Information: Data were obtained on specific timing and type of cultivation, timing of planting/harvest, and crop rotation schedules for the 63 agricultural regions (Hurd 1930, 1929, Latta 1938, Iowa State College Staff Members 1946, Bogue 1963, Hurt 1994, USDA 2000a, 2000b, CTIC 1998, Piper et al. 1924, Hardies and Hume 1927, Holmes 1902, 1929, Spillman 1902, 1905, 1907, 1908, Chilcott 1910, Smith 1911, Kezer ca 1917, Hargreaves 1993, ERS 2002, Warren 1911, Langston et al. 1922, Russell et al. 1922, Elliott and Tapp 1928, Elliott 1933, Ellsworth 1929, Garey 1929, Holmes 1929, Hodges et al. 1930, Bonnen and Elliott 1931, Brenner et al. 2002, 2001, Smith et al. 2002). As with N fertilizer and manure additions, data were not complete, so regional averages were used to fill spatial gaps in the datasets and interpolation/extrapolation was used to fill temporal gaps. The amount of agricultural residue burning was based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996).

Native Vegetation by County: Pre-agricultural land cover for each county was designated according to the potential native vegetation used in the Vegetation-Ecosystem Modeling and Analysis Project (VEMAP 1995), which was based on the Kuchler (1964) Potential Vegetation Map for the conterminous United States.

Daily Weather Data by County: Daily maximum/minimum temperature and precipitation data were obtained from the DAYMET model, which generates daily surface precipitation, temperature, and other meteorological data at 1 km^2 resolution driven by weather station observations and an elevation model (Thornton et al. 2000 and 1997, Thornton and Running 1999, DAYMET no date). It is necessary to use computer-generated weather data because weather station data do not exist in each county, and moreover weather station data are for a point in space, while the DAYMET uses this information with interpolation algorithms to derive weather patterns for areas between these stations. DAYMET weather data are available for the United States at 1 km^2 resolution for 1980 through 2003. For each county, DAYMET weather data were selected from the 1 km^2 cell that occurred in agricultural lands according the National Land Cover Dataset (Vogelman et al. 2001). The grid cells formed the basis for county-scale PDFs based on the frequency of cells with same weather patterns. Separate PDFs were developed for cropland, pasture/hay land, and rangeland. A weather record was then randomly selected from the PDFs in each iteration of the Monte Carlo analysis to represent variation in precipitation and temperature at the county scale. Weather data were randomly selected from the previous 23 years to represent 2004 through 2009, accounting for uncertainty in the weather during the years that have no data. The time series will be updated when new weather data are available.

Soil Properties by County: Soil texture data required by DAYCENT were obtained from STATSGO (Soil Survey Staff 2005). Observed data for soil hydraulic properties needed for model inputs were not available, so they were calculated from STATSGO (Soil Survey Staff 2005) texture class and Saxton et al.'s (1986) hydraulic properties calculator. Similar to the weather data, soil types within the STATSGO map that occurred in agricultural lands according to the National Land Cover Dataset (Vogelman et al. 2001) were used to form a county-scale PDF. Specifically, the PDFs were an area-weighted proportion for the extent of overlap between STATSGO map units and agricultural land. Separate PDFs were developed for cropland, pasture/hay land, and rangeland. Individual soil types were randomly selected from

the PDFs during each iteration of the Monte Carlo analysis to represent variation in soil texture and depth at the county scale.

Crop Areas by County: County-level total crop area data were downloaded from the NASS web site for the years 1990 through 2009 (USDA 2010a, 2010b), and these data formed the basis to scale emissions from individual crop types to an entire county.

Non-Major Crop Types: Tier 1 Method

The activity data required for calculating emissions from non-major crop types include: (1) the amount of mineral N in synthetic fertilizers that are applied annually, (2) managed manure N, (3) the amount of N in other commercial organic fertilizers and (4) the amount of N in the above- and below-ground residue retained on and in soils of all non-major crops.

Application of Synthetic Commercial Fertilizers: A process-of-elimination approach was used to estimate synthetic N fertilizer additions to non-major crop types. The total amount of fertilizer used on farms has been estimated by the USGS from 1990-2001 on a county scale from fertilizer sales data (Ruddy et al. 2006). For 2002-2009, county-level fertilizer used on farms was adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 1995 through 2009). In addition, fertilizer application data are available for major crops and grasslands (discussed in Step 1 sections for Major Crops and Grasslands). Thus, the amount of N applied to non-major crops was assumed to be the remainder of the fertilizer used on farms after subtracting the amount applied to major crops and grasslands. The differences were aggregated to the state level and PDFs were derived based on uncertainties in the amount of N applied to major crops and grasslands. Total fertilizer application is found in Table A- 200.

Manure and Other Commercial Organic Fertilizers:[58] Manure N applied to non-major crops was estimated using the activity data described for major crops (Table A- 198). Estimates of total national annual N additions from other commercial organic fertilizers were derived from organic fertilizer statistics (TVA 1991 through 1994; AAPFCO 1995 through 2009). AAPFCO fertilizer data were not yet available for 2009, so 2008 values were used as a placeholder until data become available. Commercial organic fertilizers include dried blood, tankage, compost, and other; dried manure and sewage sludge that are used as commercial fertilizer were subtracted from totals to avoid double counting. The dried manure N is counted with the non-commercial manure applications, and sewage sludge is assumed to be applied only to grasslands. The organic fertilizer data, which are recorded in mass units of fertilizer, had to be converted to mass units of N by multiplying the consumption values by the average organic fertilizer N contents provided in the annual fertilizer publications. These N contents are weighted average values, and vary from year to year (ranging from 2.3 percent to 3.9 percent over the period 1990 through 2008). The fertilizer consumption data are recorded in "fertilizer year" totals, (i.e., July to June), but 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 not available for calendar year 2008 so a "least squares line" statistical extrapolation using the previous 14 years of data was used to arrive at an approximate value. PDFs were derived for the organic fertilizer applications assuming a default ±50 percent uncertainty. Annual consumption of other organic fertilizers is presented in Table A- 201.

Retention of Crop Residue: Annual crop yield (metric tons per hectare) and area harvested (hectare) statistics for non-major N-fixing crops, including bean and pulse crops, were taken from U.S. Department of Agriculture crop production reports (USDA 1994, 1998, 2003, 2005, 2006, 2008, 2009, 2010a,b). Crop yield per hectare and area planted were multiplied to determine total crop yield for each crop, which was then converted to tons of dry matter product using the residue dry matter fractions shown in

Table A- 202. Dry matter yield was then converted to tons of above- and below-ground biomass N. Above-ground biomass was calculated by using linear equations to estimate above-ground biomass given dry matter crop yields, and below-ground biomass was calculated by multiplying above-ground biomass by the below-to-above-ground biomass ratio. N inputs were estimated by multiplying above- and below-ground biomass by respective N concentrations. All ratios and equations used to calculate residue N inputs (shown in Table A- 203) are from IPCC (2006) and Williams (2006). PDFs were derived assuming a ±50 percent uncertainty in the yield estimates (NASS does not provide uncertainty), along with uncertainties provided by the IPCC (2006) for dry matter fractions, above-ground residue, ratio of

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[58] Other commercial organic fertilizers include, dried blood, dried manure, tankage, compost, sewage, and other minor organic fertilizer types, but manure and sewage sludge have been excluded in order to avoid double-counting and ensure consistency across the Inventory as these inputs are calculated using alternative data sources and methods.

below-ground to above-ground biomass, and residue N fractions. The resulting annual biomass N inputs are presented in Table A- 203.

Step 1b: Activity Data for Direct Emissions from Drainage and Cultivation of Organic Cropland Soils

Tier 1 Method

Estimates and associated uncertainty for the area of drained and cultivated organic cropland soils in 1992 and 1997 were obtained from the U.S. Department of Agriculture 1997 *National Resources Inventory* (USDA 2000a, as extracted by Eve 2001, and revised by Ogle 2002).[59] These areas were grouped by broad climatic region[60] using temperature and precipitation estimates from Daly et al. (1994, 1998) and then further aggregated to derive total land in temperate and sub-tropical regions. Areas for 1992 were assumed to represent 1990 through 1992 and areas for 1997 were assumed to represent 1993 through 2009 (Table A- 204).

Step 1c: Activity Data for Direct Emissions from Grassland Management

N_2O emissions from non-federal grasslands were estimated using DAYCENT. DAYCENT simulations addressed the influence of legume seeding, managed manure N amendments, unmanaged manure N excreted by livestock and deposited directly onto pasture, range, and paddock (PRP) soils, and synthetic fertilizer applications. N_2O emissions from PRP manure N deposition on federal grasslands and sewage sludge amendments to agricultural soils were addressed using the Tier 1 method.

Tier 3 DAYCENT Simulations

Activity data for DAYCENT simulations of grasslands (i.e., climate, soils, and N inputs) were based on the same sources as those used for major crop types described in Step 1a. In addition to the data sources used for major crops, county-level area data on non-federal pasture and rangeland (i.e., mostly privately-owned) were needed for U.S. grasslands. This information was based on U.S. Land Representation Analysis for Land Use, Land Use Change and Forestry sector (See Section 7.1), and included data compiled from the U.S. Department of Agriculture *National Resources Inventory* (USDA 2000a, Nusser and Goebel 1997, http://www.ncgc.nrcs.usda.gov/products/nri/index.htm), the USDA Forest Service (USFS) Forest Inventory and Analysis Database (FIA, http://fia.fs.fed .us/tools-data/data) and the U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD, Vogelman et al. 2001, http://www.mrlc.gov). Grassland on non-federal lands is classified using the NRI and grassland on federal lands is classified using the NLCD. Grassland area data from the NRI and NLCD were adjusted to achieve consistency with FIA estimates of Forest Land. Another key source of N for grasslands is PRP manure N deposition. Activity data for PRP manure N excretion from dairy cattle, beef cattle, swine, sheep, goats, poultry, and horses were derived from multiple sources as described in the Manure Management section (Section 6.2) and Annex 3.10. The amount of PRP manure N deposited on non-federal grasslands (non-federal grasslands are mostly under private ownership) was based on the relative proportion of federal and non-federal grasslands in each county based on the U.S. Land Representation Analysis (See Section 7.1) . For example, if 75 percent of the grasslands in a county were non-federal then 75 percent of PRP manure N was assumed to be deposited on non-federal grasslands.

Nitrogen fixation by legumes, and N residue inputs from senesced grass litter were included as sources of N to the soil, and were estimated in the DAYCENT simulations as a function of vegetation type, weather, and soil properties. Similar to the methodology for major crops, "other N inputs" were simulated within the DAYCENT model framework in order to estimate all greenhouse gas emissions from managed lands (IPCC 2006), including mineralization from decomposition of soil organic matter and litter, as well as asymbiotic N fixation from the atmosphere. Decomposition rates are a function of litter quality and quantity, soil texture, water content and temperature, and other factors. Total annual amounts of PRP manure N, mineral N fertilizer application, manure N amendments, forage legume N and "other N inputs" can be found in Table A- 205.

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[59] 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.

[60] The 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.

Tier 1 Method: Additional Direct Soil N₂O Emissions

The Tier 1 method was used to estimate emissions from PRP manure that were not simulated with DAYCENT, in addition to emissions due to sewage sludge amendments to agricultural soils.

PRP Manure: PRP manure N data were derived using methods described in the Manure Management section (Section 6.2) and Annex 3.10. The amount of PRP manure N deposited on federal grasslands was based on the relative proportion of federal to non-federal grassland area in each county. As discussed in the Tier 3 DAYCENT Simulations section, the area data were based on the U.S. Department of Agriculture's *National Resources Inventory* (USDA 2000a) and the National Land Cover Dataset (Vogelman et al. 2001), respectively, and were reconciled with the Forest Inventory and Analysis dataset in order to produce the U.S. Land Representation (See Section 7.1). Soil N₂O emissions from the proportion of PRP manure N deposited on federal grasslands were estimated with the Tier 1 method.

Sewage Sludge Amendments: Sewage sludge is generated from the treatment of raw sewage in public or private wastewater treatment works and is typically used as a soil amendment or is sent to waste disposal facilities such as landfills. In this Inventory, all sewage sludge that is amended to agricultural soils is assumed to be applied to grasslands. Estimates of the amounts of sewage sludge N applied to agricultural lands were derived from national data on sewage sludge generation, disposition, and N content. Total sewage sludge generation data for 1988, 1996, and 1998, in dry mass units, were obtained from EPA (1999) and estimates for 2004 were obtained from an independent national biosolids survey (NEBRA 2007). These values were linearly interpolated to estimate values for the intervening years. Sewage sludge generation data are not available after 2004 (Bastian 2007), so the 1990 through 2004 data were linearly extrapolated for the most recent years. The total sludge generation estimates were then converted to units of N by applying an average N content of 3.9 percent (McFarland 2001), and disaggregated into use and disposal practices using historical data in EPA (1993) and NEBRA (2007). The use and disposal practices were agricultural land application, other land application, surface disposal, incineration, landfilling, ocean dumping (ended in 1992), and other disposal. The resulting estimates of sewage sludge N applied to agricultural land were used here; the estimates of sewage sludge N applied to other land and surface-disposed were used in estimating N₂O fluxes from soils in *Settlements Remaining Settlements* (see section 7.5 of the Land Use, Land-Use Change, and Forestry chapter). Sewage sludge disposal data are provided in Table A- 206.

Step 1d: Activity Data for Indirect N₂O Emissions from Managed Soils of all Land-Use Types and Managed Manure Systems

Volatilization of N that was applied or deposited as synthetic fertilizer, livestock manure, sewage sludge, and other organic amendments leads to emissions of NH_3 and NO_x to the atmosphere. In turn, this N is returned to soils through atmospheric deposition, thereby increasing mineral N availability and enhancing N₂O production. Additional N is lost from soils through leaching as water percolates through a soil profile and through runoff with overland water flow. N losses from leaching and runoff enter groundwater and waterways, from which a portion is emitted as N₂O. However, N leaching was assumed to be an insignificant source of indirect N₂O in cropland and grassland systems where the amount of precipitation plus irrigation did not exceed 80 percent of the potential evapotranspiration. These areas are typically semi-arid to arid, and nitrate leaching to groundwater is a relatively uncommon event; moreover IPCC (2006) recommends limiting the amount of nitrate leaching assumed to be a source of indirect N₂O emissions based on precipitation, irrigation and potential evapotranspiration.

The activity data for synthetic fertilizer, livestock manure, other organic amendments, residue N inputs, sewage sludge N, and other N inputs are the same as those used in the calculation of direct emissions from agricultural mineral soils, and may be found in Table A- 197 through Table A- 201, Table A- 203, and Table A- 206. The activity data for computing direct and indirect N₂O emissions from settlements and forest lands are described in the Land Use, Land-Use Change, and Forestry chapter.

Using the DAYCENT model, volatilization and leaching/surface run-off of N from soils was computed internally for major crop types and non-federal grasslands. DAYCENT simulates the processes leading to these losses of N based on environmental conditions (i.e., weather patterns and soil characteristics), management impacts (e.g., plowing, irrigation, harvest), and soil N availability. Note that the DAYCENT method accounts for losses of N from all anthropogenic activity, not just the inputs of N from mineral fertilization and organic amendments, which are addressed in the Tier 1 methodology. Similarly, the N available for producing indirect emissions resulting from grassland management as well as deposited PRP manure was also estimated by DAYCENT. Estimated leaching losses of N from DAYCENT were not used in the indirect N₂O calculation if the amount of precipitation plus irrigation did not exceed 80 percent of the potential evapotranspiration. Volatilized losses of N were summed for each day in the annual cycle to provide an estimate of the

amount of N subject to indirect N_2O emissions. In addition, the daily losses of N through leaching and runoff in overland flow were summed for the annual cycle. Uncertainty in the estimates was derived from uncertainties in the activity data for the N inputs (i.e., fertilizer and organic amendments; see Step 1a for further information)

The Tier 1 method was used to estimate N losses from mineral soils due to volatilization and leaching/runoff for non-major crop types, forestland, settlements, sewage sludge applications, and PRP manure on federal grasslands not accounted for by DAYCENT simulations. To estimate volatilized losses, synthetic fertilizers, manure, sewage sludge, and other organic N inputs were multiplied by the fraction subject to gaseous losses using the respective default values of 0.1 kg N/kg N added as mineral fertilizers and 0.2 kg N/kg N added as manure (IPCC 2006). Uncertainty in the volatilized N ranged from 0.03-0.3 kg NH_3-N+NOx-N/kg N for synthetic fertilizer and 0.05-0.5 kg NH_3-N+NOx-N/kg N for organic amendments (IPCC 2006). Leaching/runoff losses of N were estimated by summing the N additions from synthetic and other organic fertilizers, manure, sewage sludge, and above- and below-ground crop residues, and then multiplying by the default fraction subject to leaching/runoff losses of 0.3 kg N/kg N applied, with an uncertainty from 0.1–0.8 kg NO_3-N/kg N (IPCC 2006). However, N leaching was assumed to be an insignificant source of indirect N_2O emissions if the amount of precipitation plus irrigation did not exceed 80 percent of the potential evapotranspiration. PDFs were derived for each of the N inputs in the same manner as direct N_2O emissions, discussed in Steps 1a and 1c.

Volatilized N was summed for losses from major crop types, minor crop types, grasslands, settlements, and forest lands. Similarly, the annual amounts of N lost from soil profiles through leaching and surface runoff were summed to obtain the total losses for this pathway.

Step 2: Estimate Direct N_2O Emissions from Cropland Soils

In this step, N_2O emissions were calculated for major crop types and non-major crop types on mineral soils, in addition to emissions associated with drainage and cultivation of organic soils.

Step 2a: Direct N_2O Emissions from Cropland Mineral Soils

Two methods were used to estimate direct N_2O emissions from N additions and crop production on mineral soils. The DAYCENT ecosystem model was used to estimate emissions from major crop types, while the Tier 1 methodology was used to estimate emissions from crops considered non-major types, which are grown on a considerably smaller portion of land than the major types.

Major Crops: Tier 3 DAYCENT Simulations

Simulations were performed over three major time periods for each county in the United States using the DAYCENT model. The first time period was used for simulation of native vegetation up to date of cultivation in the county (1 A.D. to plow out). Plow out was assumed to occur between 1600 and 1850, depending on the state in which the county lies. Simulation of at least 1600 years of native vegetation was needed to initialize soil organic matter (SOM) pools in the model. The second time period of the simulation started at plowout and represents historical agricultural practices up to the modern period (plow out to 1970). Simulation of the historical cropping period was needed to establish modern day SOM levels, which is important because N_2O emissions are sensitive to the amount of SOM. Lastly, simulations were performed for the modern agricultural period (1971 through 2009).

Corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton are defined as major crops and were simulated in every county where they were grown. These crops represent approximately 90 percent of total principal cropland in the United States as defined by the U.S. Department of Agriculture (USDA 2003). Overall, the DAYCENT simulations included approximately 86 percent of total cropland area. For rotations that include a cycle that repeats every two or more years (e.g., corn/soybeans, wheat/corn/fallow), different simulations were performed where each phase of the rotation was simulated every year. For example, 3 rotations were simulated in regions where wheat/corn/fallow cropping is a dominant rotation—one with wheat grown the first year, a second with corn the first year and a third with fallow the first year. This ensured that each crop was represented during each year in one of the three simulations. In cases where the same crop was grown in the same year in two or more distinct rotations for a region, N_2O emissions were averaged across the different rotations to obtain a value for that crop. Emissions from cultivated fallow land were also included. Fallow area was assumed to be equal to winter wheat area in regions where winter wheat/fallow rotations are the dominant land management for winter wheat.

The simulations reported here assumed conventional tillage cultivation, gradual improvement of cultivars, and gradual increases in fertilizer application until 1989. Note that there is a planned improvement to incorporate use of conservation tillage in the United States into this Inventory. The productivity of cultivars (cultivated varieties) has

steadily improved over the last century and therefore it is unrealistic to assume that modern varieties of crops, such as corn, are identical to the popular varieties grown in 1900 in terms of yield potential, N demand, etc. Realistic simulations of historical land management and vegetation type are important because they influence present day soil C and N levels, which influence present-day N cycling and associated N_2O emissions.

Uncertainty estimation was an integral part of this analysis; uncertainty in the input data for the county-scale simulations and structural uncertainty associated with the DAYCENT model predictions were both addressed (Del Grosso et al. 2010). In the first step, a Monte Carlo Analysis was used to propagate input data uncertainty through the modeling process. Thus, input data were randomly selected from PDFs for weather records, soil type, mineral N fertilization rate, and organic amendments. See Step 1a for additional discussion about the PDFs. After selecting a set of inputs for a county, DAYCENT was used to simulate each crop and then the process was repeated until 100 iterations were completed. Due to the computationally intensive requirements for DAYCENT, it was not possible to simulate every county with the Monte Carlo Analysis. Two counties were selected from each of the 63 agricultural regions, and additional counties were added based on the variance in N_2O emissions across regions from the past year's Inventory, using a Neyman allocation (Cochran 1977). A Neyman allocation is based on the variance in N_2O emissions across the 63 regions; regions with larger variances were allocated a larger number of counties for the Monte Carlo Analysis. A total of 300 counties were included in the Monte Carlo Analysis, which is approximately 10 percent of all counties with agricultural land. In addition, all counties were simulated once based on the dominant conditions from the PDFs (i.e., most common soil type, weather condition, manure amendment, and mineral fertilizer rate).

In the second step of the uncertainty analysis, a structural uncertainty estimator was developed to account for uncertainty inherent in model formulation and parameterization using an empirically-based procedure described by Ogle et al. (2007). The procedure is based on developing a statistical relationship between modeled results and field measurements. Specifically, DAYCENT was used to simulate 11 agricultural experiments with 108 treatments, and the results were analyzed using a linear-mixed effect model in which measurements were statistically modeled as a function of simulated emissions. Simulated DAYCENT emissions were a highly significant predictor of the measurements, with a p-value of <0.01. Several other variables were tested in the statistical model to evaluate if DAYCENT exhibited bias under certain conditions related to climate, soil types, and management practices. The type of crop or grassland was significant at an alpha level of 0.05, demonstrating that DAYCENT tended to over-estimate emissions for small grains systems and grassland, but was accurate in predicting the N_2O emissions for other crops. Random effects were included in the model to capture the dependence in time series and data collected from the same site, which were needed to estimate appropriate standard deviations for parameter coefficients.

The structural uncertainty estimator accounted for bias and prediction error in the DAYCENT model results, as well as random error associated with fine-scale emission predictions in counties over a time series from 1990 to 2009. To apply the uncertainty estimator, DAYCENT N_2O emission estimates were used as an input to the linear mixed effect model after randomly selecting statistical parameter coefficients from their joint probability distribution, in addition to random draws from PDFs representing the uncertainty due to site, site by year random effects and the residual error from the linear-mixed effect model (Del Grosso et al. 2010).

In DAYCENT, once N enters the plant/soil system, the model cannot distinguish among the original sources of the N to determine which management activity led to specific N_2O emissions. This means, for example, that N_2O emissions from applied synthetic fertilizer cannot be separated from emissions due to other N inputs, such as crop residues. It is desirable, however, to report emissions associated with specific N inputs. Thus, for each crop in a county, the N inputs in a simulation were determined for anthropogenic practices discussed in IPCC (2006), including synthetic mineral N fertilization, organic amendments, and crop residue N added to soils (including N-fixing crops). The percentage of N input for anthropogenic practices was divided by the total N input, and this proportion was used to determine the amount of N_2O emissions assigned to each of the practices.[61] For example, if 70 percent of the mineral N made available in the soil was due to mineral fertilization, then 70 percent of the N_2O emissions were assigned to this practice. The remainder of soil N_2O emissions is reported under "other N inputs," which includes mineralization due to decomposition of soil organic matter and litter, as well as asymbiotic fixation of mineral N in soils from the atmosphere. Asymbiotic N fixation by soil bacteria is a minor source of N, typically not exceeding 10 percent of total N inputs to agroecosystems. Mineralization of soil organic matter is a more significant source of N, but is still typically less than half of the amount of N made available in the soil compared to fertilization, manure amendments, and symbiotic fixation. Accounting for the

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[61] This method is a simplification of reality to allow partitioning of N_2O emissions, as it assumes that all N inputs have an identical chance of being converted to N_2O. This is unlikely to be the case, but DAYCENT does not track N_2O emissions by source of mineral N so this approximation is the only approach that can be used for partitioning N_2O emissions by source of N input. Moreover, this approach is similar to the IPCC Tier 1 method (IPCC 2006), which uses the same direct emissions factor for most N sources (e.g., PRP).

influence of "other N inputs" was necessary in order to meet the recommendation of reporting all emissions from managed lands (IPCC 2006). While this method allows for attribution of N_2O emissions to the individual N inputs to the soils, it is important to realize that sources such as synthetic fertilization may have a larger impact on N_2O emissions than would be suggested by the associated level of N input for this source (Delgado et al. 2009). Further research will be needed to improve upon this attribution method, however.

The final N_2O emission estimate was determined by summing the estimates from the single simulation conducted in each county for the dominant condition to the 63 regions. Estimates were then adjusted to account for the difference between the emissions estimated in the Monte Carlo analysis and the dominant condition simulation on a region-by-region basis (i.e., if the Monte Carlo mean was slightly higher than the dominant condition among the counties included in the Monte Carlo analysis, the total emission estimate for the region would be raised by the difference) (Del Grosso et al. 2010). In turn, regional values were summed to produce the national total. The uncertainty was based on the variance in simulated N_2O emissions for the iterations in the Monte Carlo Analysis and the variance associated with difference between the means from the Monte Carlo Analysis and the simulated N_2O emissions for the dominant condition, expressed as a 95 percent confidence interval (Del Grosso et al. 2010).

Non-Major Crops: Tier 1 Method

To estimate direct N_2O emissions from N additions to non-major crops, the amount of N in applied synthetic fertilizer, manure and other commercial organic fertilizers (i.e., dried blood, tankage, compost, and other) was added to N inputs from crop residues, and the resulting annual totals were multiplied by the IPCC default emission factor of 0.01 kg N_2O-N/kg N (IPCC 2006). The uncertainty was determined based on simple error propagation methods (IPCC 2006). The uncertainty in the default emission factor ranged from 0.3–3.0 kg N_2O-N/kg N (IPCC 2006). Uncertainty in activity data is ± 20 percent for fertilizer additions (Mosier 2004).[62] Uncertainties in the emission factor and fertilizer additions were combined with uncertainty in the equations used to calculate residue N additions from above- and below-ground biomass dry matter and N concentration to derive overall uncertainty.

Step 2b: Direct N_2O Emissions Due to Drainage and Cultivation of Organic Cropland Soils

To estimate annual N_2O emissions from drainage and cultivation of organic soils, the area of cultivated organic soils in temperate regions was multiplied by the IPCC (2006) default emission factor for temperate soils and the corresponding area in sub-tropical regions was multiplied by the average (12 kg N_2O-N/ha cultivated) of IPCC (2006) default emission factors for temperate (8 kg N_2O-N/ha cultivated) and tropical (16 kg N_2O-N/ha cultivated) organic soils. The uncertainty was determined based on simple error propagation methods (IPCC 2006), including uncertainty in the default emission factor ranging from 2–24 kg N_2O-N/ha (IPCC 2006).

Step 2c: Estimate Total Direct N_2O Emissions from Cropland Soils

In this step, total direct N_2O emissions from cropland soils are calculated by summing direct emissions on mineral soils with emissions resulting from the drainage and cultivation of organic soils (i.e., histosols) (Table A- 207). Uncertainties were combined using the simple error propagation method (IPCC 2006).

Step 3: Estimate Direct N_2O Emissions from Grasslands

DAYCENT was used to estimate direct N_2O emissions from soils in non-federal grasslands (pastures and rangeland), and the Tier 1 method was used for federal grasslands. Managed pastures were simulated with DAYCENT by assuming that the vegetation mix includes forage legumes and grasses, and that grazing intensity was moderate to heavy. Rangelands were simulated without forage legumes and grazing intensity was assumed to be light to moderate. The methodology used to conduct the DAYCENT simulations of grasslands was similar to that for major crop types described above in Step 2a, including the analysis addressing uncertainty in the model inputs and model structure. Carbon and nitrogen additions to grasslands from grazing animals were obtained from county level animal excretion data and area data for federal and non-federal grasslands, as described in Step1c.

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[62] Note that due to lack of data, uncertainties in managed manure N production, PRP manure N production, other commercial organic fertilizer amendments, indirect losses of N in the DAYCENT simulations, and sewage sludge amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventories.

The Tier 1 method was used to estimate emissions from N excreted by livestock on federal lands (i.e., PRP manure N). The Tier 1 method was also used to estimate emissions from sewage sludge application to grasslands. These two sources of N inputs to soils were multiplied by the IPCC (2006) default emission factors (0.01 kg N_2O-N/kg N from sludge and horse, sheep, and goat manure, and 0.02 kg N_2O-N/kg N from cattle, swine, and poultry manure) to estimate N_2O emissions. This emission estimate was summed with the DAYCENT simulated emissions to provide the national total for direct N_2O losses from grasslands (Table A- 208). The uncertainty was determined based on the Tier 1 error propagation methods provided by the IPCC (2006) with uncertainty in the default emission factor ranging from 0.007 to 0.06 kg N_2O-N/kg N (IPCC 2006).

Step 4: Estimate Indirect N_2O Emissions for All Land-Use Types

In this step, N_2O emissions were calculated for the two indirect emission pathways (N_2O emissions due to volatilization, and N_2O emissions due to leaching and runoff of N), which were then summed to yield total indirect N_2O emissions from croplands, grasslands, forest lands, and settlements.

Step 4a: Indirect Emissions Due to Volatilization

Indirect emissions from volatilization of N inputs from synthetic and commercial organic fertilizers, and PRP manure, were calculated according to the amount of mineral N that was transported in gaseous forms from the soil profile and later emitted as soil N_2O following atmospheric deposition. See Step 1d for additional information about the methods used to compute N losses due to volatilization. The estimated N volatilized for all land-use and livestock activities was multiplied by the IPCC default emission factor of 0.01 kg N_2O-N/kg N (IPCC 2006) to compute total N_2O emissions from volatilization. The resulting estimates are provided in Table A- 209. The uncertainty was determined using simple error propagation methods (IPCC 2006), by combining uncertainties in the amount of N volatilized, with uncertainty in the default emission factor ranging from 0.002–0.05 kg N_2O-N/kg N (IPCC 2006).

Step 4b: Indirect Emissions Due to Leaching and Runoff

The amount of mineral N (i.e., synthetic fertilizers, commercial organic fertilizers, PRP manure, crop residue, N mineralization, asymbiotic fixation) that was transported from the soil profile in aqueous form was used to calculate indirect emissions from (1) leaching of mineral N from soils and (2) losses in runoff of water associated with overland flow. See Step 1d for additional information about the methods used to compute N losses from soils due to leaching and runoff in overland water flows.

The total amount of N transported from soil profiles through leaching and surface runoff was multiplied by the IPCC default emission factor of 0.0075 kg N_2O-N/kg N (IPCC 2006) to estimate emissions for this source. The resulting emission estimates are provided in Table A- 210. The uncertainty was determined based on simple error propagation methods (IPCC 2006), including uncertainty in the default emission factor ranging from 0.0005 to 0.025 kg N_2O-N/kg N (IPCC 2006).

Step 5: Estimate Total N_2O Emissions for U.S. Soils

Total emissions were estimated by adding total direct emissions (from major crop types and non-major crop types on mineral cropland soils, drainage and cultivation of organic soils, and grassland management) to indirect emissions for all land use and management activities. U.S. national estimates for this source category are provided in Table A- 210. Uncertainties in the final estimate were combined using simple error propagation methods (IPCC 2006), and expressed as a 95 percent confidence interval.

Direct and indirect emissions of soil N_2O vary regionally in both croplands and grasslands as a function of N inputs, weather, and soil type. A little more than half of the total N_2O emissions from major crops occur in Iowa, Illinois, Nebraska, Minnesota, Texas, Kansas and Indiana where N inputs associated with corn rotations are high or where large land areas are cropped (Table A- 211). On a per area unit basis, direct N_2O emissions are also high in many of the Mississippi River Basin states where there are also high N input to corn and soybean crops (Figure A- 9). Emissions are also high in some western and New England states. Only a small portion of the land in these regions is used for crop production, but management and conditions lead to higher emissions on a per unit area basis than other regions. For example, emissions are high in California, Arizona, and other western states due to intensive irrigation management systems. For some New England states, emissions are high on a per unit area because subsurface soil layers remain frozen

when surface soil layers thaw in spring. This creates saturated conditions near the surface that facilitate denitrification and N_2O emissions. Indirect emissions tend to be high on an area basis in the central and eastern United States because relatively high rainfall facilitates N losses from leaching and runoff and in some western states where irrigation can contribute to leaching and runoff (Figure A- 10).

Direct and indirect emissions from grasslands are typically lower than those from croplands (Table A- 211, Figure A- 11, and Figure A- 12) because N inputs tend to be lower, particularly from synthetic fertilizer. Texas was by far the highest emitter for this category, followed by Nebraska, Montana, Oklahoma, New Mexico Colorado and South Dakota. On a per area unit basis, emissions are lower in the western United States because grasslands in the East and Central regoins are more intensively managed (legume seeding, fertilization) while western rangelands receive few, if any, N inputs. Also, rainfall is limited in most of the western United States, and grasslands are not typically irrigated so minimal leaching and runoff of N occurs in these grasslands.

Figure A- 7: DAYCENT Model Flow Diagram

Figure A- 8: Comparisons of Results from DAYCENT Model and IPCC Tier 1 Method with Measurements of Soil N_2O Emissions

Figure A- 9: Major Crops, Average Annual Direct N_2O Emissions, Estimated Using the DAYCENT Model, 1990-2009 (Metric Tons CO_2 Eq./ha/year)

Figure A- 10: Major Crops, Average Annual N Losses Leading to Indirect N_2O Emissions, Estimated Using the DAYCENT Model, 1990-2009 (kg N/ha/year)

Figure A- 11: Grasslands, Average Annual Direct N_2O Emissions, Estimated Using the DAYCENT Model, 1990-2009 (Metric Tons CO_2 Eq./ha/year)

Figure A- 12: Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions, Estimated Using the DAYCENT Model, 1990-2009 (kg N/ha/year)

Table A- 197: Synthetic Fertilizer N Added to Major Crops (Gg N)

	1990		1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Fertilizer N	7,468		7,307	7,915	7,705	7,641	7,412	7,575	7,450	7,547	7,370	7,355	7,000	6,855	7,428	6,663	6194

Table A- 198: Fate of Livestock Manure Nitrogen (Gg N)

Activity	1990		1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Managed Manure N Applied to Major Crops and Grasslands[a,b]	993		968	1,038	1,063	1,116	1,103	1,099	1,086	1,164	1,079	1,077	1,036	847	1,195	1,110	948
Managed Manure N Applied to Non-Major Crops[b]	1,473		1,618	1,568	1,563	1,519	1,561	1,587	1,583	1,585	1,549	1,598	1,687	1,878	1,655	1,649	1,722
Managed Manure N Applied to Grasslands	446		515	514	503	542	478	463	466	470	470	472	475	479	475	474	462
Pasture, Range, & Paddock Manure N	4,083		4,458	4,412	4,296	4,237	4,158	4,056	4,043	4,049	4,072	4,077	4,157	4,209	4,201	4,170	4,123
Total	**6,994**		**7,559**	**7,532**	**7,426**	**7,414**	**7,300**	**7,204**	**7,177**	**7,268**	**7,171**	**7,223**	**7,355**	**7,413**	**7,527**	**7,403**	**7,255**

[a] Accounts for N volatilized and leached/runoff during treatment, storage and transport before soil application.
[b] Includes managed manure and daily spread manure amendments
[c] Totals may not sum exactly due to rounding.

Table A- 199: Crop Residue N and Other N Inputs to Major Crops as Simulated by DAYCENT (Gg N)

Activity	1990		1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Residue N[a]	2,982		3,305	3,322	3,329	3,099	3,659	3,450	3,151	3,253	3,407	3,231	3,041	3,186	3,164	3,210	2,996
Mineralization & Asymbiotic Fixation	12,406		12,010	12,590	12,811	14,166	12,926	13,548	13,520	13,238	13,216	13,361	12,740	12,800	13,084	12,943	12,345

[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Table A- 200: Synthetic Fertilizer N Added to Non-Major Crops (Gg N)

	1990		1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Fertilizer N	1,076		1,884	1,326	1,638	1,669	1,841	1,546	1,571	1,540	1,838	1,905	2,155	2,039	1,692	2,229	2,653

Table A- 201: Other Organic Commercial Fertilizer Consumption on Agricultural Lands (Gg N)

	1990		1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Other Commercial Organic Fertilizer N[a]	4		10	13	14	12	11	9	7	8	8	9	10	12	15	13	13

[a] Includes dried blood, tankage, compost, other. Excludes dried manure and sewage sludge used as commercial fertilizer to avoid double counting.

Table A- 202: Key Assumptions for Production of Non-Major Crops and Retention of Crop Residues

Crop	Dry Matter Fraction of Harvested Product	Above-ground Residue		Ratio of Below-ground Residue to Above-ground Biomass	Residue N Fraction	
		Slope	Intercept		Above-ground	Below-ground
Peanuts for Nuts	0.94	1.07	1.54	0.20	0.016	0.014
Dry Edible Beans	0.90	0.36	0.68	0.19	0.010	0.010
Dry Edible Peas	0.91	1.13	0.85	0.19	0.008	0.008
Austrian Winter Peas	0.91	1.13	0.85	0.19	0.008	0.008
Lentils	0.91	1.13	0.85	0.19	0.008	0.008
Wrinkled Seed Peas	0.91	1.13	0.85	0.19	0.008	0.008
Barley	0.89	0.98	0.59	0.22	0.007	0.014
Oats	0.89	0.91	0.89	0.25	0.007	0.008
Rye	0.88	1.09	0.88	0.22	0.005	0.011
Millet	0.90	1.43	0.14	0.22	0.007	0.009
Rice	0.89	0.95	2.46	0.16	0.007	0.009

Table A- 203: Nitrogen in Crop Residues Retained on Soils Producing Non-Major Crops (Gg N)

Crop	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Peanuts for Nuts	64	63	65	64	68	66	61	71	61	69	71	77	63	65	79	65
Dry Edible Beans	16	16	15	16	16	16	15	13	16	14	13	15	14	15	15	14
Dry Edible Peas	9	11	9	11	11	10	10	10	10	11	14	15	8	8	14	17
Austrian Winter Peas	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Lentils	9	9	9	9	9	9	10	10	9	9	10	11	10	10	9	11
Wrinkled Seed Peas	9	9	8	8	8	8	8	8	8	8	9	8	8	8	8	9
Barley	112	96	105	96	94	74	86	68	63	76	76	59	51	59	66	63
Oats	55	29	28	30	30	27	28	24	23	27	23	23	20	20	20	20
Rye	9	9	9	8	9	9	9	8	8	9	8	8	8	8	8	8
Millet	7	7	7	7	7	7	3	7	2	5	6	5	4	6	6	4
Rice	80	87	86	91	91	99	94	103	101	97	109	106	95	96	99	105
Total	**378**	**343**	**349**	**348**	**352**	**336**	**331**	**330**	**311**	**333**	**347**	**336**	**290**	**304**	**332**	**324**

Table A- 204: Drained and Cultivated Organic Soil Area (Thousand Hectares)

Year	Temperate Area	Sub-Tropical Area
1990	444	194
1995	450	196
1996	450	196
1997	450	196
1998	450	196
1999	450	196
2000	450	196
2001	450	196
2002	450	196
2003	450	196
2004	450	196
2005	450	196
2006	450	196
2007	450	196
2008	450	196
2009	450	196

Table A- 205: Synthetic Fertilizer N, PRP Manure N, Organic Manure N Amendment, Forage Legume N, and Other N Inputs Simulated with the DAYCENT Model (Gg N)

N Source	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Fertilizer N	9,678	9,662	10,245	9,973	9,891	9,628	9,747	9,620	9,723	9,553	9,536	9,213	9,088	9,656	8,871	8,385
PRP Manure N	3,718	4,065	4,021	3,906	3,856	3,787	3,697	3,688	3,701	3,728	3,731	3,806	3,856	3,850	3,819	3,781
Managed Manure	1,438	1,483	1,552	1,566	1,658	1,581	1,561	1,552	1,634	1,549	1,549	1,511	1,326	1,670	1,584	1,410
Residue N[a] Mineralization & Asymbiotic Fixation	11,164	11,560	11,054	11,069	10,667	12,264	11,056	11,078	10,631	11,234	10,855	10,731	10,840	10,875	10,890	10,577
	23,864	23,237	23,649	24,172	25,721	23,703	24,190	24,412	23,731	23,942	24,175	23,635	23,549	23,830	23,731	23,285

[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Table A- 206: Sewage Sludge Nitrogen by Disposal Practice (Gg N)

Disposal Practice	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Applied to Agricultural Soils	52	69	72	75	78	81	30	86	89	91	94	98	101	104	106	109
Other Land Application	25	28	29	29	29	30	30	30	30	30	30	31	31	32	32	32
Surface Disposal	20	16	15	14	13	12	10	9	8	6	5	5	4	4	3	3
Total	**98**	**113**	**116**	**118**	**121**	**122**	**124**	**125**	**127**	**128**	**130**	**134**	**136**	**139**	**141**	**144**

Note: Totals may not sum due to independent rounding.

Table A- 207: Direct N$_2$O Emissions from Cropland Soils (Tg CO$_2$ Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Mineral Soils	**100.1**	**107.1**	**115.5**	**112.9**	**116.5**	**111.1**	**112.7**	**120.1**	**112.5**	**109.7**	**116.2**	**115.2**	**112.7**	**114.9**	**115.0**	**109.1**
Major Crops	**85.8**	**88.3**	**99.6**	**95.6**	**99.2**	**92.9**	**95.7**	**103.1**	**95.7**	**91.5**	**97.4**	**94.8**	**92.1**	**97.1**	**94.4**	**86.1**
Synthetic Fertilizer	27.1	27.4	31.7	29.6	29.4	27.4	28.4	30.4	28.8	27.0	28.7	28.1	26.7	29.1	26.5	23.9
Managed Manure	3.6	3.6	4.2	4.1	4.1	4.0	4.0	4.4	4.3	3.9	4.1	4.1	3.3	4.6	4.4	3.6
Residue N[a]	10.6	12.4	13.5	12.8	11.6	13.7	12.7	12.7	12.4	12.4	12.6	12.1	12.4	12.4	12.6	11.5
Mineralization and Asymbiotic Fixation	44.6	44.8	50.2	49.0	54.0	47.7	50.6	55.5	50.2	48.3	52.1	50.5	49.7	50.9	50.9	47.1
Non-Major Crops	**14.3**	**18.8**	**15.9**	**17.4**	**17.3**	**18.3**	**16.9**	**17.0**	**16.8**	**18.2**	**18.8**	**20.4**	**20.6**	**17.9**	**20.6**	**23.0**
Synthetic Fertilizer	5.2	9.2	6.5	8.0	8.1	9.0	7.5	7.7	7.5	9.0	9.3	10.5	9.9	8.2	10.9	12.9
Managed Manure and Other Organic Commercial Fertilizer	7.2	7.9	7.7	7.7	7.5	7.7	7.8	7.7	7.8	7.6	7.8	8.3	9.2	8.1	8.1	8.5
Residue N	1.8	1.7	1.7	1.7	1.7	1.6	1.6	1.6	1.5	1.6	1.7	1.6	1.4	1.5	1.6	1.6
Organic Soils	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**
Total*	**102.9**	**110.0**	**118.4**	**115.8**	**119.4**	**114.0**	**115.6**	**123.0**	**115.4**	**112.6**	**119.1**	**118.1**	**115.6**	**117.8**	**117.9**	**112.0**

+ Less than 0.05 Tg CO$_2$ Eq.
[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Table A- 208: Direct N$_2$O Emissions from Grasslands (Tg CO$_2$ Eq.)

	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
DAYCENT	**47.1**	**45.2**	**49.4**	**46.2**	**47.3**	**42.9**	**43.3**	**47.3**	**47.5**	**42.6**	**44.5**	**45.6**	**44.3**	**43.4**	**44.9**	**44.4**
Synthetic Fertilizer	3.9	4.1	4.5	4.1	4.2	3.7	3.9	4.1	4.3	3.8	4.0	4.1	4.0	3.9	4.0	3.9
PRP Manure	4.6	4.7	5.2	4.7	4.6	4.4	4.5	4.7	4.7	4.4	4.6	4.9	4.8	4.7	4.9	4.7
Managed Manure	1.5	1.8	2.0	1.8	1.8	1.5	1.6	1.7	1.8	1.5	1.6	1.6	1.6	1.6	1.6	1.6
Residue N[a]	15.6	14.6	15.5	14.6	14.5	14.9	13.8	15.5	15.3	13.9	14.2	14.6	14.2	13.9	14.4	14.1
Mineralization and Asymbiotic Fixation	21.5	20.0	22.3	21.2	22.2	18.4	19.5	21.2	21.3	19.0	20.1	20.4	19.7	19.3	20.0	20.1
Tier 1	**3.7**	**4.1**	**4.1**	**4.0**	**4.0**	**3.9**	**3.8**	**3.7**	**3.7**	**3.7**	**3.7**	**3.8**	**3.8**	**3.8**	**3.8**	**3.8**
PRP Manure	3.5	3.7	3.7	3.7	3.6	3.5	3.4	3.3	3.3	3.2	3.3	3.3	3.3	3.3	3.3	3.2
Sewage Sludge	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5
Total	**50.9**	**49.2**	**53.5**	**50.3**	**51.3**	**46.8**	**47.1**	**51.0**	**51.2**	**46.3**	**48.2**	**49.4**	**48.1**	**47.3**	**48.7**	**48.2**

+ Less than 0.05 Tg CO$_2$ Eq.
[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Table A- 209: Indirect N$_2$O Emissions (Tg CO$_2$ Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Volatilization and Atm. Deposition	**16.9**	**18.2**	**17.6**	**17.9**	**17.8**	**17.8**	**17.6**	**17.6**	**17.5**	**17.6**	**17.8**	**18.2**	**19.3**	**17.7**	**17.8**	**18.3**
Croplands	11.6	12.8	12.4	12.6	12.4	12.6	12.7	12.5	12.5	12.5	12.8	13.1	14.2	12.8	12.9	13.4
Settlements	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Forest Land	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Grasslands	5.1	5.2	5.0	5.1	5.2	5.0	4.7	4.9	4.7	4.8	4.8	4.8	4.8	4.7	4.7	4.7
Surface Leaching & Run-off	**27.1**	**30.3**	**29.8**	**25.8**	**29.1**	**24.5**	**26.5**	**28.8**	**24.8**	**25.9**	**26.7**	**25.7**	**25.9**	**26.6**	**26.3**	**26.1**
Croplands	25.8	29.1	28.1	24.4	27.5	23.0	25.0	27.2	23.2	24.0	24.9	23.7	24.4	24.9	24.5	24.1
Settlements	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Forest Land	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Grasslands	1.0	0.8	1.4	0.9	1.3	1.0	1.2	1.1	1.2	1.4	1.3	1.5	1.1	1.2	1.2	1.5
Total	**44.0**	**48.5**	**47.4**	**43.7**	**46.9**	**42.3**	**44.1**	**46.3**	**42.3**	**43.5**	**44.5**	**43.9**	**45.2**	**44.3**	**44.1**	**44.4**

+ Less than 0.05 Tg CO$_2$ Eq.

Table A- 210: Total N$_2$O Emissions from Agricultural Soil Management (Tg CO$_2$ Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Direct	**153.8**	**159.2**	**171.9**	**166.1**	**170.7**	**160.9**	**162.6**	**174.0**	**166.6**	**158.9**	**167.3**	**167.5**	**163.7**	**165.1**	**166.6**	**160.2**
Direct Emissions from Mineral Cropland Soils	**100.1**	**107.1**	**115.5**	**112.9**	**116.5**	**111.1**	**112.7**	**120.1**	**112.5**	**109.7**	**116.2**	**115.2**	**112.7**	**114.9**	**115.0**	**109.1**
Synthetic Fertilizer	32.3	36.6	38.2	37.6	37.5	36.4	36.0	38.1	36.3	35.9	37.9	38.6	36.7	37.4	37.3	36.9
Organic Amendment[a]	10.8	11.6	11.9	11.8	11.6	11.7	11.8	12.2	12.1	11.5	12.0	12.3	12.5	12.8	12.5	12.1
Residue N[b]	12.4	14.0	15.2	14.5	13.4	15.3	14.3	14.3	13.9	14.0	14.3	13.7	13.8	13.9	14.3	13.1
Mineralization and Asymbiotic Fixation	44.6	44.8	50.2	49.0	54.0	47.7	50.6	55.5	50.2	48.3	52.1	50.5	49.7	50.9	50.9	47.1
Direct Emissions from Drained Organic Cropland Soils	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**
Direct Emissions from Grasslands*	**50.9**	**49.2**	**53.5**	**50.3**	**51.3**	**46.8**	**47.1**	**51.0**	**51.2**	**46.3**	**48.2**	**49.4**	**48.1**	**47.3**	**48.7**	**48.2**
Synthetic Mineral Fertilizer	3.9	4.1	4.5	4.1	4.2	3.7	3.9	4.1	4.3	3.8	4.0	4.1	4.0	3.9	4.0	3.9
PRP Manure*	8.1	8.4	8.9	8.4	8.2	7.9	7.9	8.1	8.0	7.6	7.8	8.2	8.1	8.0	8.2	7.9
Managed Manure	1.5	1.8	2.0	1.8	1.8	1.5	1.6	1.7	1.8	1.5	1.6	1.6	1.6	1.6	1.6	1.6
Sewage Sludge	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5
Residue[b]	15.6	14.6	15.5	14.6	14.5	14.9	13.8	15.5	15.3	13.9	14.2	14.6	14.2	13.9	14.4	14.1
Mineralization and Asymbiotic Fixation	21.5	20.0	22.3	21.2	22.2	18.4	19.5	21.2	21.3	19.0	20.1	20.4	19.7	19.3	20.0	20.1
Total Indirect	**44.0**	**48.5**	**47.4**	**43.7**	**46.9**	**42.3**	**44.1**	**46.3**	**42.3**	**43.5**	**44.5**	**43.9**	**45.2**	**44.3**	**44.1**	**44.4**
Volatilization	16.9	18.2	17.6	17.9	17.8	17.8	17.6	17.6	17.5	17.6	17.8	18.2	19.3	17.7	17.8	18.3
Leaching/Runoff	27.1	30.3	29.8	25.8	29.1	24.5	26.5	28.8	24.8	25.9	26.7	25.7	25.9	26.6	26.3	26.1
Total Emissions	**197.8**	**207.6**	**219.3**	**209.7**	**217.6**	**203.2**	**206.8**	**220.4**	**208.8**	**202.4**	**211.8**	**211.3**	**208.9**	**209.4**	**210.7**	**204.6**

+ Less than 0.05 Tg CO$_2$ Eq.

[a] Organic amendment inputs include managed manure amendments, daily spread manure and other commercial organic fertilizer (i.e., dried blood, tankage, compost, and other).

[b] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Table A- 211: Total 2009 N$_2$O Emissions (Direct and Indirect) from Agricultural Soil Management by State (Tg CO$_2$ Eq.)

State	Croplands[1]	Grasslands[2]	Settlements[3]	Forest Lands[4]		Total	Lower Bound	Upper Bound
AL	0.67	0.71	0.03	n.e.		1.42	0.87	2.51
AR	3.07	0.76	0.02	n.e.		3.85	2.47	7.37
AZ	0.91	0.93	0.02	n.e.		1.86	0.95	4.58
CA	6.96	1.80	0.19	n.e.		8.95	5.73	17.46
CO	1.23	2.46	0.02	n.e.		3.71	2.36	6.14
CT	0.57	0.03	0.02	n.e.		0.62	0.36	1.58
DE	0.77	0.01	0.01	n.e.		0.78	0.45	2.38
FL	2.02	1.03	0.22	n.e.		3.27	2.28	5.58
GA	1.22	0.36	0.01	n.e.		1.59	1.02	3.23
HI5	0.00	n.e.	n.e.	n.e.		1.59	1.02	3.23
IA	15.79	0.85	0.07	n.e.		16.71	11.99	33.98
ID	2.19	1.57	0.02	n.e.		3.78	2.34	7.60
IL	11.86	0.37	0.12	n.e.		12.34	8.81	19.28
IN	7.55	0.30	0.07	n.e.		7.92	5.05	12.74
KS	5.66	2.21	0.07	n.e.		7.94	5.58	12.16
KY	2.00	1.14	0.03	n.e.		3.17	1.91	5.69
LA	1.58	0.54	0.04	n.e.		2.16	1.65	3.44
MA	0.13	0.02	0.04	n.e.		0.19	0.13	0.77
MD	1.03	0.09	0.05	n.e.		1.18	0.30	3.27
ME	0.22	0.02	0.01	n.e.		0.25	0.17	1.36
MI	4.48	0.37	0.08	n.e.		4.92	3.50	8.35
MN	9.71	0.80	0.03	n.e.		10.54	7.38	16.41
MO	6.07	1.82	0.07	n.e.		7.96	5.34	12.65
MS	2.44	0.42	0.03	n.e.		2.90	1.81	6.33
MT	2.01	3.09	0.01	n.e.		5.11	3.21	8.22
NC	2.38	0.65	0.05	n.e.		3.08	2.14	6.28
ND	5.46	1.17	0.03	n.e.		6.66	4.46	10.67
NE	6.38	2.98	0.07	n.e.		9.43	6.72	14.63
NH	0.06	0.01	0.01	n.e.		0.08	0.06	0.41
NJ	1.61	0.02	0.07	n.e.		1.71	0.34	5.10
NM	0.54	2.91	0.01	n.e.		3.46	1.66	6.09
NV	0.31	0.61	0.01	n.e.		0.93	0.04	9.01
NY	3.19	0.33	0.07	n.e.		3.60	2.35	7.02
OH	7.37	0.49	0.11	n.e.		7.97	5.67	12.54
OK	1.21	3.02	0.03	n.e.		4.27	1.97	7.83
OR	1.12	1.43	0.01	n.e.		2.56	1.60	5.42
PA	3.05	0.12	0.06	n.e.		3.24	1.77	7.60
RI	0.02	0.00	0.01	n.e.		0.03	0.02	0.58
SC	0.66	0.15	0.03	n.e.		0.85	0.16	2.10
SD	3.25	2.53	0.02	n.e.		5.79	3.97	9.35
TN	1.60	0.77	0.05	n.e.		2.42	1.46	6.22
TX	5.32	8.93	0.09	n.e.		14.34	8.26	22.86
UT	0.64	0.92	0.01	n.e.		1.57	1.06	3.24
VA	4.26	0.84	0.06	n.e.		5.16	3.34	12.17
VT	0.46	0.06	0.00	n.e.		0.52	0.37	1.11
WA	2.28	1.00	0.03	n.e.		3.31	1.24	7.93
WI	6.64	0.77	0.04	n.e.		7.45	5.23	12.13
WV	0.44	0.21	0.01	n.e.		0.66	0.36	1.62
WY	0.51	1.95	0.01	n.e.		2.47	1.69	4.02

[1] Emissions from non-manure organic N inputs for minor crops were not estimated (n.e.) at the state level.

[2] Emissions from sewage sludge applied to grasslands and were not estimated (n.e.) at the state level

[3] Emissions from sewage sludge applied to settlements were not estimated (n.e.) at the state level.

[4] Forestland emissions were not estimated (n.e.) at the state level.

[5] N$_2$O emissions are not reported for Hawaii except from cropland organic soils.

3.12. Methodology for Estimating Net Carbon Stock Changes in Forest Lands Remaining Forest Lands

This sub-annex expands on the methodology used to calculate net changes in carbon (C) stocks in forest ecosystems and in harvested wood products. Some of the details of C conversion factors and procedures for calculating net CO_2 flux for forests are provided below; full details of selected topics may be found in the cited references.

Carbon Stocks and Net Changes in Forest Ecosystem Carbon Stocks

At least two forest inventories exist for most forest land in the United States. C stocks are estimated based on data from each inventory, at the level of permanent inventory plots. C per hectare (for a sample location) is multiplied by the total number of hectares that the plot represents, and then totals are summed for an area of interest, such as the state of Maine. Net annual C stock changes are calculated by taking the difference between the inventories and dividing by the number of years between the inventories for a selected state or sub-state area.

Forest inventory data

The estimates of forest C stocks are based on data derived from forest inventory surveys. Forest inventory data were obtained from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (Frayer and Furnival 1999). FIA data include remote sensing information and collection of measurements in the field at sample locations called plots. Tree measurements include diameter and species. On a subset of plots, additional measurements or samples are taken of down dead wood, litter, and soil C; however, these are not yet available nationwide for C estimation. The field protocols are thoroughly documented and available for download from the USDA Forest Service (2010c). The inventory was designed for timber volume estimation rather than C stock estimation, so most C pools are not measured directly or are sampled only on a subset of plots. Bechtold and Patterson (2005) provide the estimation procedures for standard forest inventory results. The data are freely available for download at USDA Forest Service (2010b) as the Forest Inventory and Analysis Database (FIADB) Version 4.0; these data are the primary sources of forest inventory used to estimate forest C stocks.

Forest surveys have begun in the U.S. territories and in Hawaii. Meanwhile this inventory assumes that these areas account for a net C change of zero. Survey data are available for the temperate oceanic ecoregion of Alaska (southeast and south central). Inventory data are publicly available for 6.1 million hectares of forest land, and these inventoried lands, comprising 12% of the total forest land in Alaska, contribute to the forest carbon stocks presented here.

Agroforestry systems are also not currently accounted for in the U.S. Inventory, since they are not explicitly inventoried by either of the two primary national natural resource inventory programs: the FIA program of the USDA Forest Service and the National Resources Inventory (NRI) of the USDA Natural Resources Conservation Service (Perry et al. 2005). The majority of these tree-based practices do not meet the size and definitions for forests within each of these resource inventories. The size characteristics that exclude them from inventories also allow these systems to provide their many services without taking the land out of agricultural production, making them an appealing C sequestration option. Agroforestry in the United States has been defined as "intensive land-use management that optimizes the benefits (physical, biological, ecological, economic, social) from bio-physical interactions created when trees and/or shrubs are deliberately combined with crops and/or livestock" (Gold et al. 2000). In the United States, there are six categories of agroforestry practices: riparian forest buffers, windbreaks, alley cropping, silvopasture, forest farming and special applications.[63] These practices are used to address many issues facing agricultural lands, such as economic diversification, habitat fragmentation, and water quality. While providing these services and regardless of intent, these tree-based plantings will also reduce atmospheric CO_2. This occurs directly through CO_2 sequestration into woody biomass, and indirectly through enhancement of agricultural production, trapping wind-blown and surface runoff sediments, and/or reducing CO_2 emissions through fuel-use savings (Quam et al. 1992). The effects of these individual practices can potentially be quite large when taken into account within a whole-farm or within an aggregating larger entity (i.e., state-level) (Quam et al. 1992, Schoeneberger 2006). One estimate of the sequestration potential through agroforestry practices in the United States is 90.3 Mt C/year by 2025 (Nair and Nair 2003).

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[63] More information on agroforestry practices can be found online at <http://www.unl.edu/nac>.

Summing state-level C stocks to calculate United States net C flux in forest ecosystems

The overall approach for determining forest C stocks and stock change is based on methodology and algorithms coded into the computer tool described in Smith et al. (2010). It focuses on estimating forest C stocks based on data from two or more forest surveys conducted several years apart for each state or sub-state. There are generally two or more surveys available for download for each state. C stocks are calculated separately for each state based on available inventories conducted since 1990 and for the inventory closest to, but prior to, 1990 if such data are available and consistent with these methods. This approach ensures that the period 1990 (the base year) to present can be adequately represented. Surveys conducted prior to and in the early to mid 1990s focused on land capable of supporting timber production (timberland).[64] As a result, information on less productive forest land or lands reserved from harvest was limited. Inventory field crews periodically measured all the plots in a state at a frequency of every 5 to 14 years. Generally, forests in states with fast-growing (and therefore rapidly changing) forests tended to be surveyed more often than states with slower-growing (and therefore slowly changing) forests. Older surveys for some states, particularly in the West, also have National Forest System (NFS) lands or reserved lands that were surveyed at different times than productive, privately-owned forest land in the state. Periodic data for each state thus became available at irregular intervals and determining the year of data collection associated with the survey can sometimes be difficult.

Table A-212: Source of Unique Forest Inventory and Average Year of Field Survey Used to Estimate Statewide Carbon Stocks

State/Substate[a]	Source of Inventory Data, Report/Inventory Year[b]	Average Year Assigned to Inventory[c]
Alabama	FIADB 4.0, 1982	1982
	FIADB 4.0, 1990	1990
	FIADB 4.0, 2000	1999
	FIADB 4.0, 2005	2003
Alaska, non-reserved Southcentral	FIADB 4.0, 2009	2007
Alaska, non-reserved Southeast	FIADB 4.0, 2009	2007
Alaska, reserved Southcentral	FIADB 4.0, 2009	2006
Alaska, reserved Southeast	FIADB 4.0, 2009	2006
Arizona, NFS non-woodlands	1987 RPA	1985
	FIADB 4.0, 1999	1996
	FIADB 4.0, 2009	2005
Arizona, NFS woodlands	1987 RPA	1984
	FIADB 4.0, 1999	1996
	FIADB 4.0, 2009	2005
Arizona, non-NFS non-woodlands	FIADB 4.0, 1985	1986
	FIADB 4.0, 1999	1996
	FIADB 4.0, 2009	2006
Arizona, non-NFS woodlands	FIADB 4.0, 1999	1990
	FIADB 4.0, 2009	2006
Arkansas	FIADB 4.0, 1988	1988
	FIADB 4.0, 1995	1996

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[64] Forest land is defined as land at least 120 feet wide and 1 acre in size with at least 10 percent cover (or equivalent stocking by live trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. . Forest land includes transition zones, such as areas between forest and nonforest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Roadside, streamside, and shelterbelt strips of trees must have a crown width of at least 120 feet and continuous length of at least 363 feet to qualify as forest land. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet wide or an acre in size. Tree-covered areas in agricultural production settings, such as fruit orchards, or tree-covered areas in urban settings, such as city parks, are not considered forest land. (Smith et al. 2009) Timberland is the most productive type of forest land, which is on unreserved land and is producing or capable of producing crops of industrial wood. Productivity is at a minimum rate of 20 cubic feet of industrial wood per acre per year (Woudenberg and Farrenkopf 1995). There are about 203 million hectares of timberland in the conterminous United States, which represents 81 percent of all forest lands over the same area (Smith et al. 2009).

	FIADB 4.0, 2005	2003
	FIADB 4.0, 2009	2007
California, NFS	IDB, 1990s	1997
	FIADB 4.0, 2009	2006
California, non-NFS	IDB, 1990s	1993
	FIADB 4.0, 2009	2006
Colorado, NFS non-woodlands	1997 RPA	1981
	FIADB 4.0, 2009	2006
Colorado, NFS woodlands	1997 RPA	1975
	FIADB 4.0, 1984	1997
	FIADB 4.0, 2009	2006
Colorado, non-NFS non-woodlands	Westwide, 1983	1980
	FIADB 4.0, 2009	2006
Colorado, non-NFS woodlands	Westwide, 1983	1983
	FIADB 4.0, 2009	2006
Connecticut	FIADB 4.0, 1985	1985
	FIADB 4.0, 1998	1998
	FIADB 4.0, 2007	2006
Delaware	FIADB 4.0, 1986	1986
	FIADB 4.0, 1999	1999
	FIADB 4.0, 2008	2007
Florida	FIADB 4.0, 1987	1987
	FIADB 4.0, 1995	1995
	FIADB 4.0, 2007	2005
Georgia	FIADB 4.0, 1989	1989
	FIADB 4.0, 1997	1997
	FIADB 4.0, 2004	2001
	FIADB 4.0, 2008	2006
Idaho, Caribou-Targhee NF	Westwide, 1991	1992
	FIADB 4.0, 2009	2007
Idaho, Kootenai NF	1987 RPA	1988
	FIADB 4.0, 1991	1995
	FIADB 4.0, 2009	2007
Idaho, non-NFS non-woodlands	FIADB 4.0, 1991	1990
	FIADB 4.0, 2009	2007
Idaho, non-NFS woodlands	FIADB 4.0, 1991	1982
	FIADB 4.0, 2009	2007
Idaho, other NFS	Westwide, 1991	1988
	FIADB 4.0, 1991	2000
	FIADB 4.0, 2009	2007
Idaho, Payette NF	1987 RPA	1982
	FIADB 4.0, 2009	2007
Idaho, Salmon-Challis NF	1987 RPA	1978
	FIADB 4.0, 2009	2007
Idaho, Sawtooth NF	Westwide, 1991	1983
	FIADB 4.0, 1991	1996
	FIADB 4.0, 2009	2007
Illinois	FIADB 4.0, 1985	1985
	FIADB 4.0, 1998	1998
	FIADB 4.0, 2005	2004

	FIADB 4.0, 2008	2006
Indiana	FIADB 4.0, 1986	1986
	FIADB 4.0, 1998	1998
	FIADB 4.0, 2003	2001
	FIADB 4.0, 2008	2007
Iowa	FIADB 4.0, 1990	1990
	FIADB 4.0, 2003	2002
	FIADB 4.0, 2008	2006
Kansas	FIADB 4.0, 1981	1981
	FIADB 4.0, 1994	1994
	FIADB 4.0, 2005	2003
	FIADB 4.0, 2008	2007
Kentucky	FIADB 4.0, 1988	1987
	FIADB 4.0, 2004	2002
	FIADB 4.0, 2007	2005
Louisiana	FIADB 4.0, 1984	1984
	FIADB 4.0, 1991	1991
	FIADB 4.0, 2005	2004
Maine	Eastwide, 1982	1983
	FIADB 4.0, 1995	1995
	FIADB 4.0, 2003	2002
	FIADB 4.0, 2008	2007
Maryland	FIADB 4.0, 1986	1986
	FIADB 4.0, 1999	2000
	FIADB 4.0, 2008	2007
Massachusetts	FIADB 4.0, 1985	1985
	FIADB 4.0, 1998	1998
	FIADB 4.0, 2007	2006
Michigan	FIADB 4.0, 1980	1980
	FIADB 4.0, 1993	1993
	FIADB 4.0, 2004	2003
	FIADB 4.0, 2008	2006
Minnesota	FIADB 4.0, 1990	1989
	FIADB 4.0, 2003	2001
	FIADB 4.0, 2008	2006
Mississippi	FIADB 4.0, 1987	1987
	FIADB 4.0, 1994	1994
	FIADB 4.0, 2006	2007
Missouri	FIADB 4.0, 1989	1988
	FIADB 4.0, 2003	2002
	FIADB 4.0, 2008	2006
Montana, NFS	1987 RPA	1988
	FIADB 4.0, 1989	1996
	FIADB 4.0, 2009	2007
Montana, non-NFS non-reserved	FIADB 4.0, 1989	1989
	FIADB 4.0, 2009	2006
Montana, non-NFS reserved	1997 RPA	1990
	FIADB 4.0, 2009	2007
Nebraska	FIADB 4.0, 1983	1983
	FIADB 4.0, 1994	1995

	FIADB 4.0, 2005	2004
	FIADB 4.0, 2008	2006
Nevada, NFS non-woodlands	1987 RPA	1974
	FIADB 4.0, 1989	1997
	FIADB 4.0, 2005	2005
Nevada, NFS woodlands	1987 RPA	1978
	FIADB 4.0, 1989	1997
	FIADB 4.0, 2005	2005
Nevada, non-NFS non-woodlands	1997 RPA	1985
	FIADB 4.0, 2005	2005
Nevada, non-NFS woodlands	FIADB 4.0, 1989	1980
	FIADB 4.0, 2005	2005
New Hampshire	FIADB 4.0, 1983	1983
	FIADB 4.0, 1997	1997
	FIADB 4.0, 2007	2005
New Jersey	FIADB 4.0, 1987	1987
	FIADB 4.0, 1999	1999
	FIADB 4.0, 2008	2007
New Mexico, NFS non-woodlands	1987 RPA	1986
	FIADB 4.0, 1999	1997
New Mexico, NFS woodlands	1987 RPA	1986
	FIADB 4.0, 1999	1997
New Mexico, non-NFS non-woodlands	FIADB 4.0, 1987	1987
	FIADB 4.0, 1999	1999
New Mexico, non-NFS woodlands	FIADB 4.0, 1999	1989
New York, non-reserved	Eastwide, 1980	1981
	FIADB 4.0, 1993	1993
	FIADB 4.0, 2007	2005
New York, reserved	1987 RPA	1988
	FIADB 4.0, 2007	2005
North Carolina	FIADB 4.0, 1984	1984
	FIADB 4.0, 1990	1990
	FIADB 4.0, 2002	2001
	FIADB 4.0, 2007	2006
North Dakota	FIADB 4.0, 1980	1979
	FIADB 4.0, 1995	1995
	FIADB 4.0, 2005	2003
	FIADB 4.0, 2008	2007
Ohio	FIADB 4.0, 1991	1991
	FIADB 4.0, 2006	2005
Oklahoma, Central & West	FIADB 4.0, 1989	1989
Oklahoma, East	FIADB 4.0, 1986	1986
	FIADB 4.0, 1993	1993
	FIADB 4.0, 2008	2008
Oregon, NFS East	IDB, 1990s	1995
	FIADB 4.0, 2009	2006
Oregon, NFS West	IDB, 1990s	1996
	FIADB 4.0, 2009	2006
Oregon, non-NFS East	Westwide, 1992	1991
	IDB, 1990s	1999

	FIADB 4.0, 2009	2005
Oregon, non-NFS West	Westwide, 1992	1989
	IDB, 1990s	1997
	FIADB 4.0, 2009	2006
Pennsylvania	FIADB 4.0, 1989	1990
	FIADB 4.0, 2004	2003
	FIADB 4.0, 2008	2007
Rhode Island	FIADB 4.0, 1985	1985
	FIADB 4.0, 1998	1999
	FIADB 4.0, 2007	2006
South Carolina	FIADB 4.0, 1986	1986
	FIADB 4.0, 1993	1993
	FIADB 4.0, 2001	2001
	FIADB 4.0, 2006	2005
South Dakota, NFS	1997 RPA	1986
	FIADB 4.0, 1995	1999
	FIADB 4.0, 2005	2004
	FIADB 4.0, 2008	2006
South Dakota, non-NFS	1987 RPA	1986
	FIADB 4.0, 1995	1995
	FIADB 4.0, 2005	2004
	FIADB 4.0, 2008	2007
Tennessee	FIADB 4.0, 1989	1989
	FIADB 4.0, 1999	1998
	FIADB 4.0, 2004	2003
	FIADB 4.0, 2007	2006
Texas, Central & West	FIADB 4.0, 2007	2006
Texas, East	FIADB 4.0, 1986	1986
	FIADB 4.0, 1992	1992
	FIADB 4.0, 2003	2003
	FIADB 4.0, 2008	2006
Utah, non-woodlands	FIADB 4.0, 1993	1993
	FIADB 4.0, 2009	2005
Utah, woodlands	FIADB 4.0, 1993	1994
	FIADB 4.0, 2009	2005
Vermont	FIADB 4.0, 1983	1983
	FIADB 4.0, 1997	1997
	FIADB 4.0, 2007	2006
Virginia	FIADB 4.0, 1985	1985
	FIADB 4.0, 1992	1991
	FIADB 4.0, 2001	2000
	FIADB 4.0, 2007	2005
Washington, NFS East	IDB, 1990s	1996
	FIADB 4.0, 2009	2006
Washington, NFS West	IDB, 1990s	1996
	FIADB 4.0, 2009	2006
Washington, non-NFS East	IDB, 1990s	1992
	FIADB 4.0, 2009	2006
Washington, non-NFS West	IDB, 1990s	1990
	FIADB 4.0, 2009	2006

West Virginia	FIADB 4.0, 1989	1988
	FIADB 4.0, 2000	2001
	FIADB 4.0, 2008	2007
Wisconsin	FIADB 4.0, 1983	1982
	FIADB 4.0, 1996	1995
	FIADB 4.0, 2004	2002
	FIADB 4.0, 2008	2006
Wyoming, NFS	1997 RPA	1982
	FIADB 4.0, 2000	2000
Wyoming, non-NFS non-reserved non-woodlands	FIADB 4.0, 1984	1984
	FIADB 4.0, 2000	2002
Wyoming, non-NFS non-reserved woodlands	FIADB 4.0, 1984	1984
	FIADB 4.0, 2000	2002
Wyoming, non-NFS reserved	1997 RPA	1985
	FIADB 4.0, 2000	2000

[a] Substate areas (Smith et al. 2010) include National Forests (NFS), all forest ownerships except National Forest (non-NFS), woodlands (forest land dominated by woodland species, such as pinyon and juniper, where stocking cannot be determined (USDA Forest Service 2010c)), non-woodlands (used for clarity to emphasize that woodlands are classified separately), reserved (forest land withdrawn from timber utilization through statute, administrative regulation, or designation, Smith et al. (2009)), and non-reserved (forest land that is not reserved, used for clarity). Some National Forests are listed individually by name, e.g., Payette NF. Oregon and Washington were divided into eastern and western forests (east or west of the crest of the Cascade Mountains). Oklahoma and Texas are divided into East versus Central & West according to forest inventroy survey units (USDA Forest Service 2010d). Alaska is represented by a portion of forest land, in the southcentral and southeast part of the state.

[b] FIADB 4.0 is the current, publicly available, format of FIA inventory data, and these files were downloaded from the Internet September 12, 2010 (USDA Forest Service 2010b). IDB (Integrated Database) data are a compilation of periodic inventory data from the 1990s for California, Oregon, and Washington (Waddell and Hiserote 2005). Eastwide (Hansen et al. 1992) and Westwide (Woudenberg and Farrenkopf 1995) inventory data are formats that predate the FIADB data. RPA data are periodic national summaries. The year is the nominal, or reporting, year associated with each dataset.

[c] Average year is based on average measurement year of forest land survey plots and rounded to the nearest integer year.

A new national plot design and annualized sampling (USDA Forest Service 2010a) was introduced by FIA with most new surveys beginning after 1998. These surveys include sampling of all forest land including reserved and lower productivity lands. Most states have annualized inventory data available as of September 2010. Annualized sampling means that a portion of plots throughout the state is sampled each year, with the goal of measuring all plots once every 5 to 10 years, depending on the region of the United States. The full unique set of data with all measured plots, such that each plot has been measured one time, is called a cycle. Sampling is designed such that partial inventory cycles provide usable, unbiased samples of forest inventory, but with higher sampling errors than the full cycle. After all plots have been measured once, the sequence continues with remeasurement of the first year's plots, starting the next new cycle. Most Eastern states have completed the first full cycle of the annualized inventories and are providing annual updates to the state's forest inventory with each year's remeasurements, such that one plot's measurements are included in subsequent year's annual updates. Thus, annually updated estimates of forest C stocks are accurate, but estimates of stock change cannot utilize the annually updated inventory measurements directly, as there is redundancy in the data used to generate the annual updates of C stock. For example, a typical annual inventory update for an eastern state will include new data from remeasurement on 20 percent of plots; data from the remaining 80 percent of plots is identical to that included in the previous year's annual update. The interpretation and use of the sequence of annual inventory updates can affect trends in annualized stock and stock change. In general, the C stock and stock change calculations use annual inventory summaries (updates) with unique sets of plot-level data (that is, without redundant sets); the most-recent annual update is the exception because it is included in stock change calculations if at least half of the plots in a state include new measurements. Table A-212 lists the specific surveys used in this report, and this list can be compared with the full set of summaries available for download (USDA Forest Service 2010b).

For each pool in each state in each year, C stocks are estimated by linear interpolation between survey years. Similarly, fluxes, or net stock changes, are estimated for each pool in each state by dividing the difference between two successive stocks by the number of intervening years between surveys. Thus, the number of separate stock change estimates for each state or sub-state is one less than the number of available inventories. Annual estimates of stock and net change since the most recent survey are based on linear extrapolation. C stock and flux estimates for each pool are summed over all forest land in all states as identified in Table A-212 to form estimates for the United States. Summed net annual stock change and stock are presented in Table A-213 and Table A-214, respectively. Table A-214 also provides an

estimate of forest area based on the interpolation and extrapolation procedure described above. Estimated net stock change of non-soil forest ecosystem carbon for 2009 for each of the states is shown in Table A-215, which also includes estimated forest area and total non-soil forest carbon stock. The state-level forest areas and carbon stocks are from the most recent inventory available (USDA Forest Service 2010a), and the estimate for net stock change is the mean of the 2000 through 2009 estimates from the carbon calculator (Smith et al. 2010).

Table A-213: Net Annual Changes in Carbon Stocks (Tg C yr⁻¹) in Forest and Harvested Wood Pools, 1990–2009

Carbon Pool	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Forest	(149.8)	(151.4)	(149.8)	(139.5)	(147.1)	(148.4)	(130.3)	(128.6)	(102.8)	(76.9)	(72.4)	(113.0)	(162.3)	(210.3)	(219.6)	(219.9)	(220.6)	(220.6)	(220.6)	(220.6)
Live, aboveground	(98.2)	(99.9)	(100.5)	(97.4)	(101.5)	(102.8)	(92.7)	(95.8)	(84.7)	(78.3)	(78.3)	(89.3)	(103.0)	(118.9)	(122.1)	(122.1)	(122.1)	(122.1)	(122.1)	(122.1)
Live, belowground	(19.3)	(19.7)	(19.8)	(19.3)	(20.1)	(20.5)	(18.4)	(19.0)	(16.9)	(15.7)	(15.7)	(17.9)	(20.5)	(23.5)	(24.1)	(24.1)	(24.1)	(24.1)	(24.1)	(24.1)
Dead Wood	(8.6)	(8.6)	(8.3)	(7.6)	(7.7)	(7.7)	(7.1)	(6.2)	(4.8)	(4.0)	(3.5)	(4.0)	(5.2)	(7.6)	(8.1)	(8.4)	(9.1)	(9.1)	(9.1)	(9.1)
Litter	(8.8)	(8.8)	(9.0)	(8.1)	(7.6)	(6.0)	(5.1)	(5.1)	(0.5)	4.9	7.5	1.8	(5.3)	(9.9)	(11.4)	(11.4)	(11.4)	(11.4)	(11.4)	(11.4)
Soil Organic Carbon	(14.9)	(14.4)	(12.1)	(7.2)	(10.2)	(11.4)	(7.1)	(2.5)	4.1	16.2	17.6	(3.7)	(28.3)	(50.3)	(53.8)	(53.8)	(53.8)	(53.8)	(53.8)	(53.8)
Harvested Wood	(35.9)	(33.8)	(33.8)	(32.9)	(33.4)	(32.3)	(30.6)	(32.0)	(31.1)	(32.5)	(30.8)	(25.5)	(26.8)	(25.9)	(28.7)	(28.7)	(29.6)	(28.1)	(22.4)	(14.8)
Products in Use	(17.7)	(14.9)	(16.3)	(15.0)	(15.9)	(15.1)	(14.1)	(14.7)	(13.4)	(14.1)	(12.8)	(8.7)	(9.6)	(9.7)	(12.4)	(12.4)	(12.3)	(10.7)	(5.2)	1.9
SWDS	(18.3)	(18.8)	(17.4)	(17.9)	(17.5)	(17.2)	(16.5)	(17.3)	(17.7)	(18.4)	(18.0)	(16.8)	(17.2)	(16.2)	(16.3)	(16.3)	(17.3)	(17.4)	(17.2)	(16.7)
Total Net Flux	(185.7)	(185.1)	(183.6)	(172.4)	(180.5)	(180.7)	(160.9)	(160.7)	(133.9)	(109.4)	(103.2)	(138.5)	(189.1)	(236.1)	(248.3)	(248.6)	(250.2)	(248.7)	(243.0)	(235.4)

Table A-214: Carbon Stocks (Tg C) in Forest and Harvested Wood Pools, 1990–2010

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Forest Area (1000 ha)	269,137	269,764	270,395	270,992	271,535	272,071	272,602	273,081	273,553	273,950	274,183	274,386	274,717	275,234	275,976	276,769	277,561	278,354	279,147	279,939	280,732
Carbon Pool																					
Forest	42,783	42,933	43,085	43,234	43,374	43,521	43,669	43,800	43,928	44,031	44,108	44,180	44,293	44,456	44,666	44,886	45,105	45,326	45,547	45,767	45,988
Live, aboveground	15,072	15,171	15,271	15,371	15,468	15,570	15,673	15,765	15,861	15,946	16,024	16,102	16,192	16,295	16,414	16,536	16,658	16,780	16,902	17,024	17,147
Live, belowground	2,995	3,014	3,034	3,053	3,073	3,093	3,113	3,132	3,151	3,168	3,183	3,199	3,217	3,237	3,261	3,285	3,309	3,333	3,357	3,381	3,405
Dead Wood	2,960	2,969	2,978	2,986	2,994	3,001	3,009	3,016	3,022	3,027	3,031	3,035	3,039	3,044	3,052	3,060	3,068	3,077	3,086	3,096	3,105
Litter	4,791	4,799	4,808	4,817	4,825	4,833	4,839	4,844	4,849	4,850	4,845	4,837	4,835	4,841	4,851	4,862	4,873	4,885	4,896	4,908	4,919
Soil Organic Carbon	16,965	16,980	16,995	17,007	17,014	17,024	17,035	17,043	17,045	17,041	17,025	17,007	17,011	17,039	17,089	17,143	17,197	17,251	17,304	17,358	17,412
Harvested Wood	1,859	1,895	1,929	1,963	1,996	2,029	2,061	2,092	2,124	2,155	2,187	2,218	2,244	2,271	2,296	2,325	2,354	2,383	2,412	2,434	2,449
Products in Use	1,231	1,249	1,264	1,280	1,295	1,311	1,326	1,340	1,355	1,368	1,382	1,395	1,404	1,413	1,423	1,436	1,448	1,460	1,471	1,476	1,474
SWDS	628	646	665	683	701	718	735	752	769	787	805	823	840	857	873	890	906	923	941	958	974
Total Carbon Stock	44,643	44,828	45,014	45,197	45,370	45,550	45,731	45,892	46,052	46,186	46,296	46,399	46,537	46,726	46,962	47,211	47,459	47,710	47,958	48,201	48,437

Table A-215: State-level forest area, carbon stock, and net annual stock change. Estimates are forest ecosystem carbon and do not include harvested wood

State	Mean year of field data collection	Forest area (1000 ha)	Nonsoil C stock (Mt C)	Mean net annual nonsoil stock change 2000–2009 (Mt C/yr)
Alabama	2006	9,219	682	(1.2)
Alaska	2007	6,132	1,217	0.0
Arizona	2006	7,572	436	2.0
Arkansas	2007	7,560	644	(3.6)
California	2006	13,333	2,165	(5.2)
Colorado	2006	9,294	915	(5.2)
Connecticut	2007	698	89	0.7
Delaware	2007	143	18	(0.1)
Florida	2005	6,838	471	(5.0)
Georgia	2006	10,046	802	(7.7)
Idaho	2007	8,656	1,053	2.1
Illinois	2006	1,942	215	(5.3)
Indiana	2007	1,920	225	(3.7)
Iowa	2006	1,227	113	(2.8)
Kansas	2007	902	74	(1.5)
Kentucky	2005	5,006	502	(5.3)
Louisiana	2004	5,722	447	0.1
Maine	2007	7,146	741	(1.9)
Maryland	2007	1,009	131	(1.2)
Massachusetts	2007	1,222	166	(0.4)
Michigan	2006	8,021	826	(6.5)
Minnesota	2006	6,876	536	(4.1)
Mississippi	2007	7,941	610	(6.2)
Missouri	2006	6,231	605	(10.5)
Montana	2007	10,356	1,132	(4.2)
Nebraska	2006	538	44	(0.6)
Nevada	2005	4,520	247	(0.8)
New Hampshire	2006	1,944	254	(0.5)
New Jersey	2007	810	86	(0.0)
New Mexico	1994	6,753	484	(3.8)
New York	2006	7,669	943	(6.3)
North Carolina	2006	7,521	727	(6.8)
North Dakota	2007	289	20	0.2
Ohio	2007	3,255	353	(3.0)
Oklahoma	2003	3,235	237	(0.8)
Oregon	2006	12,163	2,007	(8.2)
Pennsylvania	2007	6,739	804	(7.0)
Rhode Island	2007	141	17	(0.0)
South Carolina	2006	5,239	440	(5.7)
South Dakota	2007	753	51	(0.9)
Tennessee	2006	5,659	576	(3.8)
Texas	2006	24,363	977	(2.4)
Utah	2005	7,396	510	(3.4)
Vermont	2007	1,857	250	(0.3)
Virginia	2006	6,400	683	(3.4)
Washington	2006	9,060	1,711	(10.0)
West Virginia	2007	4,846	592	(4.6)
Wisconsin	2006	6,757	620	(6.0)
Wyoming	2001	4,633	468	(1.1)

Table A-216 shows average C density values for forest ecosystem C pools according to region and forest types based on forest lands in this Inventory. These values were calculated by applying plot-level C estimation procedures as described below to the most recent inventory per state as available 12 September 2010 (USDA 2010b). C density values

reflect the most recent survey for each state as available in the FIADB, not potential maximum C storage. C densities are affected by the distribution of stand sizes within a forest type, which can range from regenerating to mature stands. A large proportion of young stands in a particular forest type are likely to reduce the regional average for C density.

Table A-216: Average carbon density (Mg C/ha) by carbon pool and forest area (1000 ha) according to region and forest type, based on the most recent inventory survey available for each state from FIA, corresponding to an average year of 2006

Region (States) Forest Types	Above-ground Biomass	Below-ground Biomass	Dead Wood	Litter	Soil Organic Carbon	Forest Area
	Carbon Density (Mg C/ha)					(1,000 ha)
Northeast						
(CT,DE,MA,MD,ME,NH,NJ,NY,OH,PA,RI,VT,WV)						
White/Red/Jack Pine	91.6	19.0	11.9	13.7	78.1	1,584
Spruce/Fir	52.7	11.2	13.3	30.7	98.0	2,970
Oak/Pine	77.0	15.2	9.8	27.4	66.9	1,234
Oak/Hickory	82.5	15.6	11.1	8.1	53.1	13,007
Elm/Ash/Cottonwood	59.3	11.3	9.9	6.9	111.7	1,450
Maple/Beech/Birch	77.9	15.0	13.3	27.1	69.6	13,673
Aspen/Birch	48.1	9.5	9.3	8.6	87.4	1,704
Minor Types and Nonstocked	48.2	9.5	10.3	10.9	73.7	1,855
All	74.5	14.4	11.9	17.8	69.0	37,478
Northern Lake States						
(MI,MN,WI)						
White/Red/Jack Pine	54.1	11.3	9.0	12.3	120.8	1,821
Spruce/Fir	40.5	8.6	8.6	33.1	261.8	3,213
Oak/Hickory	70.4	13.3	10.8	7.9	97.1	3,815
Elm/Ash/Cottonwood	52.4	10.0	9.2	7.5	179.9	2,118
Maple/Beech/Birch	74.1	14.2	11.5	27.3	134.3	4,301
Aspen/Birch	40.9	7.9	9.5	8.3	146.1	5,272
Minor Types and Nonstocked	34.5	6.8	8.8	18.0	122.6	1,113
All	54.5	10.7	9.9	16.4	152.3	21,654
Northern Prairie States						
(IA,IL,IN,KS,MO,ND,NE,SD)						
Ponderosa Pine	40.3	8.5	7.1	14.3	48.5	576
Oak/Pine	52.0	10.1	7.5	25.5	40.1	551
Oak/Hickory	69.8	13.2	9.7	7.7	49.4	9,570
Elm/Ash/Cottonwood	74.7	14.0	11.8	6.8	83.2	1,874
Minor Types and Nonstocked	41.6	8.1	8.3	17.9	60.3	1,231
All	66.0	12.5	9.7	9.5	54.5	13,803
Ponderosa Pine	40.3	8.5	7.1	14.3	48.5	576
South Central						
(AL,AR,KY,LA,MS,OK,TN,TX)	40.6	8.3	5.5	10.9	55.5	1,198
Loblolly/Shortleaf Pine	45.8	9.4	7.0	9.6	41.9	13,256
Pinyon/Juniper	16.4	3.2	1.9	12.2	37.7	3,894
Oak/Pine	48.1	9.4	6.6	9.3	41.7	5,115
Oak/Hickory	58.5	11.0	6.8	6.4	38.6	24,619
Oak/Gum/Cypress	76.2	14.5	9.2	6.5	52.8	5,131
Elm/Ash/Cottonwood	51.9	9.8	7.1	5.9	49.9	3,441
Woodland Hardwoods	10.3	1.7	0.9	5.0	65.0	8,977
Minor Types and Nonstocked	32.3	6.2	5.8	7.1	54.3	4,271
All	45.9	8.8	5.9	7.4	45.5	68,704
Loblolly/Shortleaf Pine	45.8	9.4	7.0	9.6	41.9	13,256
Southeast						
(FL,GA,NC,SC,VA)						
Longleaf/Slash Pine	34.7	7.1	6.2	9.7	110.0	4,139
Loblolly/Shortleaf Pine	48.6	10.0	8.5	9.6	72.9	9,137
Oak/Pine	52.6	10.3	6.7	9.3	61.4	4,054
Oak/Hickory	73.1	13.8	8.9	6.4	45.3	12,014
Oak/Gum/Cypress	74.2	14.3	9.7	6.5	158.0	4,551
Elm/Ash/Cottonwood	57.9	10.9	9.7	5.6	95.7	760
Minor Types and Nonstocked	45.7	8.7	9.0	5.8	107.0	1,389
All	59.0	11.5	8.4	7.9	79.2	36,044
Coastal Alaska						
(approximately 12 percent of						

forest land in Alaska)

Spruce/Fir	24.2	5.0	5.6	33.8	62.1	367
Fir/Spruce/Mountain Hemlock	96.0	20.3	26.8	43.2	62.1	2,233
Hemlock/Sitka Spruce	142.2	30.0	37.5	50.5	116.3	2,754
Aspen/Birch	42.0	8.0	9.1	10.6	42.5	310
Minor Types and Nonstocked	40.0	7.8	10.7	19.5	75.7	469
All	105.5	22.2	28.2	42.5	86.5	6,132
Spruce/Fir	24.2	5.0	5.6	33.8	62.1	367
Pacific Northwest, Westside						
(Western OR and WA)						
Douglas-fir	146.2	30.7	39.0	32.0	94.8	5,956
Fir/Spruce/Mountain Hemlock	150.1	31.7	41.6	38.3	62.1	1,187
Hemlock/Sitka Spruce	174.7	36.8	50.0	37.8	116.3	1,566
Alder/Maple	84.8	16.6	24.2	7.6	115.2	1,189
Minor Types and Nonstocked	68.9	13.7	18.0	13.5	85.9	1,216
All	135.6	28.3	37.0	28.8	95.5	11,114
Pacific Northwest, Eastside						
(Eastern OR and WA)						
Douglas-fir	77.5	16.2	19.5	36.3	94.8	2,089
Ponderosa Pine	48.8	10.2	11.2	22.5	50.7	2,742
Fir/Spruce/Mountain Hemlock	95.3	20.1	27.8	37.9	62.1	1,781
Lodgepole Pine	41.2	8.7	12.0	21.1	52.0	1,041
Western Larch	63.5	13.3	19.2	35.7	45.1	204
Other Western Softwoods	15.7	3.0	4.5	36.2	78.8	1,252
Minor Types and Nonstocked	36.0	7.1	16.1	25.1	81.5	999
All	57.1	11.9	15.8	30.1	68.4	10,109
Pacific Southwest						
(CA)						
Pinyon/Juniper	24.1	4.7	2.3	21.1	26.3	742
Douglas-fir	162.8	33.8	37.3	35.7	40.1	442
Ponderosa Pine	63.7	13.2	15.0	22.4	41.3	899
Fir/Spruce/Mountain Hemlock	158.0	33.4	45.0	38.3	51.9	824
Redwood	219.6	45.9	48.1	60.5	53.8	299
Other Western Softwoods	33.7	6.6	7.6	37.5	49.8	806
California Mixed Conifer	127.8	26.8	32.8	37.9	49.8	3,159
Western Oak	67.0	12.8	7.9	29.7	27.6	3,791
Tanoak/Laurel	132.0	26.0	20.1	28.0	27.6	830
Minor Types and Nonstocked	57.8	11.7	17.7	25.2	37.0	1,540
All	92.0	18.7	20.0	31.9	38.6	13,333
Rocky Mountain, North						
(ID,MT)						
Douglas-fir	72.8	15.4	14.5	37.0	38.8	5,587
Ponderosa Pine	40.0	8.3	8.2	22.9	34.3	1,865
Fir/Spruce/Mountain Hemlock	67.6	14.3	22.1	37.4	44.1	4,471
Lodgepole Pine	50.3	10.7	10.9	23.1	37.2	2,761
Western Larch	60.1	12.7	15.4	36.3	34.2	492
Other Western Softwoods	44.8	9.4	6.9	39.3	31.4	649
Aspen/Birch	31.8	6.0	12.5	26.8	56.6	533
Minor Types and Nonstocked	28.4	5.7	17.0	22.5	42.9	2,655
Rocky Mountain, South						
(AZ,CO,NM,NV,UT,WY)						
Pinyon/Juniper	22.9	4.7	1.0	21.1	19.7	18,738
Douglas-fir	74.7	15.9	16.9	38.1	30.9	1,797
Ponderosa Pine	47.3	10.0	8.2	23.6	24.1	3,570
Fir/Spruce/Mountain Hemlock	79.6	16.9	22.9	38.8	31.5	4,262
Lodgepole Pine	52.0	11.1	13.0	24.0	27.0	2,024
Aspen/Birch	56.9	11.0	13.2	28.5	58.8	2,555
Woodland Hardwoods	19.0	3.6	4.6	28.2	25.9	4,135
Minor Types and Nonstocked	18.7	3.6	7.9	22.6	25.4	3,088
All	36.3	7.5	6.9	25.4	25.8	40,168
United States (forest land included in Inventory)	**60.0**	**11.9**	**11.1**	**17.6**	**62.0**	**277,552**

Note: The forest area values in this table do not equal the forest area values reported in Table A-214, because the forest area values in this table are estimated using the most recent dataset per state, with an average year of 2006. The time series of forest area values reported in Table A-214,

in contrast, is constructed following the CCT methods used to construct the carbon stock series. The forest area values reported in Table A-214 and Table A-216 would only be identical if all states were measured simultaneously or they all had identical rates of change.

The Inventory is derived primarily from the current FIADB 4.0 data (USDA Forest Service 2010b), but it also draws on older FIA survey data where necessary. The Resources Planning Act Assessment (RPA) database, which includes periodic summaries of state inventories, is one example. Information about the RPA data is available on the Internet (USDA Forest Service 2010a, see Program Features), and compilations of analytical estimates based on these databases are found in Waddell et al. (1989) and Smith et al. (2001). The basic difference between the RPA database and the FIADB is that the FIADB includes some informative additional details such as individual-tree data. Having only plot-level information (such as volume per hectare) limits the conversion to biomass. This does not constitute a substantial difference for the overall state-wide estimates, but it does affect plot-level precision (Smith et al. 2004). In the past, FIA made their data available in tree-level Eastwide (Hansen et al. 1992) or Westwide (Woudenberg and Farrenkopf 1995) formats, which included inventories for Eastern and Western states, respectively. The current Inventory estimates rely in part on older tree-level data that are not available on the current FIADB site. The Integrated Database (IDB) is a compilation of periodic forest inventory data from the 1990s for California, Oregon, and Washington (Waddell and Hiserote 2005). These data were identified by Heath et al. (submitted) as the most appropriate non-FIADB sources for these states.

An historical focus of the FIA program was to provide information on timber resources of the United States. For this reason, prior to 1998, some forest land, which were less productive or reserved (i.e., land where harvesting was prohibited by law), were less intensively surveyed. This generally meant that on these less productive lands, forest type and area were identified but data were not collected on individual tree measurements. The practical effect that this evolution in inventories has had on estimating forest C stocks from 1990 through the present is that some older surveys of lands do not have the stand-level values for merchantable volume of wood or stand age. Any data gaps identified in the surveys taken before 1998 were filled by assigning average C densities calculated from the more complete, later inventories from the respective states. The overall effect of this necessary approach to generate estimates for C stock is that no net change in C density occurs on those lands with gaps in past surveys.

Estimating C stocks from forest inventory data

For each inventory summary in each state, data are converted to C units or augmented by other ecological data. This collection of conversion factors and models used for inventory-based forest carbon estimates (Smith et al. 2010, Heath et al. in press) was intitially developed as an offshoot of the forest carbon simulation model FORCARB (Heath et al. 2010) and is incorporated into a number of applications (Birdsey and Heath 1995, Birdsey and Heath 2001, Heath et al. 2003, Smith et al. 2004, Smith et al. 2007, Hoover and Rebain 2008). The conversion factors and model coefficients are usually categorized by region, and forest type. Classifications for both region and forest type are subject to change depending on the particular coefficient set. Thus, region and type are specifically defined for each set of estimates. Factors are applied to the survey data at the scale of FIA inventory plots. The results are estimates of C density (Mg per hectare) for the various forest pools. C density for live trees, standing dead trees, understory vegetation, down dead wood, litter, and soil organic matter are estimated. All non-soil pools except litter can be separated into aboveground and belowground components. The live tree and understory C pools are pooled as biomass in this inventory. Similarly, standing dead trees and down dead wood are pooled as dead wood in this inventory. C stocks and fluxes for *Forest Land Remaining Forest Land* are reported in pools following IPCC (2003).

Live tree C pools

The tree C pools include aboveground and belowground (coarse root) C mass of live trees. Separate estimates are made for full-tree and aboveground-only biomass to estimate the belowground component. Most tree C estimates are based on Jenkins et al. (2003) and are functions of species groups and diameter. For example, the equation for estimating aboveground biomass for a live tree of a species in the aspen/alder/cottonwood/willow group is:

$$\text{Biomass (kg dry weight)} = e^{(-2.2094 + 2.3867 \times \ln(\text{diameter}))}$$

Diameter is cm at diameter breast height (d.b.h.), which is measured at 1.37 m above the forest floor. C is calculated by multiplying biomass by 0.5 because biomass is 50 percent of dry weight (IPCC/UNEP/OECD/IEA 1997). A full set of coefficients can be found in Jenkins et al. (2003; Table 4). Belowground root biomass is estimated as a ratio of roots to total aboveground biomass. The equation for ratio of root biomass of a live tree in the aspen/alder/cottonwood/willow group is:

$$\text{Ratio} = e^{(-1.6911 + 0.8160/\text{diameter})}$$

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Belowground biomass is calculated by multiplying the ratio by total aboveground biomass. A full set of coefficients can be found in Jenkins et al. (2003; Table 6). The C per tree is summed for each plot, and multiplied by the appropriate expansion factors to obtain a C stock estimate for the plot.

Some inventory data do not provide measurements of individual trees; tree C in these plots is estimated from plot-level growing stock volume of live trees and equations given in Table A-217 and Table A-218. These equations are updates of those in Smith et al. (2003), modified to reduce error and correspond to common forest types defined by inventories. Separate estimates are made for whole-tree and aboveground-only biomass based on forest type group and region. The belowground portion is determined as the difference between the two estimates. C density is estimated based on the growing stock volume of the plot, where growing stock includes live trees of commercial species meeting specified standards. Only trees 12.7 cm (5 inches) d.b.h. and larger are included in growing stock volume. The full sets of coefficients are in Table A-217 and Table A-218. For example, the total C in tree biomass per hectare of aspen-birch in the North averages 8.1 Mg C/ha if growing-stock volume is zero. If growing-stock volume is greater than zero, the estimate is in two parts. Average C density of non-growing-stock trees (sapling and cull trees) is 14.3 Mg C/ha, and the equation for C in growing-stock trees is:

$$\text{Growing-stock trees (Mg C/ha)} = e^{(-0.337 + \ln(\text{volume}) \times 0.933)}$$

Units for volume are m^3/ha.

Table A-217: Coefficients for estimating carbon density of live trees (above- and below-ground, MgC/ha) by region and type for plot-level data such as RPA data[a]

Region[b]	Forest type group[c]	Carbon density, if Growing Stock Volume (GSV) = 0	C density for non-Growing Stock (GS), if GSV > 0	Coefficient A	Coefficient B
North	Aspen/Birch	8.138	14.335	-0.337	0.933
	Elm/Ash/Cottonwood	16.187	18.707	-0.206	0.920
	Maple/Beech/Birch	6.938	17.054	-0.170	0.925
	Oak/Hickory	13.083	15.914	-0.079	0.932
	Hardwood minor types	10.376	14.127	0.002	0.890
	Oak/Pine	4.079	15.473	-0.146	0.908
	Ponderosa Pine & Exotic Softwood	2.595	6.895	-0.074	0.886
	Loblolly/Shortleaf Pine	6.277	9.766	-0.415	0.943
	Spruce/Fir	6.424	16.903	-0.487	0.947
	White/Red/Jack Pine	3.908	12.117	-0.349	0.924
	Softwood minor types	6.277	17.234	-0.380	0.970
	Non-stocked	1.054	1.238	-0.174	0.866
Pacific Coast	Alder/Maple	8.425	4.444	0.056	0.828
	Other Western Hardwoods	8.425	10.483	0.041	0.864
	Tanoak/Laurel	8.425	10.203	-0.167	0.917
	Western Oak	8.425	7.400	0.344	0.850
	Hardwood minor types	8.425	4.802	0.333	0.770
	California Mixed Conifer	10.102	4.727	0.137	0.843
	Douglas-fir	2.752	4.961	0.180	0.834
	Fir/Spruce/Mt. Hemlock	10.102	6.462	0.171	0.834
	Hemlock/Sitka Spruce	10.102	8.034	0.085	0.830
	Lodgepole Pine	10.102	5.733	-0.129	0.857
	Pinyon/Juniper	22.552	5.065	-0.070	0.842
	Ponderosa Pine	10.102	2.262	0.145	0.813
	Western Larch	10.102	5.254	-0.264	0.853
	Softwood minor types	10.102	6.771	0.466	0.783
	RPA Western Hardwoods	8.425	7.460	0.302	0.831
	Non-stocked	0.880	0.300	0.049	0.806
Rocky Mountain	Aspen/Birch	4.594	9.516	0.324	0.792
	Harwood minor types	4.866	11.844	0.266	0.814
	Douglas-fir	1.987	5.363	0.331	0.825
	Fir/Spruce/Mt. Hemlock	1.987	6.693	0.065	0.825
	Lodgepole Pine	1.080	8.051	0.003	0.804
	Other Western Softwoods	1.987	12.217	0.361	0.796
	Ponderosa Pine	1.987	5.574	0.382	0.771
	Softwood minor types	1.987	5.496	-0.152	0.836
	RPA Western Hardwood	13.714	11.678	0.246	0.807
	Pinyon/Juniper	22.927	23.301	0.254	0.794

	West. Oak/Other West. Hardwoods	14.441	18.544	0.215	0.796
	Non-stocked	1.111	0.568	0.257	0.732
South	Elm/Ash/Cottonwood	12.841	21.633	-0.144	0.896
	Oak/Gum/Cypress	7.176	23.919	-0.216	0.907
	Oak/Hickory	14.594	20.007	-0.031	0.886
	Hardwood minor types	47.316	40.194	-0.442	0.960
	Oak/Pine	4.106	17.933	-0.086	0.858
	Loblolly/Shortleaf Pine	3.892	12.466	0.206	0.773
	Longleaf/Slash Pine	4.441	8.694	0.110	0.772
	Softwood minor types	7.161	20.189	-0.085	0.868
	Non-stocked	0.467	0.943	0.019	0.734

[a] Prediction of C in growing-stock trees is based on exp(A + B*ln(growing stock volume)).
[b] Regions are North (CT, DE, IA, IL, IN, KS, MA, MD, ME, MI, MN, MO, ND, NE, NH, NJ, NY, OH, PA, RI, SD, VT, WI, WV); Pacific Coast (CA, OR, WA); Rocky Mountain (AZ, CO, ID, MT, NM, NV, UT, WY); and South (AL, AR, FL, GA, KY, LA, MS, NC, OK, SC, TN, TX, VA).
[c] Forest type groups are identified in FIADB and RPA data (Smith et al. (2001, USDA Forest Service 2010d).

Table A-218: Coefficients for estimating carbon density of live trees (aboveground only, MgC/ha) by region and type for plot-level data such as RPA data[a]

Region[b]	Forest type group[c]	Carbon density, if Growing Stock Volume (GSV)=0	C density for non-GS, if GSV > 0	Coefficient A	Coefficient B
North	Aspen/Birch	6.697	11.880	-0.521	0.934
	Elm/Ash/Cottonwood	13.585	15.653	-0.387	0.922
	Maple/Beech/Birch	5.762	14.219	-0.352	0.926
	Oak/Hickory	10.960	13.306	-0.260	0.933
	Hardwood minor types	8.647	11.796	-0.166	0.888
	Oak/Pine	3.368	12.881	-0.335	0.909
	Ponderosa Pine & Exotic Softwood	2.116	5.671	-0.269	0.886
	Loblolly/Shortleaf Pine	5.098	8.070	-0.620	0.946
	Spruce/Fir	5.206	13.833	-0.684	0.948
	White/Red/Jack Pine	3.174	10.010	-0.548	0.926
	Softwood minor types	5.098	14.246	-0.570	0.971
	Non-stocked	0.880	1.032	-0.357	0.866
Pacific Coast	Alder/Maple	7.006	3.676	-0.138	0.830
	Other Western Hardwoods	7.006	8.709	-0.154	0.867
	Tanoak/Laurel	7.006	8.469	-0.355	0.918
	Western Oak	7.006	6.163	0.167	0.850
	Hardwood minor types	7.006	3.974	0.136	0.773
	California Mixed Conifer	8.309	3.883	-0.061	0.844
	Douglas-fir	2.235	4.072	-0.017	0.835
	Fir/Spruce/Mt. Hemlock	8.309	5.285	-0.027	0.835
	Hemlock/Sitka Spruce	8.309	6.586	-0.113	0.831
	Lodgepole Pine	8.309	4.674	-0.327	0.858
	Pinyon/Juniper	18.583	4.170	-0.263	0.842
	Ponderosa Pine	8.309	1.849	-0.053	0.814
	Western Larch	8.309	4.282	-0.461	0.853
	Softwood minor types	8.309	5.563	0.267	0.784
	RPA Western Hardwoods	7.006	6.202	0.119	0.831
	Non-stocked	0.724	0.247	-0.146	0.808
Rocky Mountain	Aspen/Birch	3.798	7.914	0.139	0.793
	Harwood minor types	4.027	9.936	0.084	0.815
	Douglas-fir	1.616	4.388	0.134	0.826
	Fir/Spruce/Mt. Hemlock	1.616	5.466	-0.133	0.826
	Lodgepole Pine	0.871	6.571	-0.195	0.805
	Other Western Softwoods	1.616	10.031	0.165	0.797
	Ponderosa Pine	1.616	4.569	0.185	0.772
	Softwood minor types	1.616	4.473	-0.350	0.837
	RPA Western Hardwood	11.341	9.704	0.054	0.809
	Pinyon/Juniper	18.867	19.173	0.059	0.794
	West. Oak/Other West. Hardwoods	11.942	15.353	0.021	0.796
	Non-stocked	0.916	0.466	0.061	0.733
South	Elm/Ash/Cottonwood	10.749	18.129	-0.323	0.897
	Oak/Gum/Cypress	5.987	20.004	-0.400	0.909
	Oak/Hickory	12.223	16.731	-0.215	0.888

Hardwood minor types	39.737	33.739	-0.631	0.964
Oak/Pine	3.394	14.923	-0.277	0.859
Loblolly/Shortleaf Pine	3.172	10.288	0.012	0.773
Longleaf/Slash Pine	3.634	7.176	-0.088	0.773
Softwood minor types	5.893	16.751	-0.280	0.869
Non-stocked	0.388	0.788	-0.171	0.735

[a] Prediction of aboveground C in growing-stock trees is based on exp(A + B*ln(growing stock volume).
[b] Regions are North (CT, DE, IA, IL, IN, KS, MA, MD, ME, MI, MN, MO, ND, NE, NH, NJ, NY, OH, PA, RI, SD, VT, WI, WV); Pacific Coast (CA, OR, WA); Rocky Mountain (AZ, CO, ID, MT, NM, NV, UT, WY); and South (AL, AR, FL, GA, KY, LA, MS, NC, OK, SC, TN, TX, VA).
[c] Forest type groups are identified in FIADB and RPA data (Smith et al. 2001, USDA Forest Service 2010d).

Understory vegetation

Understory vegetation is a minor component of biomass. Understory vegetation is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than one-inch d.b.h. In this inventory, it is assumed that 10 percent of understory C mass is belowground. This general root-to-shoot ratio (0.11) is near the lower range of temperate forest values provided in IPCC (2006) and was selected based on two general assumptions: ratios are likely to be lower for light-limited understory vegetation as compared with larger trees, and a greater proportion of all root mass will be less than 2 mm diameter.

Estimates of C density are based on information in Birdsey (1996), which was applied to FIA permanent plots. These were fit to the equation:

$$\text{Ratio} = e^{(A - B \times \ln(\text{live tree C density})}$$

In this equation, "ratio" is the ratio of understory C density (Mg C/ha) to live tree C density (above- and belowground) in Mg C/ha. An additional coefficient is provided as a maximum ratio; that is, any estimate predicted from the equation that is greater than the maximum ratio is set equal to the maximum ratio. A full set of coefficients is in Table A-219. Regions and forest types are the same classifications described in Smith et al. (2003). As an example, the basic calculation for understory C in aspen-birch forests in the Northeast is:

$$\text{Understory (Mg C/ha)} = \text{(live tree C density)} \times e^{(0.855 - 1.03 \times \ln(\text{tree C density})}$$

This calculation is followed by three possible modifications. First, the maximum value for the ratio is set to 2.02 (see value in column "maximum ratio"); this also applies to stands with zero tree C, which is undefined in the above equation. Second, the minimum ratio is set to 0.005 (Birdsey 1996). Third, nonstocked and pinyon/juniper stands are set to coefficient A, which is a carbon density (Mg C/ha) for these types only.

Table A-219: Coefficients for estimating the ratio of carbon density of understory vegetation (above- and belowground, MgC/ha)[a] by region and forest type. The ratio is multiplied by tree carbon density on each plot to produce understory vegetation

Region[b]	Forest Type[b]	A	B	Maximum ratio[c]
NE	Aspen-Birch	0.855	1.032	2.023
	MBB/Other Hardwood	0.892	1.079	2.076
	Oak-Hickory	0.842	1.053	2.057
	Oak-Pine	1.960	1.235	4.203
	Other Pine	2.149	1.268	4.191
	Spruce-Fir	0.825	1.121	2.140
	White-Red-Jack Pine	1.000	1.116	2.098
	Nonstocked	2.020	2.020	2.060
NLS	Aspen-Birch	0.777	1.018	2.023
	Lowland Hardwood	0.650	0.997	2.037
	Maple-Beech-Birch	0.863	1.120	2.129
	Oak-Hickory	0.965	1.091	2.072
	Pine	0.740	1.014	2.046
	Spruce-Fir	1.656	1.318	2.136
	Nonstocked	1.928	1.928	2.117
NPS	Conifer	1.189	1.190	2.114
	Lowland Hardwood	1.370	1.177	2.055
	Maple-Beech-Birch	1.126	1.201	2.130
	Oak-Hickory	1.139	1.138	2.072
	Oak-Pine	2.014	1.215	4.185

	Nonstocked	2.052	2.052	2.072
PSW	Douglas-fir	2.084	1.201	4.626
	Fir-Spruce	1.983	1.268	4.806
	Hardwoods	1.571	1.038	4.745
	Other Conifer	4.032	1.785	4.768
	Pinyon-Juniper	4.430	4.430	4.820
	Redwood	2.513	1.312	4.698
	Nonstocked	4.431	4.431	4.626
PWE	Douglas-fir	1.544	1.064	4.626
	Fir-Spruce	1.583	1.156	4.806
	Hardwoods	1.900	1.133	4.745
	Lodgepole Pine	1.790	1.257	4.823
	Pinyon-Juniper	2.708	2.708	4.820
	Ponderosa Pine	1.768	1.213	4.768
	Nonstocked	4.315	4.315	4.626
PWW	Douglas-fir	1.727	1.108	4.609
	Fir-Spruce	1.770	1.164	4.807
	Other Conifer	2.874	1.534	4.768
	Other Hardwoods	2.157	1.220	4.745
	Red Alder	2.094	1.230	4.745
	Western Hemlock	2.081	1.218	4.693
	Nonstocked	4.401	4.401	4.589
RMN	Douglas-fir	2.342	1.360	4.731
	Fir-Spruce	2.129	1.315	4.749
	Hardwoods	1.860	1.110	4.745
	Lodgepole Pine	2.571	1.500	4.773
	Other Conifer	2.614	1.518	4.821
	Pinyon-Juniper	2.708	2.708	4.820
	Ponderosa Pine	2.099	1.344	4.776
	Nonstocked	4.430	4.430	4.773
RMS	Douglas-fir	5.145	2.232	4.829
	Fir-Spruce	2.861	1.568	4.822
	Hardwoods	1.858	1.110	4.745
	Lodgepole Pine	3.305	1.737	4.797
	Other Conifer	2.134	1.382	4.821
	Pinyon-Juniper	2.757	2.757	4.820
	Ponderosa Pine	3.214	1.732	4.820
	Nonstocked	4.243	4.243	4.797
SC	Bottomland Hardwood	0.917	1.109	1.842
	Misc. Conifer	1.601	1.129	4.191
	Natural Pine	2.166	1.260	4.161
	Oak-Pine	1.903	1.190	4.173
	Planted Pine	1.489	1.037	4.124
	Upland Hardwood	2.089	1.235	4.170
	Nonstocked	4.044	4.044	4.170
SE	Bottomland Hardwood	0.834	1.089	1.842
	Misc. Conifer	1.601	1.129	4.191
	Natural Pine	1.752	1.155	4.178
	Oak-Pine	1.642	1.117	4.195
	Planted Pine	1.470	1.036	4.141
	Upland Hardwood	1.903	1.191	4.182
	Nonstocked	4.033	4.033	4.182

[a]Prediction of ratio of understory C to live tree C is based on the equation: Ratio=exp(A-B*ln(tree_carbon_tph)), where "ratio" is the ratio of understory C density to live tree (above-and below- ground) C density, and "tree_carbon_density" is live tree (above-and below- ground) C density in Mg C/ha.
[b] Regions and types as defined in Smith et al. (2003)
[c]Maximum ratio: any estimate predicted from the equation that is greater than the maximum ratio is set equal to the maximum ratio.

Dead Wood

The standing dead tree C pools include aboveground and belowground (coarse root) mass. Estimates for standing dead tree C are not based on newly available FIA standing dead tree data because updated methodology is not yet available for integrating dead wood carbon estimates based on both older (which do not have consistent measurements of dead wood) and newer surveys. Instead, the estimates are based on a ratio of growing stock volume of live trees, stratified by region and forest type groups, applied at the FIA plot-level. The standing dead tree equations estimate mass; they are

converted to C mass by multiplying by 0.5. An example calculation for standing dead tree C in aspen-birch forests in the Northeast is:

$$\text{Dry weight of dead trees (Mg/ha)} = 1.0 \times (\text{growing stock volume})^{0.499}$$

It is multiplied by 0.5 to obtain Mg C/ha. All coefficients are provided in Table A-220. Note that nonstocked stands are assigned a constant C density (the value of Coefficient A).

Down dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. Down dead wood includes stumps and roots of harvested trees. Ratio estimates of down dead wood to live tree biomass were developed using FORCARB2 simulations and applied at the plot level (Smith et al. 2004). Estimates for down dead wood correspond to the region and forest type classifications described in Smith et al. (2003). A full set of ratios is provided in Table A-221. An additional component of down dead wood is a regional average estimate of logging residue based on Smith et al. (2006) applied at the plot level. These are based on a regional average C density at age zero and first order decay; initial densities and decay coefficients are provided in Table A-222. These amounts are added to explicitly account for down dead wood following harvest. In practice, this modification resulted in minor changes to the estimates. Example calculations of the two components for down dead wood in 25-year-old aspen-birch forests in the Northeast are:

C density (Mg C/ha) = (live tree C density, above- and below-ground) × (0.078) = 7.8% of live tree C

Conversion to C units is not necessary because the live tree value is already in terms of C.

C density additional for logging residue (Mg C/ha) = $13.9 \times e^{(-25/12.1)} = 1.8$ (Mg C/ha)

Table A-220: Coefficients for estimating standing dead tree carbon (MgC/ha) by region and forest type group[a]

Region[b]	Forest type group[c]	Coefficient A	Coefficient B
MTN	Douglas-fir	3.935	0.312
	Fir/Spruce/Mt. Hemlock	4.550	0.358
	Hemlock/Sitka Spruce	1.000	0.569
	Lodgepole Pine	1.177	0.501
	Ponderosa Pine	1.000	0.455
	Nonstocked	12.855	--
MTS	Douglas-fir	2.200	0.460
	Fir/Spruce/Mt. Hemlock	6.923	0.293
	Lodgepole Pine	1.177	0.501
	Ponderosa Pine	1.944	0.292
	Nonstocked	4.232	--
NC	Aspen/Birch	1.962	0.400
	Elm/Ash/Cottonwood	3.755	0.253
	Maple/Beech/Birch	3.442	0.219
	Planted Pine	1.000	0.298
	Oak/Hickory	2.949	0.236
	Oak/Pine	1.364	0.394
	Spruce/Fir	1.320	0.472
	White/Red/Jack Pine	2.844	0.266
	Nonstocked	2.634	--
NE	Aspen/Birch	1.000	0.499
	Elm/Ash/Cottonwood	4.992	0.134
	Maple/Beech/Birch	3.041	0.306
	Oak/Hickory	3.332	0.191
	Oak/Pine	1.725	0.311
	Spruce/Fir	5.893	0.190
	White/Red/Jack Pine	2.841	0.254
	Nonstocked	2.876	--
PC	California Mixed Conifer	1.000	0.608
	Douglas-fir	1.237	0.559
	Douglas-fir Planted	10.145	0.112
	Fir/Spruce/Mt. Hemlock	4.235	0.415
	Hemlock/Sitka Spruce	1.546	0.562
	Redwood	5.385	0.287
	Nonstocked	7.377	--
SC	Elm/Ash/Cottonwood	2.393	0.284
	Loblolly/Shortleaf Pine	1.203	0.271

	Loblolly/Shortleaf Planted	1.000	0.138
	Oak/Gum/Cypress	4.234	0.121
	Oak/Hickory	2.396	0.186
	Oak/Pine	1.133	0.337
	Nonstocked	0.286	--
SE	Elm/Ash/Cottonwood	1.358	0.476
	Loblolly/Shortleaf Pine	1.000	0.324
	Loblolly/Shortleaf Planted	1.000	0.265
	Oak/Gum/Cypress	1.770	0.329
	Oak/Hickory	2.256	0.257
	Oak/Pine	1.000	0.351
	Nonstocked	0.349	--
South	Longleaf/Slash Pine	1.000	0.184
	Longleaf/Slash Planted	1.000	0.106
West	Alder/Maple	2.190	0.466
	Aspen/Birch	3.062	0.376
	Pinyon/Juniper	3.163	0.100
	Tanoak/Laurel	1.000	0.593
	Western Hardwood/Woodlands	5.595	0.181
	Western Larch	2.049	0.449
	Western Oak	1.996	0.348

[a] Standing dead tree C is based on the equation: mass (Mg/ha) = A* (live-tree growing stock volume)^B. Note that nonstocked stands are assigned a constant C density (the value listed under coefficient A). Note that the standing dead tree equations are for biomass. To convert to C mass, multiply by 0.5.

[b] Regions are PC (CA,OR-West,WA-West), MTN (OR-East,WA-East,ID,MT), MTS (AZ,CO,NM,NV,UT,WY), West (regions PC, MTN, and MTS), NC (IA, IL, IN, KS, MI, MN, MO, ND, NE, SD, WI), NE (CT, DE, MA, MD, ME, NH, NJ, NY, OH, PA, RI, VT, WV), SC (AL, AR, KY, LA, MS, OK, TN, TX), SE (FL, GA, NC, SC, VA), and South (regions SC and SE).

[c] Forest types are described in FIADB documentation (USDA Forest Service, 2010d). Minor forest types within a region that are not explicitly defined/listed in the table of coefficients are assigned to a similar hardwood or softwood forest type.

Table A-221: Ratio for estimating down dead wood by region and forest type. The ratio is multiplied by the live tree carbon density on a plot to produce down dead wood carbon density (MgC/ha)

Region[a]	Forest type[a]	Ratio	Region (cont'd)	Forest type (cont'd)	Ratio (cont'd)
NE	Aspen-Birch	0.078	PWW	Douglas-fir	0.100
	MBB/Other Hardwood	0.071		Fir-Spruce	0.090
	Oak-Hickory	0.068		Other Conifer	0.073
	Oak-Pine	0.061		Other Hardwoods	0.062
	Other Pine	0.065		Red Alder	0.095
	Spruce-Fir	0.092		Western Hemlock	0.099
	White-Red-Jack Pine	0.055		Nonstocked	0.020
	Nonstocked	0.019	RMN	Douglas-fir	0.062
NLS	Aspen-Birch	0.081		Fir-Spruce	0.100
	Lowland Hardwood	0.061		Hardwoods	0.112
	Maple-Beech-Birch	0.076		Lodgepole Pine	0.058
	Oak-Hickory	0.077		Other Conifer	0.060
	Pine	0.072		Pinyon-Juniper	0.030
	Spruce-Fir	0.087		Ponderosa Pine	0.087
	Nonstocked	0.027		Nonstocked	0.018
NPS	Conifer	0.073	RMS	Douglas-fir	0.077
	Lowland Hardwood	0.069		Fir-Spruce	0.079
	Maple-Beech-Birch	0.063		Hardwoods	0.064
	Oak-Hickory	0.068		Lodgepole Pine	0.098
	Oak-Pine	0.069		Other Conifer	0.060
	Nonstocked	0.026		Pinyon-Juniper	0.030
PSW	Douglas-fir	0.091		Ponderosa Pine	0.082
	Fir-Spruce	0.109		Nonstocked	0.020
	Hardwoods	0.042	SC	Bottomland Hardwood	0.063
	Other Conifer	0.100		Misc. Conifer	0.068
	Pinyon-Juniper	0.031		Natural Pine	0.068
	Redwood	0.108		Oak-Pine	0.072
	Nonstocked	0.022		Planted Pine	0.077
PWE	Douglas-fir	0.103		Upland Hardwood	0.067
	Fir-Spruce	0.106		Nonstocked	0.013
	Hardwoods	0.027	SE	Bottomland Hardwood	0.064

Lodgepole Pine	0.093	Misc. Conifer	0.081
Pinyon-Juniper	0.032	Natural Pine	0.081
Ponderosa Pine	0.103	Oak-Pine	0.063
Nonstocked	0.024	Planted Pine	0.075
		Upland Hardwood	0.059
		Nonstocked	0.012

[a] Regions and types as defined in Smith et al. (2003).

Table A-222: Coefficients for estimating logging residue component of down dead wood.

Region[a]	Forest Type Group[b] (softwood/hardwood)	Initial Carbon Density (Mg/ha)	Decay Coefficient
Alaska	hardwood	6.9	12.1
Alaska	softwood	8.6	32.3
NE	hardwood	13.9	12.1
NE	softwood	12.1	17.9
NLS	hardwood	9.1	12.1
NLS	softwood	7.2	17.9
NPS	hardwood	9.6	12.1
NPS	softwood	6.4	17.9
PSW	hardwood	9.8	12.1
PSW	softwood	17.5	32.3
PWE	hardwood	3.3	12.1
PWE	softwood	9.5	32.3
PWW	hardwood	18.1	12.1
PWW	softwood	23.6	32.3
RMN	hardwood	7.2	43.5
RMN	softwood	9.0	18.1
RMS	hardwood	5.1	43.5
RMS	softwood	3.7	18.1
SC	hardwood	4.2	8.9
SC	softwood	5.5	17.9
SE	hardwood	6.4	8.9
SE	softwood	7.3	17.9

[a] Regions are defined in Smith et al. (2003) with the addition of coastal Alaska.
[b] Forest types are according to majority hardwood or softwood species.

Litter carbon

C of the litter layer is currently sampled on a subset of the FIA plots. However, these data are not yet available electronically for general application to all inventories in Table A-1. Litter C is the pool of organic C (including material known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. Estimates therefore continue to be based on equations of Smith and Heath (2002) and applied at the plot level. The equations describe processes for decay or loss of forest floor following harvest and the net accumulation of new forest floor material following stand growth. For example, total forest floor C at a given number of years after a clearcut harvest for aspen-birch forests in the North is:

$$\text{Total forest floor C (Mg C/ha)} = (18.4 \times \text{years})/(53.7 + \text{years}) + 10.2 \times e^{(-\text{years}/9.2)}$$

See Table 4 of Smith and Heath (2002) for the complete set of coefficients. Note that these are direct estimates of C density; the 0.5 conversion does not apply to litter.

Soil organic carbon

Soil organic carbon (SOC) is currently sampled to a 20 cm depth on subsets of FIA plots, however, these data are not available for the entire United States. Thus, estimates of SOC are based on the national STATSGO spatial database (USDA 1991), and the general approach described by Amichev and Galbraith (2004). In their procedure, SOC was calculated for the conterminous United States using the STATSGO database, and data gaps were filled by representative values from similar soils. Links to region and forest type groups were developed with the assistance of the USDA Forest Service FIA Geospatial Service Center by overlaying FIA forest inventory plots on the soil C map. The average SOC densities are provided in Table A-216.

Carbon in Harvested Wood Products

Estimates of the harvested wood product (HWP) contribution to forest C sinks and emissions (hereafter called "HWP Contribution") are based on methods described in Skog (2008) using the WOODCARB II model. These methods are based on IPCC (2006) guidance for estimating HWP carbon. The 2006 IPCC Guidelines provide methods that allow Parties to report HWP Contribution using one of several different accounting approaches: production, stock change, and atmospheric flow, as well as a default method. The various approaches are described below. The approaches differ in how HWP Contribution is allocated based on production or consumption as well as what processes (atmospheric fluxes or stock changes) are emphasized.

- **Production approach**: Accounts for the net changes in carbon stocks in forests and in the wood products pool, but attributes both to the producing country.

- **Stock change approach**: Accounts for changes in the product pool within the boundaries of the consuming country.

- **Atmospheric flow approach**: Accounts for net emissions or removals of carbon to and from the atmosphere within national boundaries. C removal due to forest growth is accounted for in the producing country while C emissions to the atmosphere from oxidation of wood products are accounted for in the consuming country.

- **Default approach**: Assumes no change in C stocks in HWP. IPCC (2006) requests that such an assumption be justified if this is how a Party is choosing to report.

The United States uses the production accounting approach (as in previous years) to report HWP Contribution (Table A-223). Though reported U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches—the stock change and atmospheric flow approaches—are also presented for comparison (see Table A-224). Annual estimates of change are calculated by tracking the additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in solid waste disposal sites (SWDS).

Estimates of five HWP variables that can be used to calculate HWP contribution for the stock change and atmospheric flow approaches for imports and exports are provided in Table A-223. The HWP variables estimated are:

(1A) annual change of C in wood and paper products in use in the United States,

(1B) annual change of C in wood and paper products in SWDS in the United States,

(2A) annual change of C in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,

(2B) annual change of C in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,

(3) C in imports of wood, pulp, and paper to the United States,

(4) C in exports of wood, pulp and paper from the United States, and

(5) C in annual harvest of wood from forests in the United States.

Table A-223: Harvested wood products from wood harvested in United States—Annual additions of carbon to stocks and total stocks

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Net carbon additions per year (Tg C per year)																					
Total Harvested wood carbon	(35.9)	(33.8)	(33.8)	(32.9)	(33.4)	(32.3)	(30.6)	(32.0)	(31.1)	(32.5)	(30.8)	(25.5)	(26.8)	(25.9)	(28.7)	(28.7)	(29.6)	(28.1)	(22.4)	(14.8)	
Products in use	(17.7)	(14.9)	(16.3)	(15.0)	(15.9)	(15.1)	(14.1)	(14.7)	(13.4)	(14.1)	(12.8)	(8.7)	(9.6)	(9.7)	(12.4)	(12.4)	(12.3)	(10.7)	(5.2)	1.9	
Solid wood products	(14.4)	(11.9)	(12.6)	(12.2)	(12.1)	(11.2)	(11.5)	(11.8)	(11.4)	(12.1)	(11.9)	(10.1)	(10.7)	(10.1)	(11.6)	(11.9)	(10.6)	(8.7)	(4.4)	0.6	
Paper products	(3.3)	(3.1)	(3.7)	(2.8)	(3.8)	(3.8)	(2.6)	(3.0)	(2.0)	(2.0)	(1.0)	1.4	1.1	0.4	(0.8)	(0.5)	(1.7)	(2.0)	(0.8)	1.3	
Products in SWDS	(18.3)	(18.8)	(17.4)	(17.9)	(17.5)	(17.2)	(16.5)	(17.3)	(17.7)	(18.4)	(18.0)	(16.8)	(17.2)	(16.2)	(16.3)	(16.3)	(17.3)	(17.4)	(17.2)	(16.7)	
Solid wood products	(9.9)	(11.1)	(9.5)	(9.7)	(9.8)	(10.7)	(10.6)	(10.3)	(10.2)	(10.6)	(10.7)	(10.7)	(11.1)	(11.1)	(11.3)	(11.5)	(11.6)	(11.7)	(11.5)	(11.2)	
Paper products	(8.3)	(7.7)	(7.9)	(8.3)	(7.7)	(6.5)	(6.0)	(6.9)	(7.5)	(7.8)	(7.3)	(6.0)	(6.1)	(5.1)	(5.0)	(4.8)	(5.7)	(5.7)	(5.7)	(5.4)	
Total Carbon stocks (Tg C)																					
Total Harvested wood carbon	1,859	1,895	1,929	1,963	1,996	2,029	2,061	2,092	2,124	2,155	2,187	2,218	2,244	2,271	2,296	2,325	2,354	2,383	2,412	2,434	2,449
Products in use	1,231	1,249	1,264	1,280	1,295	1,311	1,326	1,340	1,355	1,368	1,382	1,395	1,404	1,413	1,423	1,436	1,448	1,460	1,471	1,476	1,474
Products in SWDS	628	646	665	683	701	718	735	752	769	787	805	823	840	857	873	890	906	923	941	958	974

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Table A-224: Comparison of Net Annual Change in Harvested Wood Products Carbon Stocks Using Alternative Accounting Approaches

	HWP Contribution to LULUCF Emissions/ removals (Tg CO_2 Eq.)		
Inventory Year	Stock Change Approach	Atmospheric Flow Approach	Production Approach
1990	(129.6)	(138.4)	(131.8)
1991	(116.3)	(131.4)	(123.8)
1992	(120.0)	(131.6)	(123.8)
1993	(126.8)	(127.8)	(120.7)
1994	(130.0)	(129.9)	(122.5)
1995	(126.0)	(128.0)	(118.4)
1996	(122.3)	(122.5)	(112.2)
1997	(131.4)	(127.4)	(117.3)
1998	(139.8)	(122.7)	(114.1)
1999	(149.4)	(127.3)	(119.1)
2000	(143.2)	(120.3)	(112.9)
2001	(128.3)	(100.3)	(93.4)
2002	(135.6)	(103.1)	(98.2)
2003	(134.6)	(99.2)	(94.8)
2004	(163.0)	(109.1)	(105.3)
2005	(161.4)	(109.0)	(105.4)
2006	(138.6)	(114.2)	(108.6)
2007	(115.4)	(112.1)	(103.0)

| 2008 | (78.4) | (94.3) | (82.1) |
| 2009 | (41.9) | (68.3) | (54.3) |

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Table A-225: Harvested Wood Products Sectoral Background Data for LULUCF—United States (production approach)

Inventory year	1A Annual Change in stock of HWP in use from consumption	1B Annual Change in stock of HWP in SWDS from consumption	2A Annual Change in stock of HWP in use produced from domestic harvest	2B Annual Change in stock of HWP in SWDS produced from domestic harvest	3 Annual Imports of wood, and paper products + wood fuel, pulp, recovered paper, roundwood/ chips	4 Annual Exports of wood, and paper products + wood fuel, pulp, recovered paper, roundwood/ chips	5 Annual Domestic Harvest	6 Annual release of carbon to the atmosphere from HWP consumption (from fuelwood & products in use and products in SWDS)	7 Annual release of carbon to the atmosphere from HWP (including firewood) where wood came from domestic harvest (from products in use and products in SWDS)	8 HWP Contribution to AFOLU CO2 emissions/ removals
	$\Delta C_{HWP\ IU\ DC}$	$\Delta C_{HWP\ SWDS\ DC}$	$\Delta C_{HWP\ IU\ DH}$	$\Delta C_{HWP\ SWDS\ DH}$	P_{IM}	P_{EX}	H	$\uparrow C_{HWP\ DC}$	$\uparrow C_{HWP\ DH}$	
									Gg C /yr	Gg CO$_2$ /yr
1990	17,044	18,308	17,659	18,278	12,680	15,078	142,297	104,547	106,359	(131,772)
1991	13,129	18,602	14,940	18,812	11,552	15,667	144,435	108,588	110,682	(123,758)
1992	15,718	17,006	16,334	17,427	12,856	16,032	139,389	103,489	105,627	(123,791)
1993	16,957	17,627	14,971	17,949	14,512	14,788	134,554	99,694	101,633	(120,708)
1994	18,221	17,221	15,930	17,479	15,685	15,665	134,750	99,328	101,342	(122,498)
1995	17,307	17,051	15,065	17,229	16,712	17,266	137,027	102,115	104,733	(118,411)
1996	17,018	16,348	14,092	16,513	16,691	16,733	134,477	101,069	103,872	(112,219)
1997	18,756	17,090	14,740	17,263	17,983	16,877	135,439	100,699	103,436	(117,344)
1998	20,311	17,818	13,376	17,735	19,722	15,057	135,021	101,558	103,911	(114,071)
1999	22,035	18,714	14,123	18,353	21,266	15,245	134,939	100,211	102,464	(119,078)
2000	20,491	18,560	12,828	17,962	22,426	16,185	134,458	101,648	103,667	(112,898)
2001	17,295	17,691	8,711	16,774	22,975	15,336	128,621	101,274	103,136	(93,447)
2002	18,629	18,357	9,570	17,207	24,604	15,744	127,567	99,441	100,791	(98,179)
2003	19,180	17,532	9,676	16,186	25,962	16,303	124,949	97,896	99,086	(94,828)
2004	26,384	18,077	12,429	16,298	31,650	16,948	130,460	100,700	101,733	(105,332)
2005	25,777	18,249	12,394	16,347	31,714	17,423	131,711	101,976	102,971	(105,382)
2006	19,010	18,780	12,308	17,302	25,485	18,836	127,064	95,922	97,454	(108,567)
2007	12,999	18,497	10,673	17,409	21,603	20,670	120,922	90,360	92,840	(102,967)
2008	3,589	17,786	5,203	17,188	16,822	21,156	108,339	82,630	85,948	(82,101)
2009	(5,401)	16,825	(1,857)	16,652	13,281	20,485	95,130	76,501	80,334	(54,250)

Note: $\uparrow C_{HWP\ DC}$ = H + P_{IM} − P_{EX} - $\Delta C_{HWP\ IU\ DC}$ - $\Delta C_{HWP\ SWDS\ DC}$ AND $\uparrow C_{HWP\ DH}$ = H - $\Delta C_{HWP\ IU\ DH}$ - $\Delta C_{HWP\ SWDS\ DH}$. Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Annual estimates of variables 1A, 1B, 2A and 2B were calculated by tracking the additions to and removals from the pool of products held in end uses (e.g., products in uses such as housing or publications) and the pool of products held in SWDS. In the case of variables 2A and 2B, the pools include products exported and held in other countries and the pools in the United States exclude products made from wood harvested in other countries. Solidwood products added to pools include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end uses. There is one product category and one end-use category for paper. Additions to and removals from pools are tracked beginning in 1900, with the exception that additions of softwood lumber to housing begins in 1800. Solidwood and paper product production and trade data are from USDA Forest Service and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich, 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003).

The rate of removals from products in use and the rate of decay of products in SWDS are specified by first order (exponential) decay curves with given half-lives (time at which half of amount placed in use will have been discarded from use). Half-lives for products in use, determined after calibration of the model to meet two criteria, are shown in Table A-226. The first criterion is that the WOODCARB II model estimate of C in houses standing in 2001 needed to match an independent estimate of C in housing based on U.S. Census and USDA Forest Service survey data. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needed to match EPA estimates of discards over the period 1990 to 2000. This calibration strongly influences the estimate of variable 1A, and to a lesser extent variable 2A. The calibration also determines the amounts going to SWDS. In addition ,WOODCARB II landfill decay rates have been validated by making sure that estimates of methane emissions from landfills based on EPA data are reasonable in comparison to methane estimates based on WOODCARB II landfill decay rates.

Decay parameters for products in SWDS are shown in Table A-227. Estimates of 1B and 2B also reflect the change over time in the fraction of products discarded to SWDS (versus burning or recycling) and the fraction of SWDS that are sanitary landfills versus dumps.

Variables 2A and 2B are used to estimate HWP contribution under the production accounting approach. A key assumption for estimating these variables is that products exported from the United States and held in pools in other countries have the same half lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS. Summaries of net fluxes and stocks for harvested wood in products and SWDS are in Table A-213 and Table A-214. The decline in net additions to HWP carbon stocks continued though 2009 from the recent high point in 2006. This is due to sharp declines in U.S. production of solidwood and paper products in 2009 primarily due to the decline in housing construction. The low level of gross additions to solidwood and paper products in use in 2009 was exceeded by discards from uses. The result is a net reduction in the amount of HWP carbon that is held in products in use during 2009. For 2009 additions to landfills still exceeded emissions from landfills and the net additions to landfills have remained relatively stable. Overall, there were net carbon additions to HWP in use and in landfills combined.

Table A-226: Half-life of solidwood and paper products in end uses

Parameter	Value	Units
Half life of wood in single family housing 1920 and before	78.0	Years
Half life of wood in single family housing 1920–1939	78.0	Years
Half life of wood in single family housing 1940–1959	80.0	Years
Half life of wood in single family housing 1960–1979	81.9	Years
Half life of wood in single family housing 1980 +	83.9	Years
Ratio of multifamily half live to single family half life	0.61	
Ratio of repair and alterations half life to single family half life	0.30	
Half life for other solidwood product in end uses	38.0	Years
Half life of paper in end uses	2.54	Years

Source: Skog, K.E. (2008) "Sequestration of carbon in harvested wood products for the United States." *Forest Products Journal* 58:56-72.

Table A-227: Parameters determining decay of wood and paper in SWDS

Parameter	Value	Units
Percentage of wood and paper in dumps that is subject to decay	100%	
Percentage of wood in landfills that is subject to decay	23%	
Percentage of paper in landfills that is subject to decay	56%	
Half life of wood in landfills / dumps (portion subject to decay)	29	Years
Half life of paper in landfills/ dumps (portion subject to decay)	14.5	Years

Source: Skog, K.E. (2008) "Sequestration of carbon in harvested wood products for the United States." *Forest Products Journal* 58:56-72

Uncertainty Analysis

The uncertainty analyses for total net flux of forest C (see uncertainty table in LULUCF chapter) are consistent with the IPCC-recommended Tier 2 methodology (IPCC 2006). Separate analyses are produced for forest ecosystem and HWP flux. The uncertainty estimates are from Monte Carlo simulations of the respective models and input data. Methods generally follow those described in Heath and Smith (2000), Smith and Heath (2000), and Skog et al. (2004). Uncertainties surrounding input data or model processes are quantified as probability distribution functions (PDFs), so that a series of sample values can be randomly selected from the distributions. Model simulations are repeated a large number of times to numerically simulate the effect of the random PDF selections on estimated total C flux. The separate results from the ecosystem and HWP simulations are pooled for total uncertainty (see uncertainty table in LULUCF chapter).

Uncertainty surrounding current net C flux in forest ecosystems is based on the value for 2007 as obtained from the Monte Carlo simulation. C stocks are based on forest condition level (plot-level) calculations, and, therefore, uncertainty analysis starts probabilistic sampling at the plot level. Uncertainty surrounding C density (Mg/ha) is defined for each of six C pools for each inventory plot. Live trees are generally assigned normal PDFs, which are defined according to variability information in Jenkins et al. (2003) and the species and number of trees measured on each FIA plot. Plot-level live tree C estimates from RPA data are based on volume; these PDFs also include an additional level of uncertainty based on their respective regression equations. Similarly, the normally-distributed PDFs for standing dead trees are based on both volume regression and the individual-tree uncertainties related to the Jenkins et al. (2003) based estimates. Definitions of these normal distributions, which centered on expected values, depend on region, type, and specific plot information. Where data gaps—tree or volume—are identified for older inventory data, corresponding averages from later data are applied for live and standing dead tree C densities. Uniform PDFs with a range of ±90 percent of the average are used for these plots.

Distributions for the remaining C pools are triangular or uniform, which partly reflects the lower level of information available about these estimates. Down dead wood, understory, and litter are assigned triangular distributions with the mean at the expected value for each plot and the minimum and mode at 10 percent of the expected value. The use of these PDFs skewed to the right reflects the assumption that a small proportion of plots will have relatively high C densities. Joint sampling of PDFs is specified for two pairs of samples: understory PDF sampling is slightly negatively correlated with live tree PDF sampling, and down dead wood sampling is slightly positively correlated with live tree sampling. This also reflects the structure of the estimates, which are dependent on live tree C. Soil organic C is defined as a uniform PDF at ±50 percent of the mean. Sub-state or state total carbon stocks associated with each survey are the cumulative sum of random samples from the plot-level PDFs, which are then appropriately expanded to population estimates. These expected values for each carbon pool include uncertainty associated with sampling, which is also incorporated in the Monte Carlo simulation. Sampling errors are determined according to methods described for the FIADB (Bechtold and Patterson 2005), are normally distributed, and are assigned a slight positive correlation between successive surveys for Monte Carlo sampling. More recent annual inventories are assigned higher sampling correlation between successive surveys based on the proportion of plot data jointly included in each. Errors for older inventory data are not available, and these surveys are assigned values consistent with those obtained from the FIADB.

Uncertainty about net C flux in HWP is based on Skog et al. (2004) and Skog (2008). Latin hypercube sampling is the basis for the HWP Monte Carlo simulation. Estimates of the HWP variables and HWP Contribution under the production approach are subject to many sources of uncertainty. An estimate of uncertainty is provided that evaluated the effect of uncertainty in 13 sources, including production and trade data and parameters used to make the estimate. Uncertain data and parameters include data on production and trade and factors to convert them to C, the Census-based estimate of C in housing in 2001, the EPA estimate of wood and paper discarded to SWDS for 1990 to 2000, the limits on decay of wood and paper in SWDS, the decay rate (half-life) of wood and paper in SWDS, the proportion of products produced in the United States made with wood harvested in the United States, and the rate of storage of wood and paper C in other countries that came from United States harvest, compared to storage in the United States.

A total of ten thousand samples are drawn from the PDF input to separately determine uncertainties about forest ecosystem and HWP flux before they are combined for a quantitative estimate of total forest carbon uncertainty (see uncertainty table in LULUCF chapter). Again this year, true Monte Carlo sampling is used for the forest ecosystem estimates (in contrast to Latin hypercube sampling, which was used in some previous estimates), and a part of the QA/QC process includes verifying that the PDFs are adequately sampled.

Emissions from fires

CO_2

As stated in other sections, the forest inventory approach implicitly accounts for emissions due to disturbances. Net C stock change is estimated by subtracting consecutive C stock estimates. A disturbance removes C from the forest. The inventory data, on which net C stock estimates are based, already reflects the C loss because only C remaining in the forest is estimated. Estimating the CO_2 emissions from a disturbance such as fire and adding those emissions to the net CO_2 change in forests would result in double-counting the loss from fire because the inventory data already reflect the loss. There is interest, however, in the size of the CO_2 emissions from disturbances such as fire. The IPCC (2003) methodology and IPCC (2006) default combustion factor for wildfire were employed to estimate emissions from forest fires.

The same methodology was used to estimate emissions from both wildfires and prescribed fires occurring in the lower 48 states. Wildfire area statistics are available, but they include non-forest land, such as shrublands and grasslands. It was thus necessary to develop a rudimentary estimate of the percent of area burned in forest by multiplying the reported area burned by a ratio of total forest land area to the total area considered to be under protection from fire. Data on total area of forest land were obtained from FIA (USDA Forest Service 2010b). Data on "total area considered to be under protection from fire" were available at the state level and obtained for the year 1990 from 1984-1990 Wildfire Statistics prepared by the U.S. Forest Service (USDA Forest Service 1992). Data for years 1998, 2002, 2004, and 2006 were obtained from the National Association of State Foresters (NASF 2008, 2007a, 2007b, 2007c). For states where data were available for all four years, the 1990 value was assumed for years 1990 to 1994, values for 1998 were assumed for years 1995 to 1998, values for 2002 were assumed for years 1999 to 2002, values for 2004 were assumed for years 2003 and 2004, and values for 2006 were assumed for years 2005 to 2009. For states where data were available for all years except 2002, 2004 data were assumed for years 1999 to 2004. For states where data were available for all years except 2004, 2006 data were assumed for 2003 through 2008. For years where data were available for all years except 2006, 2004 data were assumed for years 2003 to 2008. Since no 1998 value was available for Alaska, the 1990 value was assumed for years 1990 to 1997, the 2002 value was assumed for years 1998 to 2002, and the 2004 value was assumed for years 2003 and 2005 to 2009. Data for 1990, 1998, and 2006 were available for New Mexico, so the 1990 value was assumed for years 1990-1995, while the 1998 value was assumed for year 1996 through 2001, and 2006 data were assumed for all remaining years. Data for 1990, 1998, and 2002 were available for Illinois, so the 1990 value was assumed for years 1990-1995, while the 1998 value was assumed for years 1995 through 2001, and the 2002 value was assumed for all remaining years. Total forestland area for the lower 48 states was divided by total area considered to be under protection from wildfire for the lower 48 states across the 1990 to 2009 time series to create ratios that were then applied to reported area burned to estimate the area of forestland burned for the lower 48 states. The ratio was applied to area burned from wildland fires and prescribed fires occurring in the lower 48 states. Reported area burned data for prescribed fires was available from 1998 to 2009 from the National Interagency Fire Center (NIFC 2010). Data for the year 1998 was assumed for years 1990 to 1997.

Forest area burned data for Alaska are from the Alaska Department of Natural Resources (Alaska Department of Natural Resources 2008) or the Alaska Interagency Coordination Center (Alaska Interagency Coordination Center 2010). Data are acres of land which experienced fire activity on forest service land. Based on personal communication with USFS, forest areas under the protection of USFS serve as a proxy for coastal areas, which is where the majority of forest fires in Alaska occur (Heath 2008). According to expert judgment, the coastal area of Alaska included in this Inventory is mostly temperate rainforest and, therefore, there is little call for prescribed burns (Smith 2008a). It was, thus, assumed that reported area burned for prescribed fires covers only prescribed fires in the lower 48 states.

The average C density in the lower 48 states for aboveground biomass C, dead wood C, and litter layer is 91 Mg/ha, according to data from FIA. A default value of 0.45 from IPCC (2006) was assumed for the amount of biomass burned by wildfire (combustion factor value). Thus, approximately 41.0 Mg C/ha is estimated to be emitted by wildfire. For Alaska, an average C density of 179 Mg/ha was used based on data from FIA; this translates into 80.6 Mg C/ha emitted. Based on data from the U.S. Forest Service, a value of 30 Mg/ha was used as the average C density for prescribed fires, where the average C density is adjusted to reflect the fuel load included in dead wood and litter only and the thought that prescribed fires only occur in the lower 48 states (Smith 2008a). Thus, prescribed fires are estimated to emit 13.5 Mg C/ha. Estimates for Mg C/ha were multiplied by estimates of forest area burned by year; the resulting estimates are displayed in Table A-228. C estimates were multiplied by 92.8 percent to account for the proportion of carbon emitted as CO_2 and by 3.67 to yield CO_2 units. Total CO_2 emissions for wildfires and prescribed fires in the lower 48 states and wildfires in Alaska in 2009 were estimated to be 127.0 Tg/yr.

Table A-228: Areas (hectares) from wildfire statistics and corresponding estimates of carbon and CO_2 (Tg/yr) emissions for wildfires and prescribed fires in the lower 48 states and wildfires in Alaska[1]

| | Lower 48 States | | | | | | | | Alaska | | | |
| | Wildfires | | | | Prescribed Fires | | | | Wildfires | | | |
Year	Reported area burned[2] (ha)	Forest area burned[3] (ha)	Carbon emitted (Tg/yr)	CO2 emitted (Tg/yr)	Reported area burned[2] (ha)	Forest area burned[3] (ha)	Carbon emitted (Tg/yr)	CO2 emitted (Tg/yr)	Forest area burned[4] (acres)	Forest area burned (ha)	Carbon emitted (Tg/yr)	CO2 emitted (Tg/yr)
1990	579,589	302,372	12	42	355,432	185,429	3	9	8	3	0.0003	0.0009
1991	486,807	254,618	10	35	355,432	185,904	3	9	557	225	0.0182	0.0618
1992	785,892	412,111	17	57	355,432	186,384	3	9	47	19	0.0015	0.0052
1993	438,865	230,704	9	32	355,432	186,845	3	9	110	45	0.0036	0.0122
1994	1,540,987	811,927	33	113	355,432	187,273	3	9	23	9	0.0007	0.0025
1995	727,051	418,819	17	58	355,432	204,747	3	9	7	3	0.0002	0.0008
1996	2,212,309	1,313,377	54	183	355,432	211,008	3	10	103	42	0.0034	0.0115
1997	335,914	199,827	8	28	355,432	211,437	3	10	33	13	0.0011	0.0036
1998	489,246	291,647	12	41	355,432	211,878	3	10	2	1	0.0001	0.0002
1999	1,869,918	1,123,023	46	156	806,780	484,530	7	22	7	3	0.0002	0.0007
2000	2,685,981	1,615,551	66	225	77,789	46,788	1	2	1	1	0.0000	0.0001
2001	1,356,830	817,280	33	114	667,428	402,022	5	18	2,078	841	0.0677	0.2305
2002	2,023,976	1,217,243	50	170	1,086,503	653,436	9	30	28	11	0.0009	0.0031
2003	1,358,986	718,172	29	100	1,147,695	606,513	8	28	17	7	0.0006	0.0019
2004	637,258	342,999	14	48	996,453	536,332	7	25	23	9	0.0008	0.0026
2005	1,629,067	940,471	39	131	934,965	539,761	7	25	353	143	0.0115	0.0392
2006	3,888,011	2,250,696	92	314	1,100,966	637,328	9	29	8	3	0.0003	0.0009
2007	3,512,122	2,038,630	83	284	1,274,383	739,723	10	34	2	1	0.0001	0.0002
2008	2,099,842	1,212,446	50	169	783,068	452,142	6	21	1	0	0.0000	0.0001
2009	1,201,996	711,766	29	99	1,024,306	606,547	8	28	22	9	0.0007	0.0024

[1] Note that these emissions have already been accounted for in the estimates of net annual changes in carbon stocks, which accounts for the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.
[2] National Interagency Fire Center (2010).
[3] Ratios calculated using forest land area estimates from FIA (USDA Forest Service 2010b) and wildland area under protection estimates from USDA Forest Service (1992) and the National Association of State Foresters (2007).
[4] 1990–2007 Alaskan forest fires data are from the Alaska Department of Natural Resources (2008). 2008 data are from Alaska Interagency Coordination Center (2009).

Non-CO$_2$

Emissions of non-CO_2 gases from forest fires were estimated using the default IPCC (2003) methodology, IPCC (2006) emission ratios, and default IPCC (2006) combustion factor for wildfires. Emissions estimates for CH_4 and N_2O are calculated by multiplying the total estimated CO_2 emitted from forest burned by gas-specific emissions ratios and conversion factors. The equations used are:

$$CH_4 \text{ Emissions} = (CO_2 \text{ released}) \times 92.8\% \times (44/12) \times (CH_4 \text{ to } CO_2 \text{ emission ratio})$$

$$N_2O \text{ Emissions} = (CO_2 \text{ released}) \times 92.8\% \times (44/12) \times (N_2O \text{ to } CO_2 \text{ emission ratio})$$

The resulting estimates are presented in Table A-229.

Table A-229: Estimated carbon released and estimates of non-CO_2 emissions (Tg/yr) for U.S. forests[1]

Year	C emitted (Tg/yr)	CH4 emitted (Tg/yr)	N2O (Tg/yr)
1990	14.886	0.152	0.008
1991	12.954	0.132	0.007
1992	19.394	0.198	0.011
1993	11.973	0.122	0.007
1994	35.777	0.365	0.020
1995	19.915	0.203	0.011
1996	56.635	0.577	0.032
1997	11.038	0.113	0.006
1998	14.803	0.151	0.008
1999	52.529	0.535	0.030
2000	66.789	0.681	0.038
2001	38.963	0.397	0.022
2002	58.668	0.598	0.033
2003	37.598	0.383	0.021

2004	21.287	0.217	0.012
2005	45.811	0.467	0.026
2006	100.770	1.027	0.057
2007	93.468	0.953	0.053
2008	55.754	0.568	0.031
2009	37.336	0.381	0.021

[1] Calculated based on C emission estimates in Table A-228 and default factors in IPCC (2003, 2006)

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3.13. Methodology for Estimating Net Changes in Carbon Stocks in Mineral and Organic Soils on Cropland and Grassland

This sub-annex describes the methodologies used to calculate annual carbon (C) stock changes from mineral and organic soils under agricultural management, including *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*. Three types of methodologies were applied: (1) a Tier 3 approach, employing the Century simulation model, (2) Tier 2 methods with country-specific stock change and emission factors; and (3) Tier 2 methods for estimating additional changes in mineral soil C stocks due to sewage sludge additions to soils and enrollment changes in the Conservation Reserve Program (CRP) after 2003.

The Inventory uses a Tier 3 approach to estimate soil C stock changes for the majority of agricultural lands. This approach has several advantages over the IPCC Tier 1 or 2 approaches:

- It utilizes actual weather data at county scales, rather than a broad climate region classification, enabling quantification of inter-annual variability in C fluxes at finer spatial scales;
- The model uses a more detailed characterization of spatially-mapped soil properties that influence soil C dynamics, as opposed to the broad soil taxonomic classifications of the IPCC methodology;
- The simulation approach provides a more detailed representation of management influences and their interactions than are represented by a discrete factor-based approach in the Tier 1 and 2 methods; and
- Soil C changes are estimated on a more continuous basis (monthly) as a function of the interaction of climate, soil, and land management, compared with the linear change between the start and end of the inventory that is used with the Tier 1 and 2 methods.

The Century model was chosen as an appropriate tool for a Tier 3 approach based on several criteria:

- The model was developed in the United States and has been extensively tested and verified for U.S. conditions. In addition, the model has been widely used by researchers and agencies in many other parts of the world for simulating soil C dynamics at local, regional and national scales (e.g., Brazil, Canada, India, Jordan, Kenya, Mexico).
- The model is capable of simulating cropland, grassland, forest, and savanna ecosystems, and land-use transitions between these different land uses. It is, thus, well suited to model land-use change effects.
- The model was designed to simulate all major types of management practices that influence soil C dynamics, with the exception of cultivated organic soils and a few crops that have not been parameterized for Century simulations (e.g., rice, perennial/horticultural crops, and tobacco). For these latter cases, an IPCC Tier 2 method has been used.
- Much of the data needed for the model was obtainable from existing national databases. The exceptions are CRP enrollment after 2003 and sewage sludge amendments to soils, which are not known at a sufficient resolution to use the Tier 3 model. Soil C stock changes associated with these practices are addressed with a Tier 2 method.

Century Model Description

The Century model simulates C (and also N, P, and S) dynamics, soil temperature, and water dynamics for cropland, grassland, forest, and savanna (mixed forest-grassland) systems. For this analysis, only C and N dynamics have been included for several reasons: to simplify the analysis and reduce data requirements, and because P and S interactions are less important as determinants of land-use- and management-induced changes in soil C stocks for U.S. agricultural systems.

The model has four main components: (1) soil organic matter and nutrient dynamics; (2) plant growth processes; (3) water and temperature dynamics; and (4) management practices. The model was designed to work with readily available input data: monthly weather data (e.g., temperature and precipitation); soil physical properties (e.g., soil texture, drainage condition, rooting depth); and information about land use/land cover (e.g., vegetation attributes) and management activities (see below). The model operates on a monthly time step (with weekly time steps used for soil water dynamics).

Dynamics of organic C and N (Figure A-13) are simulated for the surface and subsurface litter pools and the top 20 cm of the soil profile; mineral N dynamics are simulated through the whole soil profile. Organic C and N stocks are represented by two plant litter pools (labelled metabolic and structural) and three soil organic matter (SOM) pools (labelled active, slow, and passive). The metabolic litter pool represents the easily decomposable constituents of plant residues, while the structural litter pool is composed of more recalcitrant, ligno-cellulose plant materials. The three SOM pools represent a gradient in decomposability, from active SOM (representing microbial biomass and associated

metabolites) having a rapid turnover (months to years), to passive SOM (representing highly processed, humified, condensed decomposition products), which is highly recalcitrant, with mean residence times on the order of several hundred years. The slow pool represents decomposition products of intermediate stability, having a mean residence time on the order of decades and is the fraction that tends to change the most in terms of C content in response to changes in land use and management. Soil texture influences turnover rates of the slow and passive pools   The clay and silt-sized mineral fraction of the soil provides physical protection from microbial attack, leading to slower decomposition and greater SOM stabilization in finely textured soils. Soil temperature and moisture, tillage disturbance, aeration, and other factors influence the decomposition and loss of C from the soil organic matter pools.

Figure A-13: Flow diagram of Carbon submodel (A) and Nitrogen submodel (B)

The plant-growth submodel simulates C assimilation through photosynthesis, N uptake, dry matter production, partitioning of C within the crop or forage, senescence, and mortality. The primary function of the growth submodel is to estimate the amount, type, and timing of organic matter inputs to soil and to represent the influence of the plant on soil water, temperature, and N balance. Yield and removal of harvested biomass are also simulated. Separate submodels are designed to simulate herbaceous plants (i.e., agricultural crops and grasses) and woody vegetation (i.e., trees and scrub). Only the herbaceous plant submodel is currently used in the Inventory. Maximum monthly net primary production (NPP) rate (a parameter of crop and forage species/variety, specified in the model input files) is modified by air temperature and available water to estimate a potential monthly NPP, which is then further subject to nutrient limitations in order to estimate actual NPP and biomass allocation.

The soil-water balance submodel calculates water balance components and changes in soil water availability, which influences both plant growth and decomposition/nutrient cycling processes. The moisture content of soils are simulated through a multi-layer profile based on precipitation, snow accumulation and melting, interception, soil and canopy evaporation, transpiration, soil water movement, runoff, and drainage.

The final main component of the model is the management submodel, which includes options for specifying crop type, crop sequence (e.g., rotation), tillage, fertilization, organic matter addition (e.g., manure amendments), harvest (with variable residue removal), drainage, irrigation, burning, and grazing intensity. An input "schedule" file is used to simulate the timing of management activities and temporal trends; schedules can be organized into discrete time blocks to define a repeated sequence of events (e.g., a crop rotation or a frequency of disturbance such as a burning cycle for perennial grassland). Management options can be specified for any month of a year within a scheduling block, where management codes point to operation-specific parameter files (referred to as *.100 files), which contain the information used to simulate management effects within the model process algorithms. User-specified management activities can be defined by adding to or editing the contents of the *.100 files. Additional details of the model formulation are given in Parton et al. (1987, 1988, 1994) and Metherell et al. (1993), and archived copies of the model source code are available.

The model has been tested for application in U.S. agricultural lands and has been shown to capture the general trends in C storage across approximately 870 field plots from 47 experimental sites (Figure A-14). Some biases and imprecision were found in predictions of soil organic C, which is reflected in the uncertainty associated with Century model results as described in Step 2b of this sub-annex. Additional discussion is provided in Ogle et al. (2007, 2010)

Figure A-14: Comparison of Measured Soil Organic C from Experimental Sites to Modeled Soil Organic C Using the Century Model

IPCC Tier 2 Method Description

The IPCC Tier 2 method has been developed to estimate C stock changes and CO_2 fluxes between soils and the atmosphere based on land-use and management activity (IPCC 2003, 2006; Ogle et al. 2003). For mineral soils (i.e., all soil orders from the USDA taxonomic classification except Histosols), the Tier 2 method uses reference C values to establish baseline C stocks that are modified based on agricultural activities using land-use change, tillage, and input factors. The standard IPCC approach was modified to use agricultural SOC stocks as the reference condition, rather than uncultivated soils under native vegetation. This modification was needed because soil measurements under agricultural

management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997). Measurements of soils under native vegetation are uncommon in the major agricultural regions of the United States because most of the area has been converted into cropland. In addition, country-specific factors were derived for land-use change, tillage, and input factors.

Organic soils used for agricultural production are treated in a separate calculation. These soils are made up of deep (greater than 30 cm) layers of organic material that can decompose at a steady rate over several decades following drainage for crop production or grazing (IPCC 2006). The IPCC approach uses an emission factor to estimate annual losses of CO_2 from cultivated organic soils, rather than an explicit stock change approach.

Methodological Steps for Derivation of Soil Organic C Stock Change Estimates

The inventory of soil C stock changes in U.S. agricultural land combines Tier 2 and 3 approaches. A simulation-based Tier 3 approach was used to estimate soil C changes for most agricultural land (approximately 90 percent of total cropland and grassland) comprising the dominant cropping and grazing systems in the United States, for which the model has been well-tested. Estimates for the remaining area, comprising less-common crop systems (e.g., horticultural, vegetable, tobacco, rice), land converted between non-agricultural and agricultural uses, and all agricultural land occurring on drained organic soils, were developed using the Tier 2 approach. Tier 2 methods were also used to estimate additional changes in mineral soil C stocks due to sewage sludge additions to soils, and enrollment changes in the Conservation Reserve Program after 2003. Most of the activity data sources were common to the Tier 2 and Tier 3 approaches, and, hence, they are described in an integrated manner below. Additional activity data required for the methods are described in adjoining sections, followed by the computation steps.

Step 1: Derive Activity Data

Activity data were compiled for the Tier 3 Century biogeochemical model and Tier 2 IPCC methods, including climate data, soil characteristics, and land-use/management activity data. The first step was to obtain land-use/management activity data, and determine the land base for areas under agricultural management. The areas modeled with Century and those estimated with the Tier 2 IPCC method were also subdivided. Finally, additional data, specific to each method, were collected on other key management activities (e.g., tillage management, fertilizer and manure addition rates) and environmental conditions (e.g., climate and soil characteristics).

Step 1a: Determine the Land Base and Classify Management Systems

Land Base—The *National Resources Inventory* (NRI) provided the basis for identifying the U.S. agricultural land base on non-federal lands, and classifying parcels into *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland* (USDA-NRCS 2000). Note that the Inventory does not include estimates of C stock changes for grasslands and a minor amout of croplands on federal lands, even though these areas are part of the managed land base for the United States. C stock changes on federal croplands and grasslands will be further evaluated and included in future inventories. The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the U.S. Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit, typically a 160-acre (64.75 ha) square quarter-section, three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land-use information (Nusser and Goebel 1997). In principle, the expansion factors represent the amount of area with the land use and land use change history that is the same as the point location. It is important to note that the NRI is a sampling of land use, and therefore there is some uncertainty associated with scaling the point data to a region or the country using the expansion factors. In general, those uncertainties decline at larger scales, such as states compared to smaller county units, because of a larger sample size. An extensive amount of soils, land-use, and land management data have been collected through the survey, which occurs every five years (Nusser et al. 1998).[65] Primary sources for data include aerial photography and remote sensing imagery as well as field visits and county office records. The annual NRI data product provides crop data for most years between 1979 and 2003, with the exception of 1983, 1988, and 1993. These years were gap-filled using an automated set of rules so that cropping sequences were filled with the most likely crop type given the historical cropping pattern at each NRI point location. Grassland data were reported on 5-year increments prior to 1998, but it was assumed that the land use was also grassland between the years of data collection (see Easter et al. 2008 for more information).

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[65] In the current Inventory, NRI data only provide land-use and management statistics through 2003, but additional data will be incorporated in the future to extend the time series of land use and management data.

NRI points were included in the land base for the agricultural soil C inventory if they were identified as cropland or grassland[66] between 1990 and 2003 (Table A-230). The most recent national-level data available for NRI were for 2003; and so the designation for 2003 was extended to 2009 in order to provide C stock changes over the entire time series. An additional modification was made to the time series from 2004 to 2009 for *Grassland Remaining Grassland* and *Land Converted to Grassland* associated with the modification of NRI data with the Forest Inventory and Analysis Dataset. Overall, more than 260,000 NRI points were included in the inventory calculations, and the total agricultural land base varied from 370 to 367 million hectares from 1990 through 2009. Each NRI point represents a specific land parcel based upon the weighted expansion factors.

For each year, land parcels were subdivided into *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*. Land parcels under cropping management in a specific year were classified as *Cropland Remaining Cropland* if they had been cropland for at least 20 years. Similarly land parcels under grassland management in a specific year of the inventory were classified as *Grassland Remaining Grassland* if they had been designated as grassland for at least 20 years.[67] Otherwise, land parcels were classified as *Land Converted to Cropland* or *Land Converted to Grassland* based on the most recent use in the inventory time period. Lands are retained in the land-use change categories (i.e., *Land Converted to Cropland* and *Land Converted to Grassland*) for 20 years as recommended by the IPCC guidelines (IPCC 2006).

Table A-230: Total Land Areas for the Agricultural Soil C Inventory, Subdivided by Land Use Categories (Million Hectares)

Category	Land Areas (10^6 ha)									
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Mineral Soils										
Cropland Remaining Cropland	166.38	166.14	165.89	163.32	162.27	161.95	161.61	161.26	158.40	158.67
Land Converted to Cropland	14.01	14.24	14.41	14.23	15.71	15.88	16.24	16.37	17.79	17.43
Grassland Remaining Grassland	176.03	175.67	175.38	172.75	171.52	171.43	171.20	171.12	169.79	169.70
Land Converted to Grassland	10.10	10.23	10.44	9.94	10.51	10.77	10.91	11.27	13.73	13.90
Non-Agricultural Uses[a]	2.46	2.46	2.46	8.08	8.08	8.08	8.08	8.08	8.08	8.08
Organic Soils										
Cropland Remaining Cropland	0.70	0.70	0.70	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Land Converted to Cropland	0.07	0.07	0.07	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Grassland Remaining Grassland	0.50	0.50	0.50	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Land Converted to Grassland	0.04	0.04	0.04	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Non-Agricultural Uses[a]	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Total	**370.32**	**370.10**	**369.93**	**369.66**	**369.43**	**369.45**	**369.40**	**369.44**	**369.13**	**369.12**

Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Mineral Soils										
Cropland Remaining Cropland	158.83	158.87	159.56	160.72	160.72	160.72	160.72	160.72	160.72	160.72
Land Converted to Cropland	17.09	16.83	16.09	14.87	14.87	14.87	14.87	14.87	14.87	14.87
Grassland Remaining Grassland	169.65	169.50	169.97	170.26	170.04	169.78	169.52	169.25	168.99	168.73
Land Converted to Grassland	14.24	14.64	14.28	13.98	13.91	13.83	13.74	13.66	13.58	13.50
Non-Agricultural Uses[a]	8.08	8.08	8.08	8.08	8.08	8.08	8.08	8.08	8.08	8.08
Organic Soils										
Cropland Remaining Cropland	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Land Converted to Cropland	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Grassland Remaining Grassland	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Land Converted to Grassland	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Non-Agricultural Uses[a]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Total	**369.24**	**369.27**	**369.32**	**369.25**	**368.95**	**368.62**	**368.27**	**367.93**	**367.58**	**367.23**

[a] The non-agricultural uses were converted to or from cropland or grassland between 1990 and 2003.

Subdivide Land Base for Tier 2 and 3 Inventory Approaches–The Tier 3 method based on application of the Century model was used to model NRI points on most mineral soils. Parcels of land that were not simulated with Century were allocated to the Tier 2 approach, including (1) land parcels occurring on organic soils; (2) land parcels that included non-agricultural uses such as forest and federal lands in one or more years of the inventory;68 (3) land parcels on mineral

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[66] Includes non-federal lands only, because federal lands are not classified into land uses as part of the NRI survey (i.e, they are only designated as federal lands).

[67] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifcations were based on less than 20 years from 1990 to 2001.

soils that were very gravelly, cobbly, or shaley (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale); or (4) land parcels that were used to produce vegetables, perennial/horticultural crops, tobacco or rice, which was either grown continuously or in rotation with other crops. Century has not been fully tested for non-major crops, horticultural or perennial crops, rice and agricultural use of organic soils. In addition, Century has not been adequately tested for soils with a high gravel, cobble, or shale content, or fully tested for the transitions between agricultural and non-agricultural uses.

Table A-231: Total Land Area Estimated with Tier 2[a] and 3 Inventory Approaches (Million Hectares)

Year	Land Areas (10^6 ha)		
	Tier 2*	Tier 3	Total
1990	47.27	323.05	370.32
1991	47.27	322.83	370.10
1992	47.27	322.66	369.93
1993	47.25	322.41	369.66
1994	47.25	322.17	369.43
1995	47.25	322.19	369.45
1996	47.25	322.14	369.40
1997	47.25	322.19	369.44
1998	47.25	321.88	369.13
1999	47.25	321.87	369.12
2000	47.25	321.98	369.24
2001	47.25	322.01	369.27
2002	47.25	322.07	369.32
2003	47.25	321.99	369.25
2004	47.25	321.70	368.95
2005	47.25	321.36	368.62
2006	47.25	321.02	368.27
2007	47.25	320.67	367.93
2008	47.25	320.32	367.58
2009	47.25	319.98	367.23

[a] Land use data for 1998-2003 are based on the Revised 1997 NRI data product for the Tier 2 method. Consequently, area data estimates in this table are not used for the Tier 2 portion of the Inventory.

Management System Classification—NRI points on mineral soils were classified into specific crop rotations, continuous pasture/rangeland, and other non-agricultural uses for the Tier 2 inventory analysis based on the survey data (Table A-232). NRI points were assigned to IPCC input categories (low, medium, high, and high with organic amendments) according to the classification provided in IPCC (2006). In addition, NRI differentiates between improved and unimproved grassland, where improvements include irrigation and interseeding of legumes. In order to estimate uncertainties, PDFs for the NRI land-use data were constructed as multivariate normal based on the total area estimates for each land-use/management category and associated covariance matrix. Through this approach, dependencies in land use were taken into account resulting from the likelihood that current use is correlated with past use.

For the Tier 3 inventory estimates, the actual cropping and grassland histories were simulated with the Century model so it was not necessary to classify NRI points into management systems. Uncertainty in the areas associated with each management system was determined from the estimated sampling variance from the NRI survey (Nusser and Goebel 1997). See Step 2b for additional discussion.

Table A-232: Total Land Areas by Land-Use and Management System for the Tier 2 Approach (Million Hectares)

Land-Use/Management System	Land Areas (10^6 ha)	
	1990-92 (Tier 2)	1993-2009 (Tier 2)
Cropland Systems	**31.53**	**29.25**
Irrigated Crops	7.27	6.91
Continuous Row Crops	4.12	3.63
Continuous Small Grains	1.25	1.04
Continuous Row Crops and Small Grains	2.30	1.95
Row Crops in Rotation with Hay and/or Pasture	0.30	0.23
Small Grains in Rotation with Hay and/or Pasture	0.06	0.06
Row Crops and Small Grains in Rotation with Hay and/or Pasture	0.03	0.04

[68] Federal land is treated as forest or nominal grassland for purposes of these calculations, although the specific use is not identified in the NRI survey (USDA-NRCS 2000). Future inventories will include C estimation for the disaggregated land use and land use change categories on federal lands.

Vegetable Crops	2.90	3.16
Low Residue Annual Crops (e.g., Tobacco or Cotton)	0.87	1.03
Small Grains with Fallow	2.01	1.31
Row Crops and Small Grains with Fallow	1.72	1.80
Row Crops with Fallow	0.52	0.34
Miscellaneous Crop Rotations	0.54	0.43
Continuous Rice	0.34	0.31
Rice in Rotation with other crops	1.78	1.91
Continuous Perennial or Horticultural Crops	2.57	2.50
Continuous Hay	0.59	0.50
Continuous Hay with Legumes or Irrigation	1.31	1.12
CRP	1.03	0.96
Aquaculture	0.01	0.01
Grassland Systems	**12.02**	**8.68**
Rangeland	5.98	5.16
Continuous Pasture	3.76	2.49
Continuous Pasture with Legumes or Irrigation (i.e., improved)	2.25	1.03
CRP	0.02	0.00
Non-Agricultural Systems	**2.46**	**8.08**
Forest	1.53	3.95
Federal	0.01	0.05
Water	0.11	0.25
Settlements	0.04	2.46
Miscellaneous	0.77	1.36
Total	**46.01**	**46.01**

Organic soils are also categorized into land-use systems based on drainage (IPCC 2006). Undrained soils are treated as having no loss of organic C. Drained soils are subdivided into those used for cultivated cropland, which are assumed to have high drainage and greater losses of C, and those used for managed pasture, which are assumed to have less drainage and smaller losses of C. Overall, the area of organic soils drained for cropland and grassland has remained relatively stable since 1992 (see Table A-233).

Table A-233: Total Land Areas for Drained Organic Soils By Land Management Category and Climate Region (Million Hectares)

	Land Areas (10^6 ha)					
	Cold Temperate		**Warm Temperate**		**Tropical**	
IPCC Land-Use Category for Organic Soils	**1992**	**1997**	**1992**	**1997**	**1992**	**1997**
Undrained	0.07	0.06	0.0020	0.0017	0.12	0.09
Managed Pasture (Low Drainage)	0.42	0.42	0.0136	0.0119	0.07	0.08
Cultivated Cropland (High Drainage)	0.33	0.34	0.0971	0.0974	0.19	0.20
Other Land Uses[a]	0.02	0.01	0.0002	0.0017	0.00	0.02
Total	**0.84**	**0.84**	**0.11**	**0.11**	**0.39**	**0.39**

[a]Urban, water, and miscellaneous non-cropland, which are part of the agricultural land base because these areas were converted from or into agricultural land uses during the 1990s.

Step 1b: Obtain Additional Management Activity Data for the Tier 3 Century Model

Tillage Practices—Tillage practices were estimated for each cropping system based on data compiled by the Conservation Technology Information Center (CTIC 1998). CTIC compiles data on cropland area under five tillage classes by major crop species and year for each county. Because the surveys involve county-level aggregate area, they do not fully characterize tillage practices as they are applied within a management sequence (e.g., crop rotation). This is particularly true for area estimates of cropland under no-till, which include a relatively high proportion of "intermittent" no-till, where no-till in one year may be followed by tillage in a subsequent year. For example, a common practice in maize-soybean rotations is to use tillage in the maize crop while no-till is used for soybean, such that no-till practices are not continuous in time. Estimates of the area under continuous no-till were provided by experts at CTIC to account for intermittent tillage activity and its impact on soil C (Towery 2001).

Tillage practices were grouped into 3 categories: full, reduced, and no-tillage. Full tillage was defined as multiple tillage operations every year, including significant soil inversion (e.g., plowing, deep disking) and low surface residue coverage. This definition corresponds to the intensive tillage and "reduced" tillage systems as defined by CTIC (1998). No-till was defined as not disturbing the soil except through the use of fertilizer and seed drills and where no-till is applied to all crops in the rotation. Reduced tillage made up the remainder of the cultivated area, including mulch tillage and ridge

tillage as defined by CTIC and intermittent no-till. The specific tillage implements and applications used for different crops, rotations, and regions to represent the three tillage classes were derived from the 1995 Cropping Practices Survey by the Economic Research Service (ERS 1997).

Tillage data were further processed to construct probability distribution functions (PDFs) using CTIC tillage data. Transitions between tillage systems were based on observed county-level changes in the frequency distribution of the area under full, reduced, and no-till from the 1980s through 2004. Generally, the fraction of full tillage decreased during this time span, with concomitant increases in reduced till and no-till management. Transitions that were modeled and applied to NRI points occurring within a county were full tillage to reduced and no-till, and reduced tillage to no-till. The remaining amount of cropland was assumed to have no change in tillage (e.g., full tillage remained in full tillage). Transition matrices were constructed from CTIC data to represent tillage changes for three time periods, 1980-1989, 1990-1999, 2000-2009. Areas in each of the three tillage classes—full till (FT), reduced till (RT), no-till (NT)—in 1989 (the first year the CTIC data were available) were used for the first time period, data from 1997 were used for the second time period, and data from 2004 were used for the last time period. Percentage areas of cropland in each county were calculated for each possible transition (e.g., FT→FT, FT→RT, FT→NT, RT→RT, RT→NT) to obtain a probability for each tillage transition at an NRI point. Since continuous NT constituted < 1 percent of total cropland prior to 1990, there were no transitions for NT→FT or NT→NT. Uniform probability distributions were established for each tillage scenario in the county. For example, a particular crop rotation had 80 percent chance of remaining in full tillage over the two decades, a 15 percent chance of a transition from full to reduced tillage and a 5 percent chance of a transition from full to no-till. The uniform distribution was subdivided into three segments with random draws in the Monte Carlo simulation (discussed in Step 2b) leading to full tillage over the entire time period if the value was greater than or equal to 0 and less than 80, a transition from full to reduced till if the random draw was equal to or greater than 80 and less than 95, or a transition from full to no-till if the draw was greater than or equal to 95. See step 2b for additional discussion of the uncertainty analysis.

Mineral Fertilizer Application—Data on nitrogen fertilizer rates were obtained primarily from USDA's Economic Research Service's 1995 Cropping Practices Survey (ERS 1997). In this survey, data on inorganic nitrogen fertilization rates were collected for major crops (corn, cotton, soybeans, potatoes, winter wheat, durum wheat, and other spring wheat) in the key crop producing states. Note that all wheat data were combined into one category and assumed to represent small grains in general. Estimates for sorghum fertilizer rates were derived from corn rates using a ratio of national average corn fertilizer rates to national average sorghum fertilizer rates derived from additional publications (NASS 2004, 1999, 1992; ERS 1988; Grant and Krenz 1985; USDA 1954, 1957, 1966).

The ERS survey parameter "TOT N" (total amount of N applied per acre), with a small number of records deleted as outliers, was used in determining the fraction of crop acres receiving fertilizer and the average fertilizer rates for a region. Mean fertilizer rates and standard deviations for irrigated and rainfed crops were produced for each state at the finest resolution available. State-level data were produced for surveyed states if a minimum of 15 data points existed for each of the two categories (irrigated and rainfed). If a state was not surveyed for a particular crop or if fewer than 15 data points existed for one of the categories, then data at the Farm Production Region level were substituted. If Farm Production Region data were not available, then U.S.-level estimates (all major states surveyed) were used in the simulation for that particular crop in the state lacking sufficient data. Note that standard deviations for fertilizer rates on log scale were used to construct PDFs on a log-normal scale, in order to address uncertainties in application rates (see Step 2b for discussion of uncertainty methods).

Manure Application—County-level manure N addition estimates were obtained from the Natural Resources Conservation Service (Edmonds et al. 2003). Working with the farm-level crop and animal data from the 1997 Census of Agriculture, NRCS has coupled estimates of manure nitrogen produced with estimates of manure nitrogen recoverability by animal waste management system to produce county-level estimates of manure nitrogen applied to cropland and pasture. Edmonds et al. (2003) defined a hierarchy of land use systems to which manure is applied, that included 24 crops, cropland used as pasture, and permanent pasture. They estimated the area amended with manure and manure nitrogen application rates in 1997 for both manure-producing farms and manure-receiving farms within a county, for two scenarios—before implementation of Comprehensive Nutrient Management Plans (baseline) and after implementation. The application rates for the baseline scenario were used in the inventory under the assumption that Comprehensive Nutrient Management Plans have not been fully implemented.

In order to derive estimates of manure application rates over time, the availability of managed manure N for application to soils (which are available annually) was used to adjust the amount of area amended with manure on a county scale (Note: Edmonds et al. (2003) only provide information on application rates for 1997). Specifically, the estimated available managed manure N in another year was divided by the managed manure N available in 1997. The amendment area in a county for 1997 was then multiplied by the ratio to reflect the probability of manure amendments based on the variation in available manure N across time. If more managed manure N was available in a given year for a county

relative to the amount available in 1997 (ratio > 1), it was assumed that there was a higher probability of a manure amendment. In contrast, if less managed manure N was available (ratio < 1), the probability of an amendment declined in comparison to 1997. A detailed description of the derivation of the managed manure N availability data is provided in the Manure Management section (Section 6.2) and Annex (Annex 3.10). Managed manure N availability in the 1980s was based on USDA estimates (Kellogg et al. 2000) after adjusting for relative differences in manure N production between the USDA dataset and estimates derived from the method described in Annex 3.10. Unmanaged manure classified as pasture/range/paddock manure was assumed to have negligible impacts on soil C stocks because of the tradeoff between reduced litterfall C versus C ingested by livestock and deposited on soils in manure.

For Century simulations, the amended areas were averaged for three time periods (1980-1989, 1990-1999, and 2000-2009) similar to the tillage transitions. Rates for manure-producing farms and manure-receiving farms have been area-weighted and combined to produce a manure nitrogen application rate for each crop in a county. Several of the crops in Edmonds et al. (2003) have been area-weighted and combined into broader crop categories. For example, all small grain crops have been combined into one category. In order to address uncertainty, uniform probability distributions were constructed based on the proportion of land receiving manure versus the amount not receiving manure for each crop type and pasture. For example, if the 20 percent of land producing corn in a county was amended with manure, randomly drawing a value equal to or greater than 0 and less than 20 would lead to simulation with a manure amendment, while drawing a value greater than or equal to 20 and less than 100 would lead to no amendment in the simulation (see Step 2b for further discussion of uncertainty methods).

To estimate the C inputs associated with the manure N application rates (from Edmonds et al. 2003), C:N ratios for various manure types (based on animal species and manure management system) were estimated from data in the *Agricultural Waste Management Field Handbook* (USDA 1996) and the *On-Farm Composting Handbook* (NRAES 1992). Weighted county-average C:N ratios for total manure applied were then calculated based on the C:N ratio and the manure N production rate for each manure type reported in the county. Manure C addition rates were then calculated by multiplying the county-average manure C:N ratio by the manure N application rates.

To account for the common practice of reducing inorganic nitrogen fertilizer inputs when manure is added to a cropland soil, a set of crop-specific reduction factors were derived from mineral fertilization data for land amended with manure versus land not amended with manure in the ERS 1995 Cropping Practices Survey (ERS 1997). In the simulations, mineral N fertilization rates were reduced for crops receiving manure nitrogen based on a fraction of the amount of manure nitrogen applied, depending on the crop and whether it was irrigated or a rainfed system. The reduction factors were selected from PDFs with normal densities in order to address uncertainties in this dependence between manure amendments and mineral fertilizer application.

Irrigation—NRI differentiates between irrigated and non-irrigated land but does not provide more detailed information on the type and intensity of irrigation. Hence, irrigation was modeled by assuming that applied water was sufficient to meet full crop demand (i.e., irrigation plus precipitation equaled potential evapotranspiration during the growing season).

Step 1c—Obtain Additional Management Activity Data for Tier 2 IPCC Method

Tillage Practices—PDFs were constructed for the CTIC tillage data, as bivariate normal on a log-ratio scale to reflect negative dependence among tillage classes. This structure ensured that simulated tillage percentages were non-negative and summed to 100 percent. CTIC data do not differentiate between continuous and intermittent use of no-tillage, which is important for estimating SOC storage. Thus, regionally based estimates for continuous no-tillage (defined as 5 or more years of continuous use) were modified based on consultation with CTIC experts, as discussed in Step 1a (downward adjustment of total no-tillage acres reported, Towery 2001).

Manure Amendments—Manure management is also a key practice in agricultural lands, with organic amendments leading to significant increases in SOC storage. USDA provides information on the amount of land amended with manure for 1997 based on manure production data and field-scale surveys detailing application rates that had been collected in the *Census of Agriculture* (Edmonds et al. 2003). Similar to the Century model discussion in Step1b, the amount of land receiving manure was based on the estimates provided by Edmonds et al. (2003), as a proportion of crop and grassland amended with manure within individual climate regions. The resulting proportions were used to re-classify a portion of crop and grassland into a new management category. Specifically, a portion of medium input cropping systems was re-classified as high input, and a portion of the high input systems was re-classified as high input with amendment. In grassland systems, the estimated proportions for land amended with manure were used to re-classify a portion of nominally-managed grassland as improved, and a portion of improved grassland as improved with high input. These classification approaches are consistent with the IPCC inventory methodology (IPCC 2003, 2006). Uncertainties in

the amount of land amended with manure were based on the sample variance at the climate region scale, assuming normal density PDFs (i.e., variance of the climate region estimates, which were derived from county-scale proportions).

Wetland Reserve—Wetlands enrolled in the Conservation Reserve Program have been restored in the Northern Prairie Pothole Region through the Partners for Wildlife Program funded by the U.S. Fish and Wildlife Service. The area of restored wetlands was estimated from contract agreements (Euliss and Gleason 2002). While the contracts provide reasonable estimates of the amount of land restored in the region, they do not provide the information necessary to estimate uncertainty. Consequently, a ±50 percent range was used to construct the PDFs for the uncertainty analysis.

Step 1d—Obtain Management Activity Data to Compute Additional Changes in Soil Organic C Stocks in Mineral Soils Due to Sewage Sludge Applications and CRP Enrollment after 2003

Two additional influences on soil organic C stocks in mineral soils were estimated using a Tier 2 method, including: sewage sludge additions to agricultural soils and changes in enrollment for the Conservation Reserve Program after 2003.

Total sewage sludge generation data for 1988, 1996, and 1998, in dry mass units, were obtained from an EPA report (EPA 1999) and estimates for 2004 were obtained from an independent national biosolids survey (NEBRA 2007). These values were linearly interpolated to estimate values for the intervening years. Sewage sludge generation data are not available for 2005 onwards (Bastian 2007), so the 1990 through 2004 data were linearly extrapolated for the most recent years. The total sludge generation estimates were then converted to units of N by applying an average N content of 3.9 percent (McFarland 2001), and disaggregated into use and disposal practices using historical data in EPA (1993) and NEBRA (2007). The use and disposal practices were agricultural land application, other land application, surface disposal, incineration, landfilling, ocean dumping (ended in 1992), and other disposal. Sewage sludge N was assumed to be applied at the assimilative capacity provided in Kellogg et al. (2000), which is the amount of nutrients taken up by a crop and removed at harvest, representing the recommended application rate for manure amendments. This capacity varies from year to year, because it is based on specific crop yields during the respective year (Kellogg et al. 2000). Total sewage sludge N available for application was divided by the assimilative capacity to estimate the total land area over which sewage sludge had been applied. The resulting estimates were used for the estimation of soil C stock change.

The change in enrollment for the Conservation Reserve Program after 2003 was based on the amount of land under active contracts from 2004 through 2009 relative to 2003 (USDA-FSA 2010).

Step 1e: Obtain Climate and Soils Data

Tier 3 Century Model—Monthly weather data (temperature and precipitation) from the PRISM database (Parameter-elevation Regressions on Independent Slopes Model) (Daly et al. 1994) were used as an input to the Century model simulations for the period 1895 through 2003. PRISM is based on observed weather data from the National Weather Service network database and statistical models for interpolation and orographic corrections. The primary database consists of approximately 4×4 km grid cells. These data were averaged (weighted by area) for each county in the United States, so that counties are the finest spatial scale represented in the Century simulations.

Soil texture and natural drainage capacity (i.e., hydric vs. non-hydric soil characterization) were the main soil variables used as input to the Century model. Other soil characteristics needed in the simulation, such as field capacity and wilting-point water contents, were estimated from soil texture data using pedo-transfer functions available in the model. Soil input data are derived from the NRI database, which contain descriptions for the soil type at each NRI point (used to specify land-use and management time series-see below). The data are based on field measurements collected as part of soil survey and mapping. Soils are classified according to "soil-series," which is the most detailed taxonomic level used for soil mapping in the United States. Surface soil texture and hydric condition were obtained from the soil attribute table in the NRI database. Texture is one of the main controls on soil C turnover and stabilization in the Century model, which uses particle size fractions of sand (50-2,000 μm), silt (2-50 μm), and clay (< 2 μm) as inputs. NRI points were assigned to one of twelve texture classes for the simulations. Hydric condition specifies whether soils are poorly-drained, and hence prone to water-logging, or moderately to well-drained (non-hydric), in their native (pre-cultivation) condition.[69] Poorly drained soils can be subject to anaerobic (lack of oxygen) conditions if water inputs (precipitation and irrigation) exceed water losses from drainage and evapotranspiration. Depending on moisture conditions, hydric soils can range from being fully aerobic to completely anaerobic, varying over the year. Decomposition rates are modified according to a linear

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[69] Artificial drainage (e.g., ditch- or tile-drainage) is simulated as a management variable.

function that varies from 0.3 under completely anaerobic conditions to 1.0 under fully aerobic conditions (default parameters in Century).[70]

IPCC Tier 2 Method—The IPCC inventory methodology for agricultural soils divides climate into eight distinct zones based upon average annual temperature, average annual precipitation, and the length of the dry season (IPCC 2006) (Table A-234). Six of these climate zones occur in the conterminous United States and Hawaii (Eve et al. 2001).

Table A-234: Characteristics of the IPCC Climate Zones that Occur in the United States

Climate Zone	Annual Average Temperature (°C)	Average Annual Precipitation (mm)	Length of Dry Season (months)
Cold Temperate, Dry	< 10	< Potential Evapotranspiration	NA
Cold Temperate, Moist	< 10	≥ Potential Evapotranspiration	NA
Warm Temperate, Dry	10 – 20	< 600	NA
Warm Temperate, Moist	10 – 20	≥ Potential Evapotranspiration	NA
Sub-Tropical, Dry*	> 20	< 1,000	Usually long
Sub-Tropical, Moist (w/short dry season)[a]	> 20	1,000 – 2,000	< 5

[a] The climate characteristics listed in the table for these zones are those that correspond to the tropical dry and tropical moist zones of the IPCC. They have been renamed "sub-tropical" here.

Mean climate (1961-1990) variables from the PRISM data set (Daly et al. 1994) were used to classify climate zones. Mean annual precipitation and annual temperature data were averaged (weighted by area) for each of the 4×4 km grid cells occurring within a MLRA region. These averages were used to assign a climate zone to each MLRA according to the IPCC climate classification (Figure A-15). MLRAs represent geographic units with relatively similar soils, climate, water resources, and land uses; and there are approximately 180 MLRAs in the United States (NRCS 1981).

Figure A-15: Major Land Resource Areas by IPCC Climate Zone

Soils were classified into one of seven classes based upon texture, morphology, and ability to store organic matter (IPCC 2006). Six of the categories are mineral types and one is organic (i.e., Histosol). Reference C stocks, representing estimates from conventionally managed cropland, were computed for each of the mineral soil types across the various climate zones, based on pedon (i.e., soil) data from the National Soil Survey Characterization Database (NRCS 1997) (Table A-235). These stocks are used in conjunction with management factors to compute the change in SOC stocks that result from management and land-use activity. PDFs, which represent the variability in the stock estimates, were constructed as normal densities based on the mean and variance from the pedon data. Pedon locations were clumped in various parts of the country, which reduces the statistical independence of individual pedon estimates. To account for this lack of independence, samples from each climate by soil zone were tested for spatial autocorrelation using the Moran's I test, and variance terms were inflated by 10 percent for all zones with significant p-values.

Table A-235: U.S. Soil Groupings Based on the IPCC Categories and Dominant Taxonomic Soil, and Reference Carbon Stocks (Metric Tons C/ha)

IPCC Inventory Soil Categories	USDA Taxonomic Soil Orders	Reference Carbon Stock in Climate Regions					
		Cold Temperate, Dry	Cold Temperate, Moist	Warm Temperate, Dry	Warm Temperate, Moist	Sub-Tropical, Dry	Sub-Tropical, Moist
High Clay Activity Mineral Soils	Vertisols, Mollisols, Inceptisols, Aridisols, and high base status Alfisols	42 (n = 133)	65 (n = 526)	37 (n = 203)	51 (n = 424)	42 (n = 26)	57 (n = 12)
Low Clay Activity Mineral Soils	Ultisols, Oxisols, acidic Alfisols, and many Entisols	45 (n = 37)	52 (n = 113)	25 (n = 86)	40 (n = 300)	39 (n = 13)	47 (n = 7)
Sandy Soils	Any soils with greater than 70 percent sand and less than 8 percent clay (often Entisols)	24 (n = 5)	40 (n = 43)	16 (n = 19)	30 (n = 102)	33 (n = 186)	50 (n = 18)
Volcanic Soils	Andisols	124 (n = 12)	114 (n = 2)	124 (n = 12)	124 (n = 12)	124 (n = 12)	128 (n = 9)
Spodic Soils	Spodosols	86 (n=20)	74 (n = 13)	86 (n=20)	107 (n = 7)	86 (n=20)	86 (n=20)
Aquic Soils	Soils with Aquic suborder	86 (n = 4)	89 (n = 161)	48 (n = 26)	51 (n = 300)	63 (n = 503)	48 (n = 12)

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[70] Hydric soils are primarily subject to anaerobic conditions outside the plant growing season (i.e., in the absence of active plant water uptake). Soils that are water-logged during much of the year are typically classified as organic soils (e.g., peat), which are not simulated with the Century model.

| Organic Soils[a] | Histosols | NA | NA | NA | NA | NA | NA |

[a] C stocks are not needed for organic soils.

Notes: C stocks are for the top 30 cm of the soil profile, and were estimated from pedon data available in the National Soil Survey Characterization database (NRCS 1997); sample size provided in parentheses (i.e., 'n' values refer to sample size).

Step 2: Estimate Organic C Stock Changes for Agricultural Lands on Mineral Soils Simulated with the Tier 3 Century Model

This methodology description is divided into two sub-steps. First, the model was used to establish the initial conditions and C stocks for 1979, which was the last year before the NRI survey was initiated. In the second sub-step, Century was used to estimate changes in soil organic C stocks based on the land-use and management histories recorded in the NRI (USDA-NRCS 2000), including the reporting period starting in 1990.

Step 2a: Simulate Initial Conditions (Pre-NRI Conditions)

Century model initialization involves two steps, with the goal of estimating the most accurate stock for the pre-NRI history, and the distribution of organic C among the pools represented in the model (e.g., Structural, Metabolic, Active, Slow, Passive). Each pool has a different turnover rate (representing the heterogeneous nature of soil organic matter), and the amount of C in each pool at any point in time influences the forward trajectory of the total soil organic C storage. There is currently no national set of soil C measurements that can be used for establishing initial conditions in the model. Sensitivity analysis of the Century model showed that the rate of change of soil organic matter is relatively insensitive to the *amount* of total soil organic C but is highly sensitive to the relative *distribution* of C among different pools (Parton et al. 1987). By simulating the historical land use prior to the inventory period, initial pool distributions are estimated in an unbiased way.

The first step involves running the model to a steady-state condition (e.g., equilibrium) under native vegetation, with long-term mean climate based on 30-yr averages of the PRISM data (1960-1990), and the soil physical attributes for the NRI points. Native vegetation is represented at the MLRA level for pre-settlement time periods in the United States. The model was run for 7,000 years to represent a pre-settlement era and achieve a steady-state condition.

The second step is to run the model for the period of time from settlement to the beginning of the NRI survey, representing the influence of historic land-use change and management, particularly the conversion of native vegetation to agricultural uses. This encompasses a varying time period from land conversion (depending on historical settlement patterns) to 1979. The information on historical cropping practices used for Century simulations was gathered from a variety of sources, ranging from the historical accounts of farming practices reported in the literature (e.g., Miner 1998) to national level databases (e.g., NASS 2004). A detailed description of the data sources and assumptions used in constructing the base history scenarios of agricultural practices can be found in Williams and Paustian (2005).

Step 2b—Estimate Soil Organic C Stock Changes and Uncertainties

After estimating model initialization, the model is used to simulate the NRI land use and management histories from 1979 through 2003.[71] The simulation system incorporates a dedicated MySQL database server and a 24-node parallel processing computer cluster. Input/output operations are managed by a set of run executive programs written in PERL. The assessment framework for this analysis is illustrated in Figure A-16.

Figure A-16: Uncertainty in Data Inputs

Evaluating uncertainty was an integral part of the analysis, and included three components: (1) uncertainty in the main activity data inputs affecting soil C balance (input uncertainty); (2) uncertainty in the model formulation and parameterization (structural uncertainty); and (3) uncertainty in the land-use and management system areas (scaling uncertainty) (Ogle et al. 2010). For component 1, input uncertainty was evaluated for fertilization management, manure applications, and tillage, which are the primary management activity data that were supplemental to the NRI observations and have significant influence on soil C dynamics. As described in Step 1b, PDFs were derived from surveys at the county scale in most cases. To represent uncertainty in these inputs, a Monte-Carlo Analysis was used with 100 iterations for each NRI cluster-point in which random draws were made from PDFs for fertilizer, manure application, and tillage.

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[71] The estimated soil C stock change in 2003 is currently assumed to represent the changes between 2004 and 2009. New estimates will be available in the future to extend the time series of land use and management data.

As described above, an adjustment factor was also selected from PDFs with normal densities to represent the dependence between manure amendments and N fertilizer application rates. The total number of Century simulations was over 12 million for the Monte Carlo Analysis with 100 iterations.

The second component dealt with uncertainty inherent in model formulation and parameterization. An empirically-based procedure was employed to develop a structural uncertainty estimator from the relationship between modeled results and field measurements from agricultural experiments (Ogle et al. 2007). The Century model was initialized for 45 long-term field experiments with over 800 treatments in which soil C was measured under a variety of management conditions (e.g., variation in crop rotation, tillage, fertilization rates, manure amendments). These studies were obtained from an extensive search of published studies. All studies located in North America that met minimum criteria of having sufficient site-level information and experimental designs were used, including C stock estimates, texture data, experimental designs with control plots, and land-use and management records for the experimental time period and pre-experiment condition. The inputs to the model were essentially known in the simulations for the long-term experiments, and, therefore, the analysis was designed to evaluate uncertainties associated with the model structure (i.e., model algorithms and parameterization).

The relationship between modeled soil C stocks and field measurements was statistically analyzed using linear-mixed effect modeling techniques. Additional fixed effects were included in the mixed effect model if they explained significant variation in the relationship between modeled and measured stocks (i.e., if they met an alpha level of 0.05 for significance). Several variables were tested including: land-use class; type of tillage; cropping system; geographic location; climate; soil texture; time since the management change; original land cover (i.e., forest or grassland); grain harvest as predicted by the model compared to the experimental values; and variation in fertilizer and residue management. The final model included variables for organic matter amendments, fertilizer rates, inclusion of hay/pasture in cropping rotations, use of no-till, and inclusion of bare fallow in the rotation, which were significant at an alpha level of 0.05. These fixed effects were used to make an adjustment to modeled values due to biases that were creating significant mismatches between the modeled and measured stock values. Random effects captured the statistical dependence (i.e., the data are not fully independent) in time series and data collected from the same long-term experimental site. Accounting for this statistical dependency is needed to estimate appropriate standard deviations for parameter coefficients.

A Monte Carlo approach was used to apply the uncertainty estimator (Ogle et al. 2010). Parameter values for the statistical equation (i.e., fixed effects) were selected from their joint probability distribution, as well as random error associated with fine-scale estimates at NRI points, and the residual or unexplained error associated with the linear mixed-effect model. The stock estimate and associated management information was then used as input into the equation, and adjusted stock values were computed for each C stock estimate produced in the evaluation of input uncertainty for *Cropland Remaining Cropland* (Component 1 of the uncertainty analysis). Note that the uncertainty estimator needs further development for application to *Grassland Remaining Grassland* and the land-use change categories. This development is a planned improvement for the soil C inventory. The variance of the adjusted C stock estimates were computed from the 100 simulated values from the Monte Carlo analysis.

The third element was the uncertainty associated with scaling the Century results for each NRI point to the entire land base, using the expansion factors provided with the NRI database. The expansion factors represent the number of hectares associated with the land-use and management history for a particular point. This uncertainty was determined by computing the variances of the expanded estimates, accounting for the two-stage sampling design of the NRI.

For the land base that was simulated with the Century model, soil organic C stocks ranged from losses of 4.25 Tg CO_2 Eq. to gains of 68.05 Tg CO_2 Eq. annually, depending on the land-use/land-use change category and inventory time period. Estimates and uncertainties are provided in Table A-236.

Table A-236: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Land Base Simulated with the Tier 3 Century Model-Based Approach (Tg CO_2 Eq.)

Year	Cropland Remaining Cropland Estimate	Cropland Remaining Cropland 95% CI	Land Converted to Cropland Estimate	Land Converted to Cropland 95% CI	Grassland Remaining Grassland Estimate	Grassland Remaining Grassland 95% CI	Land Converted to Grassland Estimate	Land Converted to Grassland 95% CI
1990	(55.19)	(111.72) to 1.33	(4.43)	(5.06) to (3.80)	(55.10)	(57.18) to (53.01)	(15.75)	(18.43) to (13.07)
1991	(57.50)	(90.49) to (24.51)	(4.30)	(4.93) to (3.68)	(28.04)	(29.87) to (26.21)	(15.06)	(17.58) to (12.54)
1992	(68.05)	(99.81) to (36.28)	(4.75)	(5.38) to (4.13)	(9.84)	(10.82) to (8.85)	(13.83)	(16.23) to (11.44)
1993	(64.25)	(95.93) to (32.56)	(8.66)	(9.34) to (7.98)	(1.48)	(3.29) to 0.33	(13.52)	(16.09) to (10.94)
1994	(62.38)	(94.48) to (30.29)	(12.61)	(13.42) to (11.80)	(66.74)	(68.28) to (65.20)	(17.87)	(20.62) to (15.12)
1995	(47.58)	(83.91) to (11.25)	(3.84)	(4.51) to (3.17)	(29.45)	(30.78) to (28.13)	(18.21)	(20.80) to (15.61)

Year								
1996	(54.99)	(83.65) to (26.32)	(4.55)	(5.24) to (3.85)	4.25	3.00 to 5.50	(15.19)	(17.78) to (12.60)
1997	(54.08)	(81.53) to (26.63)	(4.21)	(4.94) to (3.48)	(20.44)	(21.73) to (19.14)	(19.90)	(22.64) to (17.16)
1998	(44.34)	(77.06) to (11.61)	(10.77)	(11.60) to (9.94)	1.46	2.49 to 0.43	(17.33)	(20.33) to (14.33)
1999	(29.72)	(58.21) to (1.23)	(3.30)	(4.02) to (2.59)	(18.92)	(19.78) to (18.06)	(23.95)	(26.64) to (21.26)
2000	(54.83)	(85.86) to (23.80)	(4.41)	(5.15) to (3.67)	(55.15)	(56.04) to (54.26)	(23.11)	(26.26) to (19.97)
2001	(37.57)	(68.05) to (7.08)	(2.53)	(3.24) to (1.83)	(27.34)	(28.17) to (26.51)	(24.03)	(27.01) to (21.05)
2002	(36.14)	(67.43) to (4.85)	(1.97)	(2.68) to (1.25)	(46.81)	(47.62) to (46.00)	(22.72)	(25.70) to (19.73)
2003	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(11.65)	(12.50) to (10.79)	(20.69)	(23.50) to (17.89)
2004	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(11.49)	(12.34) to (10.64)	(20.51)	(23.31) to (17.70)
2005	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(11.32)	(12.17) to (10.47)	(20.31)	(23.11) to (17.50)
2006	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(11.14)	(11.99) to (10.29)	(20.10)	(22.90) to (17.30)
2007	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(10.97)	(11.82) to (10.12)	(19.90)	(22.70) to (17.09)
2008	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(10.79)	(11.65) to (9.94)	(19.69)	(22.49) to (16.89)
2009	(42.32)	(69.67) to (14.98)	(0.84)	(1.54) to (0.13)	(10.62)	(11.47) to (9.77)	(19.48)	(22.29) to (16.68)

Note: Does not include the change in storage resulting from the annual application of sewage sludge, or the additional Conservation Reserve Program enrollment.

Step 3: Estimate C Stock Changes in Agricultural Lands on Mineral Soils Approximated with the Tier 2 Approach, in Addition to CO$_2$ Emissions from Agricultural Lands on Drained Organic Soils

Mineral and organic soil calculations were made for each climate by soil zone across the United States. Mineral stock values were derived for non-major crop rotations and land converted from non-agricultural uses to cropland in 1982, 1992, and 1997 based on the land-use and management activity data in conjunction with appropriate reference C stocks, land-use change, tillage, input, and wetland restoration factors. C losses from organic soils were computed based on 1992 and 1997 land use and management in conjunction with the appropriate C loss rate. Each input to the inventory calculations for the Tier 2 approach had some level of uncertainty that was quantified in PDFs, including the land-use and management activity data, reference C stocks, and management factors. A Monte Carlo Analysis was used to quantify uncertainty in SOC change for the inventory period based on uncertainty in the inputs. Input values were randomly selected from PDFs in an iterative process to estimate SOC change for 50,000 times and produce a 95 percent confidence interval for the inventory results.

Step 3a: Derive Mineral Soil Stock Change and Organic Soil Emission Factors

Stock change factors representative of U.S. conditions were estimated from published studies (Ogle et al. 2003, Ogle et al. 2006). The numerical factors quantify the impact of changing land use and management on SOC storage in mineral soils, including tillage practices, cropping rotation or intensification, and land conversions between cultivated and native conditions (including set-asides in the Conservation Reserve Program), as well as the net loss of SOC from organic soils attributed to agricultural production on drained soils. Studies from the United States and Canada were used in this analysis under the assumption that they would best represent management impacts for the Inventory.

For mineral soils, studies had to report SOC stocks (or information to compute stocks), depth of sampling, and the number of years since a management change to be included in the analysis. The data were analyzed using linear mixed-effect modeling, accounting for both fixed and random effects. Fixed effects included depth, number of years since a management change, climate, and the type of management change (e.g., reduced tillage vs. no-till). For depth increments, the data were not aggregated for the C stock measurements; each depth increment (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) was included as a separate point in the dataset. Similarly, time series data were not aggregated in these datasets. Consequently, random effects were needed to account for the dependence in time series data and the dependence among data points representing different depth increments from the same study. Factors were estimated for the effect of management practices at 20 years for the top 30 cm of the soil (Table A-237). Variance was calculated for each of the U.S. factor values, and used to construct PDFs with a normal density. In the IPCC method, specific factor values are given for improved grassland, high input cropland with organic amendments, and for wetland rice, each of which

influences the C balance of soils. Specifically, higher stocks are associated with increased productivity and C inputs (relative to native grassland) on improved grassland with both medium and high input.[72] Organic amendments in annual cropping systems also increase SOC stocks due to greater C inputs, while high SOC stocks in rice cultivation are associated with reduced decomposition due to periodic flooding. There were insufficient field studies to derive factor values for these systems from the published literature, and, thus, estimates from IPCC (2003) were used under the assumption that they would best approximate the impacts, given the lack of sufficient data to derive U.S.-specific factors. A measure of uncertainty was provided for these factors in IPCC (2003), which was used to construct PDFs.

Table A-237: Soil Organic Carbon Stock Change Factors for the United States and the IPCC Default Values Associated with Management Impacts on Mineral Soils

	IPCC default	U.S. Factor			
		Warm Moist Climate	Warm Dry Climate	Cool Moist Climate	Cool Dry Climate
Land-Use Change Factors					
Cultivated[a]	1	1	1	1	1
General Uncult.[a,b] (n=251)	1.4	1.42±0.06	1.37±0.05	1.24±0.06	1.20±0.06
Set-Aside[a] (n=142)	1.25	1.31±0.06	1.26±0.04	1.14±0.06	1.10±0.05
Improved Grassland Factors[c]					
Medium Input	1.1	1.14±0.06	1.14±0.06	1.14±0.06	1.14±0.06
High Input	Na	1.11±0.04	1.11±0.04	1.11±0.04	1.11±0.04
Wetland Rice Production Factor[c]	1.1	1.1	1.1	1.1	1.1
Tillage Factors					
Conv. Till	1	1	1	1	1
Red. Till (n=93)	1.05	1.08±0.03	1.01±0.03	1.08±0.03	1.01±0.03
No-till (n=212)	1.1	1.13±0.02	1.05±0.03	1.13±0.02	1.05±0.03
Cropland Input Factors					
Low (n=85)	0.9	0.94±0.01	0.94±0.01	0.94±0.01	0.94±0.01
Medium	1	1	1	1	1
High (n=22)	1.1	1.07±0.02	1.07±0.02	1.07±0.02	1.07±0.02
High with amendment[c]	1.2	1.38±0.06	1.34±0.08	1.38±0.06	1.34±0.08

Note: The "n" values refer to sample size.
[a] Factors in the IPCC documentation (IPCC 2006) were converted to represent changes in SOC storage from a cultivated condition rather than a native condition.
[b] Default factor was higher for aquic soils at 1.7. The U.S. analysis showed no significant differences between aquic and non-aquic soils, so a single U.S. factor was estimated for all soil types.
[c] U.S.-specific factors were not estimated for land improvements, rice production, or high input with amendment because of few studies addressing the impact of legume mixtures, irrigation, or manure applications for crop and grassland in the United States, or the impact of wetland rice production in the US. Factors provided in IPCC (2003) were used as the best estimates of these impacts.

Wetland restoration management also influences SOC storage in mineral soils, because restoration leads to higher water tables and inundation of the soil for at least part of the year. A stock change factor was estimated assessing the difference in SOC storage between restored and unrestored wetlands enrolled in the Conservation Reserve Program (Euliss and Gleason 2002), which represents an initial increase of C in the restored soils over the first 10 years (Table A-238). A PDF with a normal density was constructed from these data based on results from a linear regression model. Following the initial increase of C, natural erosion and deposition leads to additional accretion of C in these wetlands. The mass accumulation rate of organic C was estimated using annual sedimentation rates (cm/yr) in combination with percent organic C, and soil bulk density (g/cm^3) (Euliss and Gleason 2002). Procedures for calculation of mass accumulation rate are described in Dean and Gorham (1998); the resulting rate and variance were used to construct a PDF with a normal density (Table A-238).

Table A-238: Factor Estimate for the Initial and Subsequent Increase in Organic Soil C Following Wetland Restoration of Conservation Reserve Program

Variable	Value
Factor (Initial Increase—First 10 Years)	1.22±0.18
Mass Accumulation (After Initial 10 Years)	0.79±0.05 Mg C/ha-yr

Note: Mass accumulation rate represents additional gains in C for mineral soils after the first 10 years (Euliss and Gleason 2002).

In addition, C loss rates were estimated for cultivated organic soils based on subsidence studies in the United States and Canada (Table A-239). PDFs were constructed as normal densities based on the mean C loss rates and associated variances.

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[72] Improved grasslands are identified in the 1997 *National Resources Inventory* as grasslands that were irrigated or seeded with legumes, in addition to those reclassified as improved with manure amendments.

Table A-239: Carbon Loss Rates for Organic Soils Under Agricultural Management in the United States, and IPCC Default Rates (Metric Ton C/ha-yr)

Region	Cropland IPCC	Cropland U.S. Revised	Grassland IPCC	Grassland U.S. Revised
Cold Temperate, Dry & Cold Temperate, Moist	1	11.2±2.5	0.25	2.8±0.5[a]
Warm Temperate, Dry & Warm Temperate, Moist	10	14.0±2.5	2.5	3.5±0.8[a]
Sub-Tropical, Dry & Sub-Tropical, Moist	20	14.0±3.3	5	3.5±0.8[a]

[a] There were not enough data available to estimate a U.S. value for C losses from grassland. Consequently, estimates are 25 percent of the values for cropland, which was an assumption used for the IPCC default organic soil C losses on grassland.

Step 3b: Estimate Annual Changes in Mineral Soil Organic C Stocks and CO_2 Emissions from Organic Soils

In accordance with IPCC methodology, annual changes in mineral soil C were calculated by subtracting the beginning stock from the ending stock and then dividing by 20.[73] For this analysis, the base inventory estimate for 1990 through 1992 is the annual average of 1992 stock minus the 1982 stock. The annual average change between 1993 and 2009 is the difference between the 1997 and 1992 C stocks. Using the Monte Carlo approach, SOC stock change for mineral soils was estimated 50,000 times between 1982 and 1992, and between 1992 and 1997. From the final distribution of 50,000 values, a 95 percent confidence interval was generated based on the simulated values at the 2.5 and 97.5 percentiles in the distribution (Ogle et al. 2003).

For organic soils, annual losses of CO_2 were estimated for 1992 and 1997 by applying the Monte Carlo approach to 1992 and 1997 land-use data in the United States. The results for 1992 were applied to the years 1990 through 1992, and the results for 1997 were applied to the years 1993 through 2009.

Mineral soils for the land base estimated with the Tier 2 approach accumulated about 1.7 to 3.0 Tg CO_2 Eq. annually in *Cropland Remaining Cropland*, while mineral soils in *Land Converted to Cropland* lost C at a rate of about 4.1 to 4.2 Tg CO_2 Eq. annually. Minerals soils in *Grassland Remaining Grassland* had small gains of about 0.2 to 0.3 Tg CO_2 Eq. annually and sequestered from 4.6 to 5.0 Tg CO_2 Eq. annually in *Land Converted to Grassland*. Organic soils lost about 27.4 to 27.7 Tg CO_2 Eq. annually in *Cropland Remaining Cropland* and 2.4 to 2.6 Tg CO_2 Eq. annually in *Land Converted to Cropland*, as well as an additional 3.7 to 3.9 Tg CO_2 Eq. annually in *Grassland Remaining Grassland* (Table A-240) and 0.5 to 0.9 Tg CO_2 Eq. annually in *Land Converted to Grassland*. Estimates and uncertainties are provided in Table A-240.

Table A-240: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Land Base Estimated with the Tier 2 Analysis using U.S. Factor Values, Reference Carbon Stocks, and Carbon Loss Rates (Tg CO_2 Eq./yr)

Year	Cropland Remaining Cropland Estimate	Cropland Remaining Cropland 95% CI	Land Converted to Cropland Estimate	Land Converted to Cropland 95% CI	Grassland Remaining Grassland* Estimate	Grassland Remaining Grassland* 95% CI	Land Converted to Grassland* Estimate	Land Converted to Grassland* 95% CI
Mineral Soils								
1990-1992	(1.65)	(2.6) to 5.8	4.18	2.5 to 6.0	(0.33)	(0.6) to (0.1)	(4.55)	(6.5) to (2.7)
1993-2009	(3.01)	(6.9) to 0.8	4.14	2.5 to 6.0	(0.15)	(0.4) to 0.04	(4.99)	(7.2) to (2.9)
Organic Soils								
1990-1992	27.43	18.3 to 39.4	2.42	1.4 to 3.8	3.85	1.97 to 6.4	0.47	0.22 to 0.8
1993-2009	27.68	18.5 to 39.5	2.64	1.5 to 4.0	3.69	1.9 to 6.1	0.88	0.4 to 1.5

* Preliminary estimates that will be finalized after public review period following completion of quality control measures.

Step 4: Compute Additional Changes in Soil Organic C Stocks Due to Organic Amendments and CRP Enrollment after 2003

There are two additional land-use and management activities in U.S. agricultural lands that were not estimated in Steps 2 and 3. The first activity involved the application of sewage sludge to agricultural lands. Minimal data exist on where and how much sewage sludge is applied to U.S. agricultural soils, but national estimates of mineral soil land area receiving sewage sludge can be approximated based on sewage sludge N production data, and the assumption that amendments are applied at a rate equivalent to the assimilative capacity from Kellogg et al. (2000). It was assumed that sewage sludge for agricultural land application was applied to grassland because of the high heavy metal content and other pollutants found in human waste, which limits its application to crops. The impact of organic amendments on SOC was

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[73] The difference in C stocks is divided by 20 because the stock change factors represent change over a 20-year time period.

calculated as 0.38 metric tonnes C/ha-yr. This rate is based on the IPCC default method and country-specific factors (see Table A- 241), by calculating the effect of converting nominal, medium-input grassland to high input improved grassland (assuming a reference C stock of 50 metric tonnes C/ha, which represents a mid-range value for the dominant cropland soils in the United States, the land use factor for grassland (1.4) and the country-specific factor of 1.11 for high input improved grassland, with the change in stocks occurring over a 20 year (default value) time period; i.e., $[50 \times 1.4 \times 1.11 - 50 \times 1.4] / 20 = 0.38$). From 1990 through 2009, sewage sludge applications in agricultural lands increased SOC storage from 0.6 to 1.3 Tg CO_2 Eq./year (Table A- 241). A nominal ±50 percent uncertainty was attached to these estimates due to limited information on application and the rate of change in soil C stock change with sewage sludge amendments.

The second activity was the change in enrollment for the Conservation Reserve Program after 2003 for mineral soils. Relative to the enrollment in 2003, the total area in the Conservation Reserve Program decreased from 2004 to 2009, leading to a reduction in enrollment of 0.16 million ha over the five-year period (USDA-FSA 2009). An average annual change in SOC of 0.5 metric tonnes C/ha-yr was used to estimate the effect of the enrollment changes. This rate is based on the IPCC default method and country-specific factors (see Table A-237) by calculating the impact of setting aside a medium input cropping system in the Conservation Reserve Program (assuming a reference C stock of 50 metric tonnes C/ha, which represents a mid-range value for the dominant cropland soils in the United States and the average country-specific factor of 1.2 for setting-aside cropland from production, with the change in stocks occurring over a 20 yr (default value) time period; i.e., $[50 \times 1.2 - 50] / 20 = 0.5$). While increases in enrollment from 2004 to 2009 generated additional accumulation of CO_2 Eq. annually, reductions in enrollment in 2009 caused emissions of 0.29 Tg CO_2 Eq (Table A-242). A nominal ±50 percent uncertainty was also attached to these estimates due to limited information about the enrollment trends at subregional scales, which creates uncertainty in the rate of the soil C stock change (stock change factors for set-aside lands vary by climate region).

Step 5: Compute Net CO_2 Emissions and Removals from Agricultural Lands

The sum of total CO_2 emissions and removals from the Tier 3 Century Model Approach (Step 2), Tier 2 IPCC Methods (Step 3) and additional land-use and management considerations (Step 4) are presented in Table A-242. Overall, there was a net accumulation of 99.2 Tg CO_2 Eq. in 1990 for agricultural soils, and this rate had decreased by the end of the reporting period in 2009 to 43.4 Tg CO_2 Eq.

The total stock change (as seen in the Land Use, Land-Use Change, and Forestry chapter) as well as per hectare rate of change varies among the states (Figure A-17 and Figure A-18). On a per hectare basis, the highest rates of C accumulation occurred in the Northeast, Midwest, northern Great Plains, and Northwest. The states with highest total amounts of C sequestration were Iowa, Illinois, Missouri, Montana, Oklahoma, North Dakota, and South Dakota (Table A- 243). For organic soils, emission rates were highest in the regions that contain the majority of the drained organic soils, including California, Florida, Michigan, Minnesota, and New York. On a per hectare basis, the emission rate patterns were very similar to the total emissions in each state, with the highest rates in those regions with warmer climates and a larger proportion of the drained organic soil managed for crop production.

Figure A-17: Net C Stock Change, per Hectare, for Mineral Soils Under Agricultural Management, 2009

Figure A-18: Net C Stock Change, per Hectare, for Organic Soils Under Agricultural Management, 2009

Table A- 241: Assumptions and Calculations to Estimate the Contribution to Soil Organic Carbon Stocks from Application of Sewage Sludge to Mineral Soils

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Sewage Sludge N Applied to Agricultural Land (Mg N)[a]	52,198	55,658	59,250	62,977	65,966	69,001	72,081	75,195	78,353	80,932	83,523	86,124	88,736	91,358	93,991	98,081	100,887	103,682	106,468	109,245
Assimilative Capacity (Mg N/ha)[b]	0.120	0.120	0.120	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122
Area covered by Available Sewage Sludge N (ha)[c]	434,985	463,816	493,746	516,202	540,707	565,583	590,828	616,357	642,240	663,381	684,612	705,932	727,341	748,836	770,418	803,942	826,940	849,851	872,686	895,452
Average Annual Rate of C storage (Mg C/ha-yr)[d]	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Contribution to Soil C (TgCO$_2$/yr)[e,f]	**(0.61)**	**(0.65)**	**(0.69)**	**(0.72)**	**(0.75)**	**(0.79)**	**(0.82)**	**(0.86)**	**(0.89)**	**(0.92)**	**(0.95)**	**(0.98)**	**(1.01)**	**(1.04)**	**(1.07)**	**(1.12)**	**(1.15)**	**(1.18)**	**(1.22)**	**(1.25)**

Values in parentheses indicate net C storage.

[a] N applied to soils described in Step 1d.

[b] Assimilative Capacity is the national average amount of manure-derived N that can be applied on cropland without buildup of nutrients in the soil (Kellogg et al., 2000).

[c] Area covered by sewage sludge N available for application to soils is the available N applied at the assimilative capacity rate. The 1992 assimilative capacity rate was applied to 1990 – 1992 and the 1997 rate was applied to 1993-2009.

[d] Annual rate of C storage based on national average increase in C storage for grazing lands that is attributed to organic matter amendments (0.38 Mg/ha-yr)

[e] Contribution to Soil C is estimated as the product of the area covered by the available sewage sludge N and the average annual C storage attributed to an organic matter amendment.

[f] Some small, undetermined fraction of this applied N is probably not applied to agricultural soils, but instead is applied to forests, home gardens, and other lands.

Table A-242: Annual Soil C Stock Change in *Cropland Remaining Cropland* (CRC), *Land Converted to Cropland* (LCC), *Grassland Remaining Grassland* (GRG), and *Land Converted to Grassland* (LCG), in U.S. Agricultural Soils (Tg CO$_2$ Eq.)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Net emissions based on Tier 3 Century-based analysis (Step 2)																				
CRC	(55.2)	(57.5)	(68.0)	(64.2)	(62.4)	(47.6)	(55.0)	(54.1)	(44.3)	(29.7)	(54.8)	(37.6)	(36.1)	(42.3)	(42.3)	(42.3)	(42.3)	(42.3)	(42.3)	(42.3)
LCC	(4.4)	(4.3)	(4.8)	(8.7)	(12.6)	(3.8)	(4.5)	(4.2)	(10.8)	(3.3)	(4.4)	(2.5)	(2.0)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
GRG	(55.1)	(28.0)	(9.8)	(1.5)	(66.7)	(29.5)	4.2	(20.4)	1.5	(18.9)	(55.2)	(27.3)	(46.8)	(11.7)	(11.5)	(11.3)	(11.1)	(11.0)	(10.8)	(10.6)
LCG	(15.8)	(15.1)	(13.8)	(13.5)	(17.9)	(18.2)	(15.2)	(19.9)	(17.3)	(24.0)	(23.1)	(24.0)	(22.7)	(20.7)	(20.5)	(20.3)	(20.1)	(19.9)	(19.7)	(19.5)
Net emissions based on the IPCC Tier 2 analysis (Step 3)																				
Mineral Soils																				
CRC	(1.6)	(1.6)	(1.6)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)	(3.0)
LCC	4.2	4.2	4.2	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1
GRG	(0.3)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
LCG	(4.5)	(4.5)	(4.5)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)
Organic Soils																				
CRC	27.4	27.4	27.4	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7	27.7
LCC	2.4	2.4	2.4	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
GRG	3.9	3.9	3.9	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
LCG	0.5	0.5	0.5	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Additional changes in net emissions from mineral soils based on application of sewage sludge to agricultural land (Step 4)																				
GRG	(0.6)	(0.6)	(0.7)	(0.7)	(0.8)	(0.8)	(0.8)	(0.9)	(0.9)	(0.9)	(1.0)	(1.0)	(1.0)	(1.0)	(1.1)	(1.1)	(1.2)	(1.2)	(1.2)	(1.3)
Additional changes in net emissions from mineral soils based on additional enrollment of CRP land (Step 4)																				
CRC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(0.4)	(0.6)	(1.4)	(2.0)	(0.4)	0.3
Total Stock Changes by Land Use/Land-Use Change Category (Step 5)																				

CRC	(29.4)	(31.7)	(42.3)	(39.6)	(37.7)	(22.9)	(30.3)	(29.4)	(19.7)	(5.1)	(30.2)	(12.9)	(11.5)	(17.7)	(18.1)	(18.3)	(19.1)	(19.7)	(18.1)	(17.4)
LCC	2.2	2.3	1.8	(1.9)	(5.8)	2.9	2.2	2.6	(4.0)	3.5	2.4	4.2	4.8	5.9	5.9	5.9	5.9	5.9	5.9	5.9
GRG	(52.2)	(25.2)	(7.0)	1.3	(64.0)	(26.7)	7.0	(17.8)	4.1	(16.3)	(52.6)	(24.8)	(44.3)	(9.2)	(9.0)	(8.9)	(8.8)	(8.6)	(8.5)	(8.3)
LCG	(19.8)	(19.1)	(17.9)	(17.6)	(22.0)	(22.3)	(19.3)	(24.0)	(21.4)	(28.0)	(27.2)	(28.1)	(26.8)	(24.8)	(24.6)	(24.4)	(24.2)	(24.0)	(23.8)	(23.6)
Total *	**(99.2)**	**(73.7)**	**(65.3)**	**(57.8)**	**(129.5)**	**(69.0)**	**(40.4)**	**(68.6)**	**(41.0)**	**(46.0)**	**(107.6)**	**(61.6)**	**(77.8)**	**(45.7)**	**(45.8)**	**(45.6)**	**(46.1)**	**(46.3)**	**(44.4)**	**(43.4)**

Table A- 243: Soil C Stock Change for Mineral and Organic Soils during 2009 within individual states (Tg CO₂ Eq.))

State	Mineral Soil	Organic Soil	Total
AL	(0.45)	-	(0.45)
AR	(1.09)	-	(1.09)
AZ	(0.80)	-	(0. 80)
CA	(0.16)	2.29	2.14
CO	(0.54)	0.00	(0.54)
CT	(0.06)	-	(0.06)
DE	0.02	-	0.02
FL	0.26	10.84	11.10
GA	(0.21)	-	(0.21)
HI	(0.02)	0.25	0.24
IA	(4.67)	0.75	(3.92)
ID	(1.53)	0.11	(1.43)
IL	(5.16)	0.54	(4.61)
IN	(1.72)	2.93	1.21
KS	(2.34)	-	(2.34)
KY	(1.90)	-	(1.90)
LA	(0.93)	0.07	(0.86)
MA	(0.02)	0.03	0.01
MD	(0.19)	0.03	(0.16)
ME	(0.17)	-	(0.17)
MI	(2.28)	2.72	0.43
MN	(2.57)	7.30	4.73
MO	(9.54)	-	(9.54)
MS	(1.19)	0.00	(1.18)
MT	(6.10)	0.11	(5.99)
NC	(0.35)	2.25	1.90
ND	(6.03)	-	(6.03)
NE	(2.03)	-	(2.03)
NH	(0.04)	0.01	(0.03)
NJ	(0.09)	0.01	(0.08)
NM	(1.18)	-	(1.18)
NV	(0.23)	0.00	(0.23)
NY	(1.83)	0.61	(1.23)
OH	(2.91)	0.42	(2.49)
OK	(6.48)	-	(6.48)
OR	(2.13)	0.12	(2.00)
PA	(1.85)	0.01	(1.84)
RI	(0.01)	0.00	(0.00)
SC	0.05	0.04	0.09
SD	(5.86)	-	(5.86)
TN	(1.85)	-	(1.85)
TX	5.46	-	5.46
UT	(0.02)	-	(0.02)
VA	(0.50)	0.02	(0.48)
VT	(0.28)	0.00	(0.27)
WA	(2.19)	0.26	(1.93)
WI	(2.48)	2.88	0.41
WV	(0.41)	-	(0.41)
WY	0.17	0.01	0.18

Note: Parentheses indicate net C accumulation. Estimates do not include soil C stock change associated with CRP enrollment after 2003 or sewage sludge application to soils, which were only estimated at the national scale. The sum of state results will not match the national results because state results are generated in a separate programming package, the sewage sludge and CRP enrollment after 2003 are not included, and differences arise due to rounding of values in this table.

3.14. Methodology for Estimating CH_4 Emissions from Landfills

Landfill gas is a mixture of substances generated when bacteria decompose the organic materials contained in solid waste. By volume, landfill gas is about half CH_4 and half CO_2.[74] The amount and rate of CH_4 generation depends upon the quantity and composition of the landfilled material, as well as the surrounding landfill environment.

Not all CH_4 generated within a landfill is emitted to the atmosphere. The CH_4 can be extracted and either flared or utilized for energy, thus oxidizing to CO_2 during combustion. Of the remaining CH_4, a portion oxidizes to CO_2 as it travels through the top layer of the landfill cover. 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.[75]To estimate the amount of CH_4 produced in a landfill in a given year, information is needed on the type and quantity of waste in the landfill, as well as the landfill characteristics (e.g., size, aridity, waste density). This information is not available for the majority landfills in the United States. Consequently, to estimate CH_4 generation, a methodology was developed based on the quantity of waste placed in landfills nationwide each year, the first order decay model, and model parameters from the analysis of measured CH_4 generation rates for U.S. landfills with gas recovery systems.

From various studies and surveys of the generation and disposal of solid waste, estimates of the amount of waste placed in MSW and industrial landfills were developed. A database of measured CH_4 generation rates at landfills with gas recovery systems was compiled and analyzed. The results of this analysis and other studies were used to develop an estimate of the CH_4 generation potential for use in the first order decay model. In addition, the analysis and other studies provided estimates of the CH_4 generation rate constant as a function of precipitation. The first order decay model was applied to annual waste disposal estimates for each year and for three ranges of precipitation to estimate CH_4 generation rates nationwide for the years of interest. Based on the organic content of industrial wastes and the estimates of the fraction of these wastes sent to industrial landfills, CH_4 emissions from industrial landfills were also estimated using the first order decay model. Total CH_4 emissions were estimated by adding the CH_4 from MSW and industrial landfills and subtracting the amounts recovered for energy or flaring and the amount oxidized in the soil. The steps taken to estimate CH_4 emissions from U.S. landfills for the years 1990 through 2009 are discussed in greater detail below.

Figure A-19 presents the CH_4 emissions process—from waste generation to emissions—in graphical format.

Step 1: Estimate Annual Quantities of Solid Waste Placed in Landfills

For 1989 to 2009, estimates of the annual quantity of waste placed in MSW landfills were developed from a survey of State agencies as reported in BioCycle's State of Garbage in America (BioCycle 2008), adjusted to include U.S. territories.[76] The BioCycle survey is the only continually updated nationwide survey of waste disposed in landfills in the United States.

Table A-244 shows estimates of waste quantities contributing to CH_4 emissions. The table shows BioCycle estimates of total waste landfilled each year from 1990 through 2000, 2002, 2004, and 2006 adjusted for U.S. territories. A linear interpolation was used for 2001, 2003, 2005, 2007, 2008, and 2009 because there are no BioCycle surveys for those years. The next BioCycle survey will be published in 2011 representing 2008 data, at which time, the waste landfilled for 2007, 2008, and 2009 will be updated.

Figure A-19: Methane Emissions Resulting from Landfilling Municipal and Industrial Waste

Table A-244: Solid Waste in MSW Landfills Contributing to CH_4 Emissions (Tg unless otherwise noted)

Description	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Waste Generated[a]	271	302	377	416	455	462	470	459	448	452	456	460
Percent of Wastes Landfilled[a]	77%	63%	61%	63%	66%	65%	64%	64%	65%	65%	65%	65%

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[74] Typically, landfill gas also contains small amounts of nitrogen, oxygen, and hydrogen, less than 1 percent nonmethane volatile organic compounds (NMVOCs), and trace amounts of inorganic compounds.

[75] See Box 8-1 "Biogenic Emissions and Sinks of Carbon" in the Waste chapter for additional background on how biogenic emissions of landfill CO_2 are addressed in the U.S. Inventory.

[76] Since the BioCycle survey does not include U.S. territories, waste landfilled in U.S. territories was estimated using population data for the U.S territories (U.S. Census Bureau 2010) and the per capita rate for waste landfilled from BioCycle (2008).

Total Wastes Landfilled[a]	209		190			230	263	298	300	301	285	289	291	294	297
Waste in Place (30 years)[b]	4,674		5,075			5,400	5,488	5,608	5,759	5,909	6,058	6,198	6,328	6,458	6,587
Waste Contributing to Emissions[c]	6,815		7,796			8,828	9,092	9,390	9,690	9,991	10,286	10,574	10,866	11,160	11,457

[a] Source: *BioCycle* (2008), adjusted for missing U.S. territories using U.S. Census Bureau (2010) population data and per capita disposal rate from *BioCycle*. The data, originally reported in short tons, are converted to metric tons. Estimates shown for 2001 and 2003 are based on an interpolation because there were no surveys in 2001 and 2003; estimates shown for 2005, 2007, 2008, and 2009 based on the increase in population.
[b] This estimate represents the waste that has been in place for 30 years or less, which contributes about 90 percent of the CH_4 generation. Values are based on EPA (1993).
[c] This estimate represents the cumulative amount of waste that has been placed in landfills from 1940 to the year indicated and is the sum of the annual disposal rates used in the first order decay model. Values are based on EPA (1993).

Estimates of the annual quantity of waste placed in landfills from 1960 through 1988 were developed from EPA's 1993 Report to Congress (EPA 1993) and a 1986 survey of MSW landfills (EPA 1988). Based on the national survey and estimates of the growth of commercial, residential and other wastes, the annual quantity of waste placed in landfills averaged 127 million metric tons in the 1960s, 154 million metric tons in the 1970s, 190 million metric tons in the 1990s, and 285 million metric tons in the 2000's. Estimates of waste placed in landfills in the 1940s and 1950s were developed based on U.S. population for each year and the per capital disposal rates from the 1960s.

Step 2: Estimate CH_4 Generation at Municipal Solid Waste Landfills

The CH_4 generation was estimated from the integrated form of the first order decay (FOD) model using the procedures and spreadsheets from IPCC (2006) for estimating CH_4 emissions from solid waste disposal. The form of the FOD model that was applied incorporates a time delay of 6 months after waste disposal before the generation of CH_4 begins.

The input parameters needed for the FOD model equations are the mass of waste disposed each year, which was discussed in the previous section, degradable organic carbon (DOC), and the decay rate constant (k). The DOC is determined from the CH_4 generation potential (L_0 in m^3 CH_4/Mg waste), which is discussed in more detail in subsequent paragraphs, and the following equation:

$$DOC = [L_0 \times 6.74 \times 10^{-4}] \div [F \times 16/12 \times DOC_f \times MCF]$$

Where,
DOC	=	degradable organic carbon (fraction, Gg C/Gg waste),
L_0	=	CH_4 generation potential (m^3 CH_4/Mg waste),
6.74×10^{-4}	=	CH_4 density (Mg/m^3),
F	=	fraction of CH_4 by volume in generated landfill gas (equal to 0.5)
16/12	=	molecular weight ratio CH_4/C,
DOC_f	=	fraction of DOC that can decompose in the anaerobic conditions in the landfill (fraction equal to 0.5 for MSW), and
MCF	=	methane correction factor for year of disposal (fraction equal to 1 for anaerobic managed sites).

The DOC value used in the CH_4 generation estimates from MSW landfills is 0.203 based on the CH_4 generation potential of 100 m^3 CH_4/Mg waste as described below. Data from a set of 52 representative landfills across the U.S. in different precipitation ranges were chosen to evaluate L_0, and ultimately the country-specific DOC value. The 2004 Chartwell Municipal Solid Waste Facility Directory confirmed that each of the 52 landfills chosen accepted or accepts both MSW and construction and demolition (C&D) waste (Chartwell 2004; RTI 2009).

The methane generation potential (L_0) varies with the amount of organic content of the waste material. A higher L_0 occurs with a higher content of organic waste. Waste composition data is not collected for all landfills nationwide; thus a default value must be used. Values for L_0 were evaluated from landfill gas recovery data for this set of 52 landfills, which resulted in a best fit value for L_0 of 99 m^3/Mg of waste (RTI 2004). This value compares favorably with a range of 50 to 162 (midrange of 106) m^3/Mg presented by Peer, Thorneloe, and Epperson (1993); a range of 87 to 91 m^3/Mg from a detailed analysis of 18 landfills sponsored by the Solid Waste Association of North America (SWANA 1998); and a value of 100 m^3/Mg recommended in EPA's compilation of emission factors (EPA 1998; EPA 2008) based on data from 21 landfills. Based on the results from these studies, a value of 100 m^3/Mg appears to be a reasonable best estimate to use in the FOD model for the national inventory.

The FOD model was applied to the gas recovery data for the 52 landfills to calculate the rate constant (k) directly for $L_0 = 100$ m³/Mg. The rate constant was found to increase with annual average precipitation; consequently, average values of k were developed for three ranges of precipitation, shown in Table A- 245 and recommended in EPA's compilation of emission factors (EPA 2008).

Table A- 245. Average Values for Rate Constant (k) by Precipitation Range (yr⁻¹)

Precipitation range (inches/year)	k (yr⁻¹)
<20	0.020
20-40	0.038
>40	0.057

These values for k show reasonable agreement with the results of other studies. For example, EPA's compilation of emission factors (EPA 1998; EPA, 2008) recommends a value of 0.02 yr⁻¹ for arid areas (less than 20 inches/year of precipitation) and 0.04 yr⁻¹ for non-arid areas. The SWANA study of 18 landfills reported a range in values of k from 0.03 to 0.06 yr⁻¹ based on CH_4 recovery data collected generally in the time frame of 1986 to 1995.

Using data collected primarily for the year 2000, the distribution of waste in place versus precipitation was developed from over 400 landfills (RTI 2004). A distribution was also developed for population vs. precipitation for comparison. The two distributions were very similar and indicated that population in areas or regions with a given precipitation range was a reasonable proxy for waste landfilled in regions with the same range of precipitation. Using U.S. Census data and rainfall data, the distributions of population versus rainfall were developed for each Census decade from 1950 through 2000. The distributions showed that the U.S. population has shifted to more arid areas over the past several decades. Consequently, the population distribution was used to apportion the waste landfilled in each decade according to the precipitation ranges developed for k, as shown in Table A-246.

Table A-246. Percent of U.S. Population within Precipitation Ranges (%)

Precipitation Range (inches/year)	1950	1960	1970	1980	1990	2000
<20	11	13	14	16	19	20
20-40	40	39	38	36	34	33
>40	49	48	48	48	47	47

Source: RTI (2004) using population data from the U.S. Bureau of Census and precipitation data from the National Climatic Data Center's National Oceanic and Atmospheric Administration.

In developing the Inventory, the proportion of waste disposed of in managed landfills versus open dumps prior to 1980 was re-evaluated. Based on the historical data presented by Mintz et al. (2003), a timeline was developed for the transition from the use of open dumps for solid waste disposed to the use of managed landfills. Based on this timeline, it was estimated that 6 percent of the waste that was land disposed in 1940 was disposed of in managed landfills and 94 percent was managed in open dumps. Between 1940 and 1980, the fraction of waste land disposed transitioned towards managed landfills until 100 percent of the waste was disposed of in managed landfills in 1980. For wastes disposed of in dumps, a methane correction factor (MCF) of 0.6 was used based on the recommended IPCC default value for uncharacterized land disposal (IPCC 2006); this MCF is equivalent to assuming 50 percent of the open dumps are deep and 50 percent are shallow. The recommended IPCC default value for the MCF for managed landfills of 1 was used for the managed landfills (IPCC 2006).

Step 3: Estimate CH_4 Generation at Industrial Landfills

Industrial landfills receive waste from factories, processing plants, and other manufacturing activities. In national inventories prior to the 1990 through 2005 inventory, CH_4 generation at industrial landfills was estimated as seven percent of the total CH_4 generation from MSW landfills, based on a study conducted by EPA (1993). For the 1990 through 2007 and current inventories, the methodology was updated and improved by using activity factors (industrial production levels) to estimate the amount of industrial waste landfilled each year and by applying the FOD model to estimate CH_4 generation. A nationwide survey of industrial waste landfills found that over 99 percent of the organic waste placed in industrial landfills originated from two industries: food processing (meat, vegetables, fruits) and pulp and paper (EPA 1993). Data for annual nationwide production for the food processing and pulp and paper industries were taken from industry and government sources for recent years; estimates were developed for production for the earlier years for which data were not available. For the pulp and paper industry, production data published by the Lockwood-Post's Directory (ERG 2010) and U.S. Department of Agriculture (2010) were the primary sources for years 1965 through 2009. An extrapolation based on U.S. real gross domestic product was used for years 1940 through 1964. For the food processing industry, production levels were obtained or developed from the U.S. Department of Agriculture (2010) for the

years 1990 through 2009 (ERG 2010). An extrapolation based on U.S. population was used for the years 1940 through 1989.

In addition to production data for the pulp and paper and food processing industries, the following inputs were needed to use the FOD model for estimating CH_4 generation from industrial landfills: 1) quantity of waste that is disposed in industrial landfills (as a function of production), 2) CH_4 generation potential (L_0) or DOC, and 3) FOD decay constant (k). Research into waste generation and disposal in landfills for the pulp and paper industry indicated that the quantity of waste landfilled was about 0.050 Mg/Mg of product compared to 0.046 Mg/Mg product for the food processing industry (Weitz and Bahner 2006). These factors were applied to estimates of annual production to estimate annual waste disposal in landfills. Estimates for DOC were derived from available data (Kraft and Orender, 1993; NCASI 2008; Flores et al. 1999). The DOC value for industrial pulp and paper waste is estimated as 0.20 (L_o of 99 m^3/Mg); the DOC value for industrial food waste is estimated as 0.26 (L_o of 128 m^3/Mg) (Coburn 2008). Estimates for k were taken from the default values in the 2006 IPCC Guidelines; the value of k given for food waste with disposal in a wet temperate climate is 0.19 yr^{-1}, and the value given for paper waste is 0.06 yr^{-1}. A literature review was conducted for the current inventory year with the intent of updating values for Lo and k in the pulp and paper industry. Insufficient data was obtained to warrant a change for the current inventory year, but ongoing efforts may result in a U.S. industry-specific value rather than a default IPCC value in future inventory years.

As with MSW landfills, a similar trend in disposal practices from open dumps to managed landfills was expected for industrial landfills; therefore, the same time line that was developed for MSW landfills was applied to the industrial landfills to estimate the average MCF. That is, between 1940 and 1980, the fraction of waste land disposed transitioned from 6 percent managed landfills in 1940 and 94 percent open dumps to 100 percent managed landfills in 1980 and on. For wastes disposed of in dumps, an MCF of 0.6 was used and for wastes disposed of in managed landfills, an MCF of 1 was used, based on the recommended IPCC default values (IPCC 2006).

The parameters discussed above were used in the integrated form of the FOD model to estimate CH_4 generation from industrial landfills.

Step 4: Estimate CH_4 Emissions Avoided

The estimate of CH_4 emissions avoided (e.g., combusted) was based on landfill-specific data on landfill gas-to-energy (LFGTE) projects and flares. A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions avoided. The value for efficiency was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in EPA's "AP-42 Compilation of Air Pollutant Emission Factors, Chapter 2.4," efficiencies used to establish new source performance standards (NSPS) for landfills, and in recommendations for closed flares used in the Landfill Methane Outreach Program (LMOP).

Step 4a: Estimate CH_4 Emissions Avoided Through Landfill Gas-to-Energy (LFGTE) Projects

The quantity of CH_4 avoided due to LFGTE systems was estimated based on information from two sources: (1) a database maintained by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007) and (2) a database compiled by LMOP (EPA 2009). The EIA database included location information for landfills with LFGTE projects, estimates of CH_4 reductions, descriptions of the projects, and information on the methodology used to determine the CH_4 reductions. Generally the CH_4 reductions for each reporting year were based on the measured amount of landfill gas collected and the percent CH_4 in the gas. For the LMOP database, data on landfill gas flow and energy generation (i.e., MW capacity) were used to estimate the total direct CH_4 emissions avoided due to the LFGTE project. Detailed information on the landfill name, owner or operator, city, and state were available for both the EIA and LMOP databases; consequently, it was straightforward to identify landfills that were in both databases. The EIA database was given priority because reductions were reported for each year and were based on direct measurements. Landfills in the LMOP database that were also in the EIA database were dropped to avoid double counting.

Step 4b: Estimate CH_4 Emissions Avoided Through Flaring

The quantity of CH_4 flared was based on data from the EIA database and on information provided by flaring equipment vendors. To avoid double-counting, flares associated with landfills in the EIA and LMOP databases were excluded from the flare vendor database. As with the LFGTE projects, reductions from flaring landfill gas in the EIA database were based on measuring the volume of gas collected and the percent of CH_4 in the gas. The information provided by the flare vendors included information on the number of flares, flare design flow rates or flare dimensions, year of installation, and generally the city and state location of the landfill. When a range of design flare flow rates was provided by the flare vendor, the median landfill gas flow rate was used to estimate CH_4 recovered from each remaining

flare (i.e., for each flare not associated with a landfill in the EIA or LMOP databases). Several vendors provided information on the size of the flare rather than the flare design gas flow rate. To estimate a median flare gas flow rate for flares associated with these vendors, the size of the flare was matched with the size and corresponding flow rates provided by other vendors. Some flare vendors reported the maximum capacity of the flare. An analysis of flare capacity versus measured CH_4 flow rates from the EIA database showed that the flares operated at 51 percent of capacity when averaged over the time series and at 72 percent of capacity for the highest flow rate for a given year. For those cases when the flare vendor supplied maximum capacity, the actual flow was estimated as 50 percent of capacity. Total CH_4 avoided through flaring from the flare vendor database was estimated by summing the estimates of CH_4 recovered by each flare for each year.

Step 4c: Reduce CH_4 Emissions Avoided Through Flaring

As mentioned in Step 4b, flares in the flare vendor database associated with landfills in the EIA and LMOP databases were excluded from the flare reduction estimates in the flare vendor database. If comprehensive data on flares were available, each LFGTE project in the EIA and LMOP databases would have an identified flare because it is assumed that most LFGTE projects have flares. However, given that the flare vendor data only covers approximately 50 to 75 percent of the flare population, an associated flare was not identified for all LFGTE projects. These LFGTE projects likely have flares, yet flares were unable to be identified for one of two reasons: 1) inadequate identifier information in the flare vendor data; or 2) a lack of the flare in the flare vendor database. For those projects for which a flare was not identified due to inadequate information, CH_4 avoided would be overestimated, as both the CH_4 avoided from flaring and the LFGTE project would be counted. To avoid overestimating emissions avoided from flaring, the CH_4 avoided from LFGTE projects with no identified flares was determined and the flaring estimate from the flare vendor database was reduced by this quantity (referred to as a flare correction factor) on a state-by-state basis. This step likely underestimates CH_4 avoided due to flaring but was applied to be conservative in the estimates of CH_4 emissions avoided.

Additional effort was undertaken to improve the methodology behind the flare correction factor for the 1990-2009 Inventory to reduce the total number of flares in the flare vendor database that were not matched (512) to landfills and/or LFGTE projects in the EIA and LMOP databases. Each flare in the flare vendor database not associated with a LFGTE project in the EIA or LMOP databases was investigated to determine if it could be matched to either a landfill in the EIA database or a LFGTE project in the LMOP database. For some unmatched flares, the location information was missing or incorrectly transferred to the flare vendor database. In other instances, the landfill names were slightly different between what the flare vendor provided and the actual landfill name as listed in the EIA and LMOP databases.

It was found that a large majority of the unmatched flares are associated with landfills in LMOP that are currently flaring, but are also considering LFGTE. These landfills projects considering a LFGTE project are labeled as candidate, potential, or construction in the LMOP database. The flare vendor database was improved to match flares with operational, shutdown as well as candidate, potential, and construction LFGTE projects, thereby reducing the total number of unidentified flares in the flare vendor database, all of which are used in the flare correction factor. The results of this effort significantly decreased the number of flares used in the flare correction factor, and consequently, increased recovered flare emissions, and decreased net emissions from landfills for the 1990-2009 Inventory. The revised state-by-state flare correction factors were applied to the entire 1990 to 2009 time series for the current Inventory year.

Step 5: Estimate CH_4 Oxidation

A portion of the CH_4 escaping from a landfill oxidizes to CO_2 in the top layer of the soil. The amount of oxidation depends upon the characteristics of the soil and the environment. For purposes of this analysis, it was assumed that of the CH_4 generated, minus the amount of gas recovered for flaring or LFGTE projects, 10 percent was oxidized in the soil (Jensen and Pipatti 2002; Mancinelli and McKay 1985; Czepiel et al 1996). The factor of 10 percent is consistent with the value recommended in the 2006 IPCC revised guidelines for managed and covered landfills, and was therefore applied to the estimates of CH_4 generation minus recovery for both MSW and industrial landfills

Literature reviews were conducted in 2006 and 2010 to provide recommendations for the most appropriate oxidation rate assumptions. It was found that oxidation values are highly variable and range from zero to over 100 percent (i.e., the landfill is considered to be an atmospheric sink by virtue of the landfill gas extraction system pulling atmospheric metane down through the cover). There is considerable uncertainty and variability surrounding estimates of oxidation because it is difficult to measure and varies considerably with the thickness and type of the cover material, climate, and the presence of cracks/fissures in the cover material through which methane can escape. IPCC (2006) notes that test results from field and laboratory studies may lead to over-estimations of oxidation in landfill cover soils, because they largely determine oxidation using uniform and homogeneous soil layers. In addition, a number of studies note that gas escapes

more readily through the side slopes of a landfill as compared to moving through the cover thus complicating the correlation between oxidation and cover type or gas recovery.

Spokas et al (2005), in particular, helps to illustrate expected patterns (e.g., seasonality of generation, effectiveness of gas recovery) associated with landfill methane production and flux through the cover system. This study also highlights the large variability in oxidation between and within sites and ultimately reports oxidation ranging between 4-50 percent. All but one of the test sites had an active gas recovery system in place. For landfills with gas collection systems, there have been studies to show that gas recovery increases oxidation because it slows the flux of methane through the cover system. Although this may be true, there does not appear to be enough data to support the premise that landfills with gas recovery systems increase oxidation. This is demonstrated by the Spokas et al (2005) data where the oxidation rates were about the same for a landfill site with and without gas recovery. However, the site also had a thin temporary cover so the oxidation would be less than a site with a final cover system. Based on this and other studies, there does not appear to be adequate justification for increasing the default oxidation value for landfills with gas recovery.

Changing the oxidation rate from 10 percent to 20 percent has a minimal impact on the overall inventory results. Changing the oxidation rate from 10 percent to 60 percent has a more significant impact on the overall inventory results, lowering the overall inventory by as much as 15 to 20 percent.

The current default oxidation factor of 10 percent is recommended for all landfills in the Inventory until more reliable, peer-reviewed data is available about the influence of climate, cover type, and gas recovery is better understood.

Step 6: Estimate Total CH$_4$ Emissions

Total CH$_4$ emissions were calculated by adding emissions from MSW and industrial landfills, and subtracting CH$_4$ recovered and oxidized, as shown in Table A- 247.

Table A- 247: CH₄ Emissions from Landfills (Gg)

Activity	1990		1995		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
MSW Generation	8,219		9,132		9,854	10,068	10,367	10,754	11,127	11,486	11,813	12,107	12,395	12,679
Industrial Generation	549		611		682	695	710	710	716	724	727	732	738	744
Potential Emissions	**8,768**		**9,742**		**10,536**	**10,763**	**11,069**	**11,464**	**11,842**	**12,210**	**12,540**	**12,839**	**13,133**	**13,423**
Landfill Gas-to-Energy	(649)		(1,070)		(2,352)	(2,548)	(2,589)	(2,563)	(2,673)	(2,691)	(2,807)	(3,033)	(3,189)	(3,429)
Flare	(321)		(1,298)		(2,276)	(2,491)	(2,738)	(2,886)	(3,364)	(3,566)	(3,820)	(3,918)	(3,810)	(3,779)
Emissions Avoided	**(970)**		**(2,368)**		**(4,628)**	**(5,039)**	**(5,326)**	**(5,448)**	**(6,037)**	**(6,257)**	**(6,628)**	**(6,951)**	**(7,000)**	**(7,208)**
Oxidation at MSW Landfills	**(725)**		**(676)**		**(523)**	**(503)**	**(504)**	**(531)**	**(509)**	**(523)**	**(518)**	**(516)**	**(540)**	**(547)**
Oxidation at Industrial Landfills	**(55)**		**(61)**		**(68)**	**(70)**	**(70)**	**(71)**	**(72)**	**(73)**	**(73)**	**(73)**	**(74)**	**(74)**
Net Emissions	**7,018**		**6,637**		**5,317**	**5,152**	**5,169**	**5,414**	**5,224**	**5,358**	**5,321**	**5,299**	**5,520**	**5,593**

Note: Totals may not sum exactly to the last significant figure due to rounding.
Note: MSW generation in
 represents emissions before oxidation. In other tables throughout the text, MSW generation estimates account for oxidation.
Note: Parentheses denote negative values.

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Figure A-4: Domestic Greenhouse Gas Emissions by Mode and Vehicle Type, 1990 to 2009 (Tg CO$_2$ Eq.)
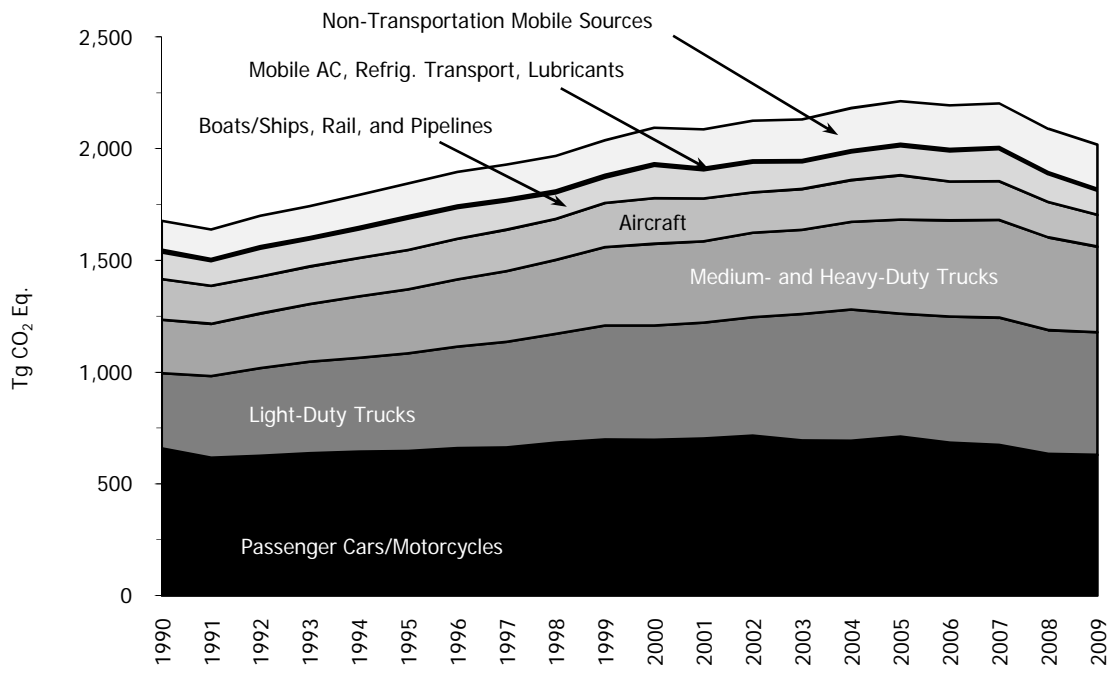
Figure A-5
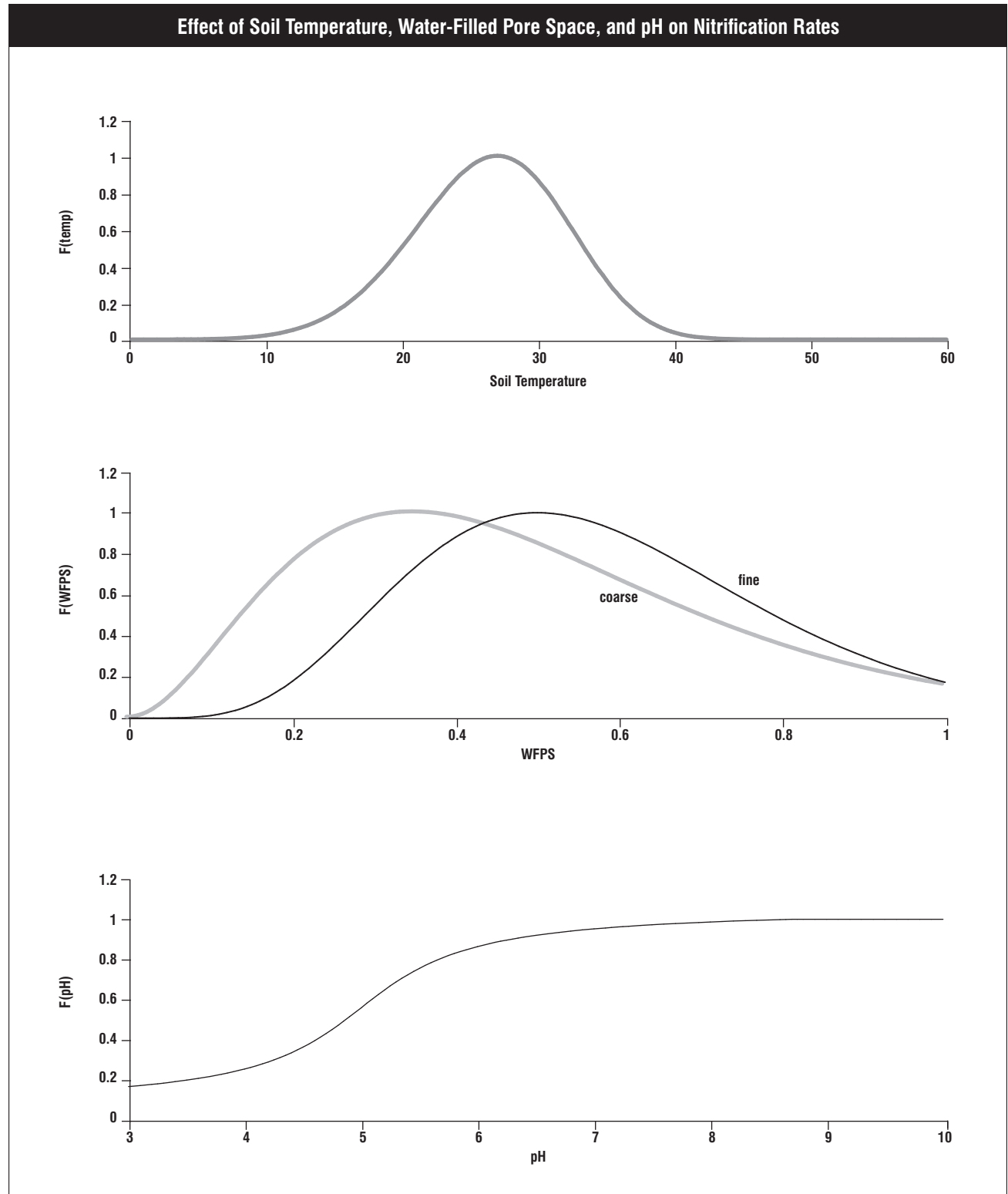
Effect of Soil Temperature, Water-Filled Pore Space, and pH on Nitrification Rates

Effect of Soil Nitrite Concentration, Heterotrophic Respiration Rates, and Water-Filled Pore Space on Denitrification Rates

DAYCENT MODEL

Figure A-7: DAYCENT model flow diagram

Figure A-8: Comparisons of Results from DAYCENT Model and IPCC Tier 1 Method with Measurements of Soil N2O Emissions

Figure A-9

Major Crops, Average Annual Direct N$_2$O Emissions Estimated Using the DAYCENT Model, 1990–2009 (Metric Tons CO$_2$ Eq./ha/year)

Metric Tons CO$_2$ Eq./ha/year

- < 0.4
- 0.4 – 0.5
- 0.5 – 0.6
- 0.6 – 0.7
- 0.7 – 0.8
- 0.8 – 1
- > 1

Major Crops, Average Annual N losses Leading to Indirect N$_2$O Emissions Estimated Using the DAYCENT Model, 1990-2009 (kg N/ha/year)

Figure A-11

Grasslands, Average Annual Direct N$_2$O Emissions Estimated Using the DAYCENT Model, 1990–2009 (Metric Tons CO$_2$ Eq./ha/year)

Metric Tons CO$_2$ Eq./ha/year

- < 0.1
- $0.1 - 0.2$
- $0.2 - 0.3$
- $0.3 - 0.4$
- $0.4 - 0.5$
- $0.5 - 0.6$
- > 0.6

Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the DAYCENT Model, 1990-2009 (kg N/ha/year)

Figure A-13

Flow diagram of Carbon submodel (A) and Nitrogen submodel (B)

Figure A-14

Comparison of Measured Soil Organic C from Experimental Sites to Modeled Soil Organic C Using the Century Model

Figure A-15

Major Land Resource Areas by IPCC Climate Zone

IPCC Climate Zones
- CTD
- CTM
- STD
- STM
- WTD
- WTM
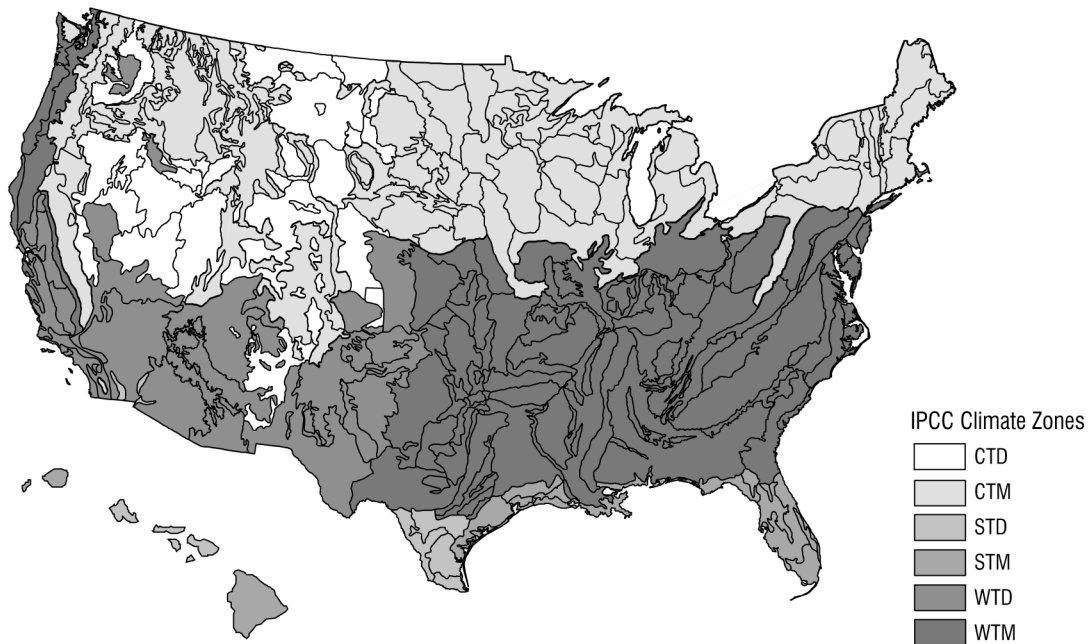
This figure shows the IPCC climate zone assigned to each of the 180 Major Land Resource Areas (MLRAs) in the United States, based on PRISM climate data averaged for each MRLA.

Figure A-16

Uncertainty in Data Inputs

Uncertainty in data inputs (i.e. fertilizer, manure and tillage practices) are estimated using a Monte-Carlo procedure with 100 random draws from input data probability distributions, for each NRI point simulated. Model uncertainty is estimated through an empirical-based approach. Uncertainty in the land representation of NRI is estimated from the statistics compiled from the NRI surveys to determine the land area expansion factors, which are used to upscale data to the national level.

Figure A-17

Net C Stock Change, per Hectare, for Mineral Soils Under Agricultural Management, 2009

Metric Tons CO$_2$ Eq./ha/year
- > 0
- -0.05 to 0
- -0.1 to -0.05
- -0.25 to -0.1
- -0.5 to -0.25
- < -0.5

Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations. See Methodology for additional details.

Figure A-18
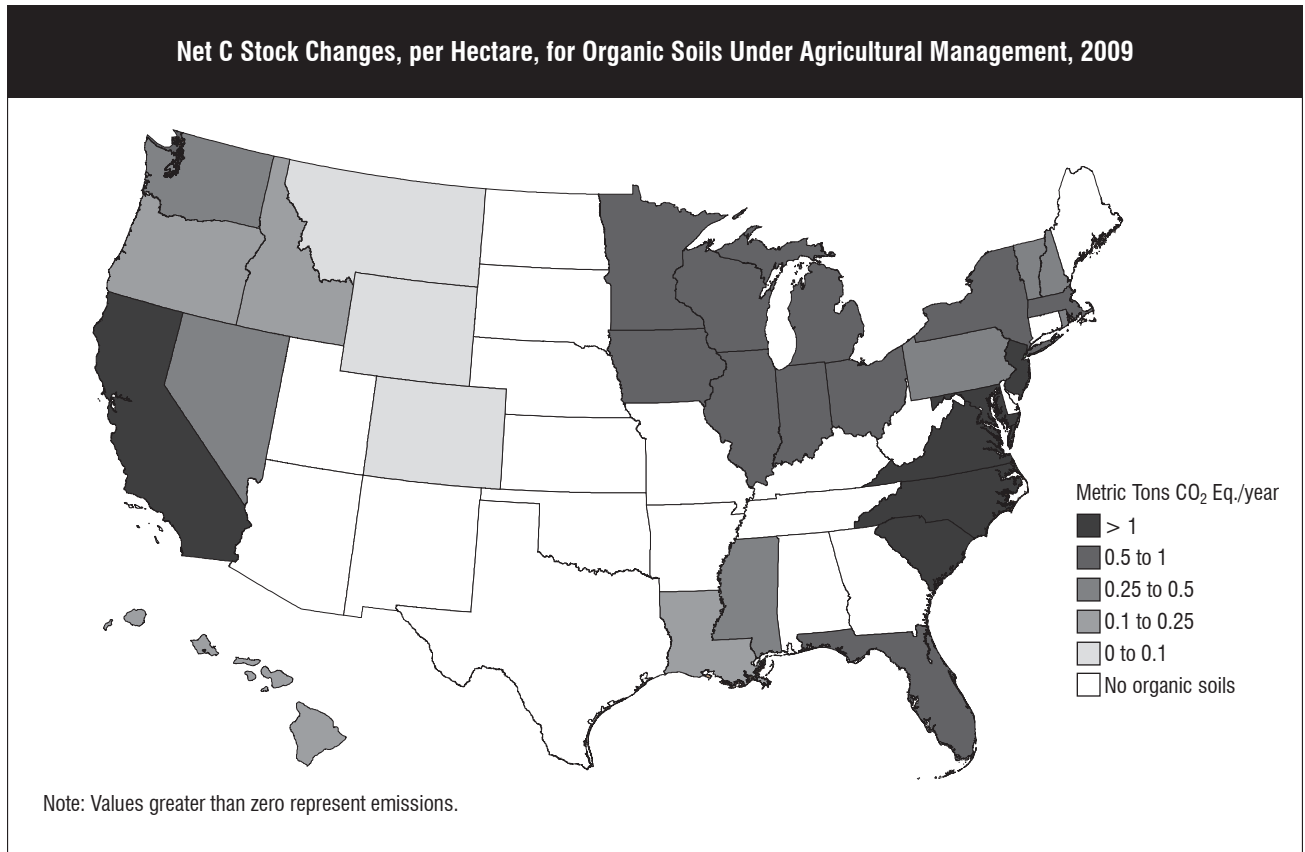
Net C Stock Changes, per Hectare, for Organic Soils Under Agricultural Management, 2009

Metric Tons CO_2 Eq./year

- > 1
- 0.5 to 1
- 0.25 to 0.5
- 0.1 to 0.25
- 0 to 0.1
- No organic soils

Note: Values greater than zero represent emissions.

Figure A-19: Methane Emissions Resulting from Landfilling Municipal and Industrial Waste
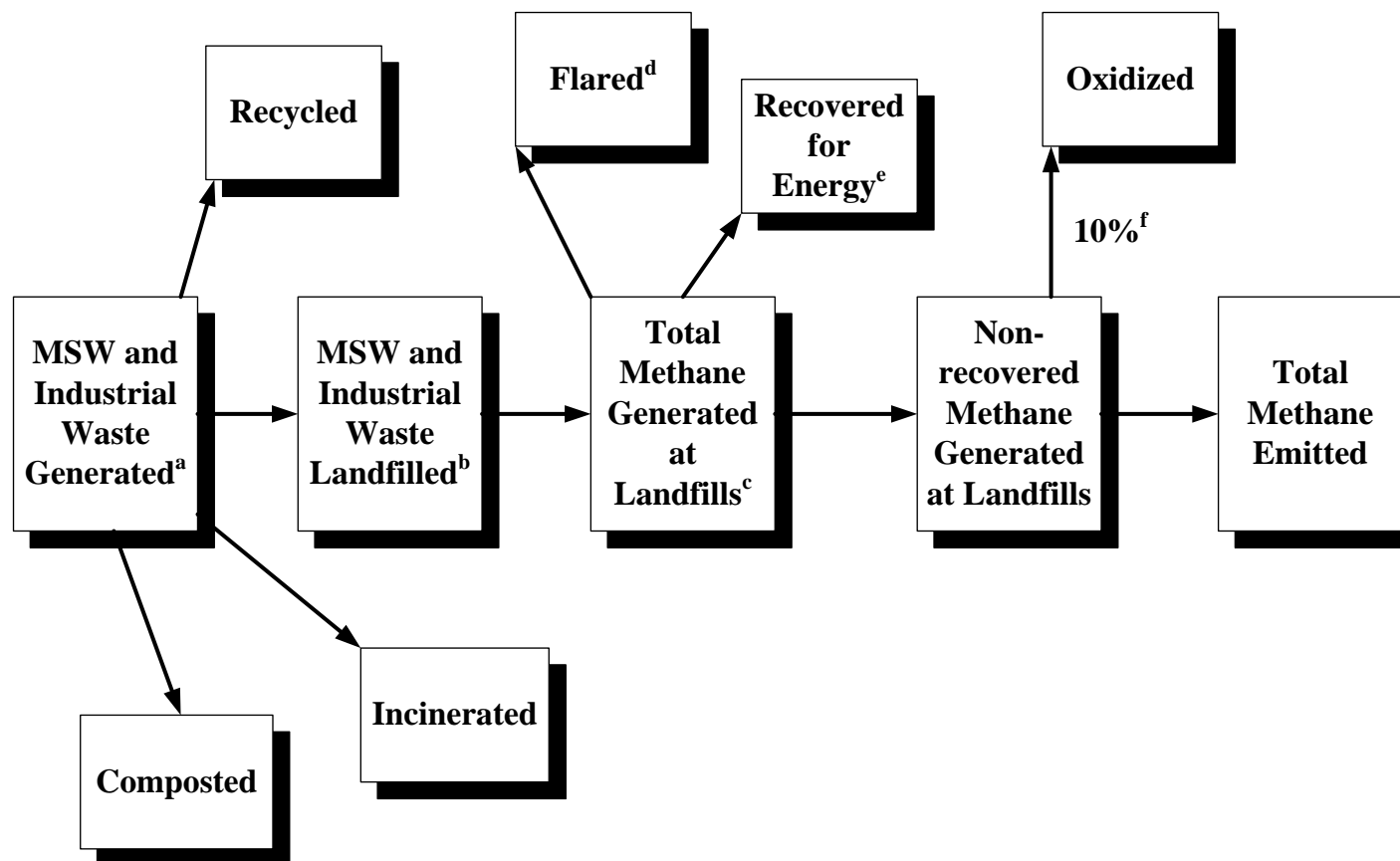
[a] BioCycle 2006 for MSW and activity factors for industrial waste.
[b] 1960 through 1988 based on EPA 1988 and EPA 1993; 1989 through 2006 based on BioCycle 2006.
[c] 2006 IPCC Guidelines – First Order Decay Model.
[d] EIA 2007 and flare vendor database.
[e] EIA 2007 and EPA (LMOP) 2007.
[f] 2006 IPCC Guidelines; Mancinelli and McKay 1985; Czepiel et al 1996

ANNEX 4 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 the Estimating Emissions from Fossil Fuel Combustion Annex. For example, the UNFCCC reporting guidelines request that countries, in addition to their "bottom-up" sectoral methodology, 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 C-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 C 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 EIA documents in order to obtain the necessary data on production, imports, exports, and stock changes.

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 the following: unspecified coal for coal coke used in iron and steel production; natural gas, distillate fuel, and coal used in iron and steel production; natural gas used for ammonia production; petroleum coke used in the production of aluminum, ferroalloys, titanium dioxide, ammonia, and silicon carbide; and other oil and residual fuel oil used in the manufacture of C black. The second modification adjusts for the fact that EIA energy statistics include synthetic natural gas in coal and natural gas data. The third modification adjusts for the inclusion of ethanol in motor gasoline statistics. Ethanol is a biofuel, and net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry (see Chapter 7). The fourth modification adjusts for consumption of bunker fuels, which refer to quantities of fuels used for international transportation estimated separately from U.S. totals. The fifth 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 A- 248.

The C 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., Btu or joules). Because detailed fuel production statistics are typically provided in physical units (as in Table A- 248 for 2009), 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 EIA. These factors and their data sources are displayed in Table A- 249. The resulting fuel type-specific energy data for 2009 are provided in Table A- 250.

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, C 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 C 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 C 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 consumption 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 has different heat contents. Therefore, United States fuel statistics were converted to their heat equivalents before estimating apparent consumption. Results are provided in Table A- 249.

Step 3: Estimate Carbon Emissions

Once apparent consumption is estimated, the remaining calculations are similar to those for the "bottom-up" Sectoral Approach (see Estimating Emissions from Fossil Fuel Combustion Annex). Potential CO_2 emissions were estimated using fuel-specific C coefficients (see Table A- 250).[77] The C in products from non-energy uses of fossil fuels (e.g., plastics or asphalt) was then estimated and subtracted (see Table A-252). This step differs from the Sectoral Approach in that emissions from both fuel combustion and non-energy uses are accounted for in this approach. Finally, to obtain actual CO_2 emissions, net emissions were adjusted for any C that remained unoxidized as a result of incomplete combustion (e.g., C contained in ash or soot).[78] The fraction oxidized was assumed to be 100 percent for petroleum, coal, and natural gas based on guidance in IPCC (2006) (see Estimating Emissions from Fossil Fuel Combustion Annex).

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 C to units of CO_2. Actual C emissions were multiplied by the molecular-to-atomic weight ratio of CO_2 to C (44/12) to obtain total CO_2 emitted from fossil fuel combustion in teragrams (Tg). The results are contained in Table A- 251.

Comparison Between Sectoral and Reference Approaches

These two alternative approaches can both produce reliable estimates that are comparable within a few percent. Note that the reference approach *includes* emissions from non-energy uses. Therefore, these totals should be compared to the aggregation of fuel use and emission totals from Emissions of CO_2 from Fossil Fuel Combustion and Carbon Emitted from Non-Energy Uses of Fossil Fuels Annexes. These two sections together are henceforth referred to as the Sectoral

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[77] 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 for more specific source information.

Approach. Other than this distinction, the major difference between methodologies employed by each approach lies in the energy data used to derive C emissions (i.e., the actual surveyed consumption for the Sectoral Approach versus apparent 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 A-254 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 1.2 percent lower than the Sectoral Approach for 2009. The greatest differences lie in lower estimates for petroleum consumption for the Reference Approach (4.2 percent) and higher estimates for natural gas consumption for the Reference Approach (2.5 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.

- *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 A-255 summarizes the differences between the two methods in estimated C emissions.

As mentioned above, for 2009, the Reference Approach resulted in a 1.2 percent lower estimate of energy consumption in the United States than the Sectoral Approach. The resulting emissions estimate for the Reference Approach was 0.8 percent lower. Estimates of natural gas emissions from the Reference Approach are higher (2.6 percent), and coal and petroleum emission estimates are lower (0.4 percent and 3.0 percent, respectively) than the Sectoral Approach. 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. Given the many sources of crude oil in the United States, it is not an easy matter to track potential differences in C content between many different sources of crude; particularly since information on the C content of crude oil is not regularly collected.

- *Carbon Coefficients.* The Reference Approach relies on several default C 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 C 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.

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Table A- 248: 2009 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	1,934	a	a	a			
	Bituminous Coal	493,661	a	a	a			
	Sub-bituminous Coal	504,679	a	a	a	440		
	Lignite	72,477	a	a	a	4,643		
	Coke		347	1,307	(140)			
	Unspecified Coal		22,639	59,097	33,711	16,926		1,712
Gas Fuels (Million Cubic Feet)	Natural Gas	20,213,850	3,984,233	1,005,724	(34,253)	249,817		26,723
Liquid Fuels (Thousand Barrels)	Crude Oil	1,956,596	3,289,675	15,985	24,132			
	Nat Gas Liquids and LRGs	697,124	70,794	50,681	(14,281)			3,883
	Other Liquids		515,169	23,625	22,558			
	Motor Gasoline	53,635	81,536	71,326	(13,387)	171,416		38,289
	Aviation Gasoline		73		(158)			
	Kerosene		1,143	1,681	228			1,344
	Jet Fuel		29,488	25,230	5,428		173,089	7,360
	Distillate Fuel		82,172	214,411	19,951	552	19,286	12,755
	Residual Fuel		120,936	151,606	1,111	10,000	96,195	26,353
	Naphtha for petrochemical feedstocks		18,014		(297)			
	Petroleum Coke		6,543	142,821	(349)	10,355		
	Other Oil for petrochemical feedstocks		30,323		(115)	2,528		
	Special Naphthas		4,638	8,116	(317)			
	Lubricants		7,006	20,692	(1,805)			172
	Waxes		1,497	2,165	(71)			
	Asphalt/Road Oil		8,023	9,950	(2,303)			
	Still Gas							
	Misc. Products		80	515	(689)			9,522

[a] Included in Unspecified Coal
Data Sources: Solid and Gas Fuels: EIA (2011); Liquid Fuels: EIA (1995-2010).

Table A- 249: 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				28.16		
	Lignite	12.87				12.87		
	Coke		25.00	25.63	25.00			
	Unspecified		25.00	25.97	20.86	25.85		25.14
Natural Gas (BTU/Cubic Foot)		1,026	1,025	1,009	1,026	1,025		1,026
Liquid Fuels (Million Btu/Barrel)	Crude Oil	5.80	5.99	5.80	5.80		5.80	5.80
	Nat Gas Liquids and LRGs	3.69	3.69	3.69	3.69		3.69	3.69
	Other Liquids	5.83	5.83	5.83	5.83		5.83	5.83
	Motor Gasoline	5.22	5.22	5.22	5.22	5.22	5.22	5.22
	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		5.55	5.67
	Distillate Fuel		5.83	5.83	5.83	5.83	5.83	5.83
	Residual Oil		6.29	6.29	6.29	6.29	6.29	6.29
	Naphtha 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	5.83
	Special Naphthas		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 (2010); Unspecified Solid Fuels: EIA (2011); Coke, Natural Gas and Petroleum Products: EIA (2011).

Table A- 250: 2009 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	43.7							**43.7**
	Bituminous Coal	11,793.6							**11,793.6**
	Sub-bituminous Coal	8,650.2				12.4			**8,637.8**
	Lignite	932.5				59.7			**872.8**
	Coke		8.7	33.5	(3.5)				**(21.3)**
	Unspecified		566.0	1,534.9	703.2	437.4		43.0	**(2,066.6)**
Gas Fuels	Natural Gas	20,739.4	4,083.8	1,014.8	(35.1)	256.1		27.4	**23,615.0**
Liquid Fuels	Crude Oil	11,348.3	19,701.9	92.7	140.0				**30,817.4**
	Nat Gas Liquids and LRGs	2,572.4	261.2	187.0	(52.7)			14.3	**2,713.6**
	Other Liquids		3,000.9	137.6	131.4				**2,731.8**
	Motor Gasoline	279.9	425.5	372.2	(69.9)	894.5		199.8	**(291.7)**
	Aviation Gasoline		0.4		(0.8)				**1.2**
	Kerosene		6.5	9.5	1.3			7.6	**3.3**
	Jet Fuel		167.2	143.1	30.8		961.0	41.7	**(925.9)**
	Distillate Fuel		478.7	1,248.9	116.2	3.2	112.3	74.3	**(927.8)**
	Residual Oil		760.3	953.1	7.0	62.9	604.8	165.7	**(701.8)**
	Naphtha for petrochemical feedstocks		94.5	0.0	(1.6)				**96.1**
	Petroleum Coke		39.4	860.4	(2.1)	62.4			**(881.2)**
	Other Oil for petrochemical feedstocks		176.6		(0.7)	14.7			**162.6**
	Special Naphthas		24.3	42.6	(1.7)				**(16.6)**
	Lubricants		42.5	125.5	(10.9)			1.0	**(71.0)**
	Waxes		8.3	12.0	(0.4)				**(3.3)**
	Asphalt/Road Oil		53.2	66.0	(15.3)				**2.5**
	Still Gas								**0.0**
	Misc. Products		0.5	3.0	(4.0)			55.2	**56.7**
Total		**56,359.8**	**29,900.3**	**6,836.8**	**931.3**	**1,803.3**	**1,678.1**	**630.1**	**75,640.9**

Note: Totals may not sum due to independent rounding.

Table A- 251: 2009 Potential CO$_2$ Emissions

Fuel Category	Fuel Type	Apparent Consumption (QBtu)	Carbon Coefficients (Tg Carbon/QBtu)	Potential Emissions (Tg CO$_2$ Eq.)
Solid Fuels	Anthracite Coal	0.044	28.28	**4.5**
	Bituminous Coal	11.794	25.44	**1,100.2**
	Sub-bituminous Coal	8.638	26.50	**839.3**
	Lignite	0.873	26.65	**85.3**
	Coke	(0.021)	31.00	**(2.4)**
	Unspecified	(2.067)	25.34	**(192.0)**
Gas Fuels	Natural Gas	23.615	14.46	**1,251.6**
Liquid Fuels	Crude Oil	30.817	20.31	**2,294.5**
	Nat Gas Liquids and LRGs	2.714	16.90	**168.2**
	Other Liquids	2.732	20.31	**203.4**
	Motor Gasoline	(0.292)	19.46	**(20.8)**
	Aviation Gasoline	0.001	18.86	**0.1**
	Kerosene	0.003	19.96	**0.2**
	Jet Fuel	(0.926)	19.70	**(66.9)**
	Distillate Fuel	(0.928)	20.17	**(68.6)**
	Residual Oil	(0.702)	20.48	**(52.7)**
	Naphtha for petrochemical feedstocks	0.096	18.55	**6.5**
	Petroleum Coke	(0.881)	27.85	**(90.0)**
	Other Oil for petrochemical feedstocks	0.163	20.17	**12.0**
	Special Naphthas	(0.017)	19.74	**(1.2)**
	Lubricants	(0.071)	20.20	**(5.3)**
	Waxes	(0.003)	19.80	**(0.2)**
	Asphalt/Road Oil	0.002	20.55	**0.2**
	Still Gas	-	18.20	**0.0**
	Misc. Products	0.057	20.31	**4.2**
Total				**5,470.2**

Data Sources: C content coefficients by coal rank from USGS (1998) and SAIC (2004); Unspecified Solid Fuels, EIA (2011), Natural Gas and Liquid Fuels: EPA (2010).
Note: Totals may not sum due to independent rounding.

Table A-252: 2009 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	6.1	31.00	0.2	0.10	**0.07**
Natural Gas	366.0	14.46	5.3	0.58	**11.26**
Asphalt & Road Oil	873.1	20.55	17.9	1.00	**65.51**
LPG	1,446.2	17.06	24.7	0.58	**52.53**
Lubricants	262.6	20.20	5.3	0.09	**1.79**
Pentanes Plus	93.4	19.10	1.8	0.58	**3.80**
Petrochemical Feedstocks	[a]	[a]	[a]	[a]	**40.33**
Petroleum Coke	133.0	27.85	3.7	0.30	**4.08**
Special Naphtha	44.2	19.74	0.9	0.58	**1.86**
Waxes/Misc.	[a]	[a]	[a]	[a]	**1.16**
Misc. U.S. Territories Petroleum	[a]	[a]	[a]	[a]	**0.41**
Total					**182.8**

[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 A-253: 2009 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	1,834.9	0.1	1,834.8	100.0%	1,834.8
Petroleum	2,383.7	171.4	2,212.2	100.0%	2,212.2
Natural Gas	1,251.6	11.3	1,240.4	100.0%	1,240.4
Total	**5,470.2**	**182.8**	**5,287.4**	**-**	**5,287.4**

Note: Totals may not sum due to independent rounding.

Table A-254: Fuel Consumption in the United States by Estimating Approach (TBtu)[*]

Approach	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Sectoral	**69,673.0**	**74,908.3**	**77,350.2**	**78,415.8**	**78,839.3**	**80,176.1**	**82,614.3**	**81,106.1**	**81,849.5**	**82,331.7**	**83,947.2**	**84,044.3**	**82,662.2**	**84,108.4**	**81,278.7**	**76,567.5**
Coal	18,071.8	19,186.2	20,067.4	20,528.6	20,822.8	20,829.6	21,747.8	21,120.4	21,191.2	21,624.8	21,892.4	22,186.3	21,832.9	22,076.5	21,749.5	19,302.0
Natural Gas	19,184.0	22,169.5	22,589.0	22,722.9	22,323.2	22,365.5	23,391.9	22,466.2	23,211.4	22,561.3	22,609.4	22,278.5	21,945.6	23,412.6	23,536.9	23,046.2
Petroleum	32,417.2	33,552.6	34,693.8	35,164.4	35,693.3	36,981.0	37,474.6	37,519.6	37,446.9	38,145.6	39,445.4	39,579.5	38,883.7	38,619.3	35,992.3	34,219.4
Reference (Apparent)	**68,941.1**	**73,951.5**	**76,275.2**	**77,822.5**	**77,838.5**	**79,082.3**	**81,543.6**	**80,610.7**	**81,307.1**	**81,732.9**	**83,416.2**	**83,495.8**	**81,854.4**	**83,727.5**	**79,932.4**	**75,640.9**
Coal	17,572.2	18,566.7	19,424.8	20,104.6	19,980.4	20,029.1	20,956.8	20,709.5	20,796.7	21,080.5	21,734.5	21,985.5	21,532.4	21,586.3	21,388.5	19,259.9
Natural Gas	19,672.0	22,274.0	22,695.8	22,827.8	22,403.3	22,458.4	23,483.9	22,535.5	23,276.0	22,630.3	22,676.2	22,344.8	22,014.7	23,473.0	23,609.6	23,615.0
Petroleum	31,696.8	33,110.8	34,154.5	34,890.0	35,454.8	36,594.7	37,102.9	37,365.7	37,234.3	38,022.1	39,005.6	39,165.4	38,307.3	38,668.1	34,934.3	32,766.0
Difference	**-1.1%**	**-1.3%**	**-1.4%**	**-0.8%**	**-1.3%**	**-1.4%**	**-1.3%**	**-0.6%**	**-0.7%**	**-0.7%**	**-0.6%**	**-0.7%**	**-1.0%**	**-0.5%**	**-1.7%**	**-1.2%**
Coal	-2.8%	-3.2%	-3.2%	-2.1%	-4.0%	-3.8%	-3.6%	-1.9%	-1.9%	-2.5%	-0.7%	-0.9%	-1.4%	-2.2%	-1.7%	-0.2%
Natural Gas	2.5%	0.5%	0.5%	0.5%	0.4%	0.4%	0.4%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	2.5%
Petroleum	-2.2%	-1.3%	-1.6%	-0.8%	-0.7%	-1.0%	-1.0%	-0.4%	-0.6%	-0.3%	-1.1%	-1.0%	-1.5%	0.1%	-2.9%	-4.2%

* Includes U.S. territories. Does not include international bunker fuels.
Note: Totals may not sum due to independent rounding.

Table A-255: CO_2 Emissions from Fossil Fuel Combustion by Estimating Approach (Tg CO_2 Eq.)

Approach	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Sectoral	**4,856.7**	**5,170.4**	**5,352.3**	**5,428.0**	**5,474.5**	**5,558.6**	**5,739.4**	**5,655.4**	**5,693.2**	**5,752.1**	**5,858.9**	**5,896.2**	**5,798.3**	**5,893.6**	**5,706.5**	**5,331.9**
Coal	1,718.7	1,823.3	1,906.8	1,949.9	1,979.8	1,982.8	2,071.4	2,011.3	2,021.7	2,065.8	2,092.7	2,120.9	2,083.4	2,106.6	2,075.9	1,842.1
Natural Gas	1,006.8	1,164.7	1,186.5	1,193.1	1,169.3	1,172.4	1,226.4	1,177.7	1,217.6	1,181.8	1,184.9	1,167.5	1,149.9	1,226.6	1,234.8	1,209.1
Petroleum	2,131.1	2,182.4	2,259.0	2,285.0	2,325.4	2,403.4	2,441.7	2,466.5	2,453.9	2,504.6	2,581.3	2,607.9	2,565.0	2,560.4	2,395.8	2,280.8
Reference (Apparent)	**4,802.2**	**5,130.6**	**5,303.0**	**5,421.9**	**5,427.4**	**5,501.3**	**5,686.5**	**5,650.1**	**5,690.1**	**5,741.1**	**5,872.1**	**5,891.3**	**5,770.6**	**5,880.8**	**5,630.2**	**5,287.4**
Coal	1,654.1	1,756.2	1,837.0	1,901.8	1,894.4	1,902.9	1,989.0	1,967.6	1,976.4	2,002.2	2,065.2	2,088.1	2,049.5	2,054.3	2,036.7	1,834.8
Natural Gas	1,034.0	1,171.4	1,193.3	1,200.0	1,174.5	1,178.3	1,232.2	1,181.5	1,221.9	1,187.0	1,190.7	1,171.7	1,154.0	1,230.8	1,239.2	1,240.4
Petroleum	2,114.1	2,202.9	2,272.7	2,320.1	2,358.5	2,420.1	2,465.2	2,501.0	2,491.9	2,551.8	2,616.3	2,631.5	2,567.1	2,595.6	2,354.2	2,212.2
Difference	**-1.1%**	**-0.8%**	**-0.9%**	**-0.1%**	**-0.9%**	**-1.0%**	**-0.9%**	**-0.1%**	**-0.1%**	**-0.2%**	**0.2%**	**-0.1%**	**-0.5%**	**-0.2%**	**-1.3%**	**-0.8%**
Coal	-3.8%	-3.7%	-3.7%	-2.5%	-4.3%	-4.0%	-4.0%	-2.2%	-2.2%	-3.1%	-1.3%	-1.5%	-1.6%	-2.5%	-1.9%	-0.4%
Natural Gas	2.7%	0.6%	0.6%	0.6%	0.4%	0.5%	0.5%	0.3%	0.3%	0.4%	0.5%	0.4%	0.4%	0.3%	0.4%	2.6%
Petroleum	-0.8%	0.9%	0.6%	1.5%	1.4%	0.7%	1.0%	1.4%	1.5%	1.9%	1.4%	0.9%	0.1%	1.4%	-1.7%	-3.0%

* Includes U.S. territories. Does not include international bunker fuels.
Note: Totals may not sum due to independent rounding.

ANNEX 5 Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included

Although this report is intended to be a comprehensive assessment of anthropogenic[79] sources and sinks of greenhouse gas emissions for the United States, certain sources have been identified but not included in 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 line with guidance from the IPCC in their guidelines for national inventories.

Given a source category that is both anthropogenic and results in net greenhouse gas emissions, reasons for not including a source related to an anthropogenic activity include one or more of the following:

- Though 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 that the sources discussed below are very low in comparison with the overall estimate of total U.S. greenhouse gas emissions, and not including them introduces a very minor bias. In general, the emission sources described in this annex are for source categories with methodologies introduced in the 2006 IPCC Guidelines for which data collection has not been sufficient to pursue an initial estimation of greenhouse gases.

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.. 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.

CO_2 and CH_4 from Calcium Carbide Production

CO_2 is formed by the oxidation of petroleum coke in the production of calcium carbide. These CO_2 emissions are implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke in the Energy chapter. There is currently not sufficient data on coke consumption for calcium carbide production to estimate emissions from this source.

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 4 of the inventory are not explicitly calculated. It is assumed that 100 percent of the C used in ferroalloy production is derived from petroleum coke and that all of the C used in iron and steel production is derived from coal coke or petroleum coke. It is also assumed that all of the C used in lead and zinc production is derived from coal coke. It is possible that some non-coke C is used in the production of ferroalloys, lead, zinc, and iron and steel, but no data are available to conduct inventory calculations for sources of C other than petroleum coke and coal coke used in these processes.

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[79] 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 ("2006 IPCC Guidelines for National Greenhouse Gas Inventories").

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, lead, zinc, 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, Land-Use Change, and Forestry chapter. It is assumed for the purposes of the CO_2 emission calculation that no wood or other biogenic C is used in any of these industrial processes. Some biogenic C 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 C used in manufacturing C 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 C used in these industrial processes may be derived from natural or synthetic graphite sources, but sufficient data to estimate emissions are not currently available.

Miscellaneous SF$_6$ Uses

Sulfur hexafluoride (SF$_6$) is used in several applications for which estimates have not been provided in this inventory. Sulfur hexafluoride 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. 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. Emissions from this source are believed to be minor, and no data were available for estimating the emissions. Sulfur hexafluoride may be emitted from the production, breakage, or leakage of soundproof double-glazed windows. Emissions from this source are believed to be minor, and no data were available for estimating the emissions. Sulfur hexafluoride may be emitted from applications involving the production of sport shoes, tires, and tennis balls. Emissions from this source are believed to be minor, and no data were available for estimating the emissions. Sulfur hexafluoride may be emitted from applications involving tracer gasses to detect leakage from pressure vessels and as a tracer gas in the open air. Emissions from this source are believed to be minor, and no data were available for estimating the emissions.

CO$_2$ from Non-Hazardous Industrial Waste Incineration

Waste incineration is incorporated in two sections of the energy chapter of the inventory: in the section on CO_2 emissions from waste incineration, 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 important category of waste incineration 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.

ANNEX 6 Additional Information

6.1.   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 teragrams of CO_2 equivalents (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, 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 A-256).

> *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.*[80]

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. However, the short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, other indirect greenhouse gases (e.g., NO_x and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and black carbon) 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.

Table A-256: 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-32	5.6	650	2,100	200
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

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[80] 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)

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-43-10mee	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_3F_8	2,600	7,000	4,800	10,100
C_4F_{10}	2,600	7,000	4,800	10,100
$c\text{-}C_4F_8$	3,200	8,700	6,000	12,700
C_5F_{12}	4,100	7,500	5,100	11,000
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 A-257 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. 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 (see note below Table A-257). The effects of these compounds on radiative forcing are not addressed in this report

Table A-257: 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)

Parentheses indicate negative values.

Note: 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 has published its Fourth Assessment Report (AR4), providing the most current and comprehensive scientific assessment of climate change (IPCC 2007). Within this report, the GWPs of several gases were revised relative to the SAR and the IPCC's Third Assessment Report (TAR) (IPCC 2001). Thus the GWPs used in this report have been updated twice by the IPCC; although the SAR GWPs are used throughout this report, it is informative to review the changes to the GWPs and the impact such improved understanding has on the total GWP-weighted emissions of the United States. All GWPs use CO_2 as a reference gas; a change in the radiative efficiency of CO_2 thus impacts the GWP of all other greenhouse gases. Since the SAR and TAR, the IPCC has applied an improved calculation of CO_2 radiative forcing and an improved CO_2 response function. The GWPs are drawn from IPCC/TEAP (2005) and the TAR, with updates for those cases where new laboratory or radiative transfer results have been published. Additionally, the atmospheric lifetimes of some gases have been recalculated. Because the revised radiative forcing of CO_2 is about 8 percent lower than that in the TAR, 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. Updates in some well-mixed HFC compounds (including HFC-23, HFC-32, HFC-134a, and HFC-227ea) for

AR4 result from investigation into radiative efficiencies in these compounds, with some GWPs changing by up to 40 percent; with this change, the uncertainties associated with these well-mixed HFCs are thought to be approximately 12 percent.

Table A- 258 compares the lifetimes and GWPs for the SAR, TAR, and AR4.

Table A- 258: Comparison of GWPs and lifetimes used in the SAR, TAR, and AR4

Gas	Lifetime (years)			GWP (100 year)			Difference (relative to SAR)			
	SAR	TAR	AR4	SAR	TAR	AR4	TAR	TAR (%)	AR4	AR4 (%)
Carbon dioxide (CO$_2$)	50-200	5-200[a]	5-200[a]	1	1	1	NC	NC	NC	NC
Methane (CH$_4$)[b]	12±3	8.4/12[c]	8.7/12[c]	21	23	25	2	10%	4	19%
Nitrous oxide (N$_2$O)	120	120/114[c]	120/114[c]	310	296	298	(14)	(5%)	(12)	(4%)
Hydrofluorocarbons										
HFC-23	264	260	270	11,700	12,000	14,800	300	3%	3,100	26%
HFC-32	5.6	5.0	4.9	650	550	675	(100)	(15%)	25	4%
HFC-125	32.6	29	29	2,800	3,400	3,500	600	21%	700	25%
HFC-134a	14.6	13.8	14	1,300	1,300	1,430	NC	NC	130	10%
HFC-143a	48.3	52	52	3,800	4,300	4,470	500	13%	670	18%
HFC-152a	1.5	1.4	1.4	140	120	124	(20)	(14%)	(16)	(11%)
HFC-227ea	36.5	33.0	34.2	2,900	3,500	3,220	600	21%	320	11%
HFC-236fa	209	220	240	6,300	9,400	9,810	3,100	49%	3,510	56%
HFC-245fa	NA	7.2	7.6	NA	950	1,030	NA	NA	NA	NA
HFC-365mfc	NA	9.9	6.6	NA	890	794	NA	NA	NA	NA
HFC-43-10mee	17.1	15	15.9	1,300	1,500	1,640	200	15%	340	26%
Fully Fluorinated Species										
SF$_6$	3,200	3,200	3200	23,900	22,200	22,800	(1,700)	(7%)	(1,100)	(5%)
CF$_4$	50,000	50,000	50,000	6,500	5,700	7,390	(800)	(12%)	890	14%
C$_2$F$_6$	10,000	10,000	10,000	9,200	11,900	12,200	2,700	29%	3,000	33%
C$_3$F$_8$	2,600	2,600	2,600	7,000	8,600	8,830	1,600	23%	1,830	26%
C$_4$F$_{10}$	2,600	2,600	2,600	7,000	8,600	8,860	1,600	23%	1,860	27%
c-C$_4$F$_8$	3,200	3,200	3,200	8,700	10,000	10,300	1,300	15%	1,600	18%
C$_5$F$_{12}$	4,100	4,100	4,100	7,500	8,900	9,160	1,400	19%	1,660	22%
C$_6$F$_{14}$	3,200	3,200	3,200	7,400	9,000	9,300	1,600	22%	1,900	26%
Others[d]										
NF$_3$	NA	740	740	NA	10,800	17,200	NA	NA	NA	NA

NC (No Change)
NA (Not Applicable)
a No single lifetime can be determined for CO$_2$. (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 determined only via indirect means or for whom there is uncertainty over the loss process.
Note: Parentheses indicate negative values.
Source: IPCC (2001)

The choice of GWPs between the SAR, TAR, and AR4 has an impact on both the overall emissions estimated by the inventory, as well as the trend in emissions over time. To summarize, Table A-259 shows the overall trend in U.S. greenhouse gas emissions, by gas, from 1990 through 2009 using the three GWP sets. The table also presents the impact of TAR and AR4 GWPs on the total emissions for 1990 and for 2009.

Table A-259: Effects on U.S. Greenhouse Gas Emissions Using TAR, SAR, and AR4 GWPs (Tg CO$_2$ Eq.)

Gas	Trend from 1990 to 2009			Revisions to Annual Estimates (relative to SAR)			
				TAR	AR4	TAR	AR4
	SAR	TAR	AR4	1990		2009	
CO$_2$	405.5	405.5	405.5	NC	NC	NC	NC
CH$_4$	11.4	12.5	13.6	64.3	128.5	65.4	130.7
N$_2$O	(19.6)	(18.7)	(18.8)	(14.2)	(12.2)	(13.4)	(11.4)
HFCs, PFCs, and SF$_6$*	54.1	59.8	57.3	(2.3)	11.8	3.3	15.0
Total	**451.4**	**459.1**	**457.6**	**47.7**	**128.1**	**55.3**	**134.3**
Percent Change	**7.3%**	**7.4%**	**7.3%**	**0.8%**	**2.1%**	**0.8%**	**2.0%**

NC (No Change)
*Includes NF$_3$
Note: Totals may not sum due to independent rounding. Excludes sinks. Parentheses indicate negative values.

When the GWPs from the AR4 are applied to the emission estimates presented in this report, total emissions for the year 2009 are 6,767.5 Tg CO_2 Eq., as compared to 6,633.2 Tg CO_2 Eq. when the GWPs from the SAR are used (a 2.0 percent difference). Table A-260 provides a detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 2009, using the GWPs from the AR4. 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 A-261 summarizes the resulting change in emissions from SAR to AR4 GWPs for 1990 through 2009 including the percent change for 2009.

Table A-260: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks using the AR4 GWPs (Tg CO_2 Eq.)

Gas/Source	1990	2000	2005	2006	2007	2008	2009
CO₂	**5,099.7**	**5,975.0**	**6,113.8**	**6,021.1**	**6,120.0**	**5,921.4**	**5,505.2**
Fossil Fuel Combustion	4,738.4	5,594.8	5,735.2	5,653.1	5,756.7	5,565.9	5,209.0
Electricity Generation	1,820.8	2,296.9	2,402.1	2,346.4	2,412.8	2,360.9	2,154.0
Transportation	1,485.9	1,809.5	1,896.6	1,878.1	1,894.0	1,789.9	1,719.7
Industrial	846.5	851.1	823.1	848.2	842.0	802.9	730.4
Residential	338.3	370.7	357.9	321.5	342.4	348.2	339.2
Commercial	219.0	230.8	223.5	208.6	219.4	224.2	224.0
U.S. Territories	27.9	35.9	50.0	50.3	46.1	39.8	41.7
Non-Energy Use of Fuels	118.6	144.9	143.4	145.6	137.2	141.0	123.4
Iron and Steel Production & Metallurgical Coke Production	99.5	85.9	65.9	68.8	71.0	66.0	41.9
Natural Gas Systems	37.6	29.9	29.9	30.8	31.1	32.8	32.2
Cement Production	33.3	40.4	45.2	45.8	44.5	40.5	29.0
Incineration of Waste	8.0	11.1	12.5	12.5	12.7	12.2	12.3
Ammonia Production and Urea Consumption	16.8	16.4	12.8	12.3	14.0	11.9	11.8
Lime Production	11.5	14.1	14.4	15.1	14.6	14.3	11.2
Cropland Remaining Cropland	7.1	7.5	7.9	7.9	8.2	8.7	7.8
Limestone and Dolomite Use	5.1	5.1	6.8	8.0	7.7	6.3	7.6
Soda Ash Production and Consumption	4.1	4.2	4.2	4.2	4.1	4.1	4.3
Aluminum Production	6.8	6.1	4.1	3.8	4.3	4.5	3.0
Petrochemical Production	3.3	4.5	4.2	3.8	3.9	3.4	2.7
Carbon Dioxide Consumption	1.4	1.4	1.3	1.7	1.9	1.8	1.8
Titanium Dioxide Production	1.2	1.8	1.8	1.8	1.9	1.8	1.5
Ferroalloy Production	2.2	1.9	1.4	1.5	1.6	1.6	1.5
Wetlands Remaining Wetlands	1.0	1.2	1.1	0.9	1.0	1.0	1.1
Phosphoric Acid Production	1.5	1.4	1.4	1.2	1.2	1.2	1.0
Zinc Production	0.7	1.0	1.1	1.1	1.1	1.2	1.0
Lead Production	0.5	0.6	0.6	0.6	0.6	0.6	0.5
Petroleum Systems	0.6	0.5	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.1
Land Use, Land-Use Change, and Forestry (Sink)[a]	*(861.5)*	*(576.6)*	*(1,056.5)*	*(1,064.3)*	*(1,060.9)*	*(1,040.5)*	*(1,015.1)*
Wood Biomass and Ethanol Consumption[b]	*219.4*	*227.4*	*229.8*	*234.8*	*242.3*	*253.1*	*245.0*

International Bunker Fuels[c]	*111.8*	*98.5*	*109.7*	*128.4*	*127.6*	*133.7*	*123.1*
CH₄	**803.4**	**785.6**	**751.7**	**800.1**	**791.2**	**805.6**	**817.0**
Natural Gas Systems	226.0	249.2	226.7	259.1	244.3	252.2	263.4
Enteric Fermentation	157.3	162.5	162.5	165.3	167.9	167.4	166.4
Landfills	175.5	132.9	133.9	133.0	132.5	138.0	139.8
Coal Mining	100.1	71.9	67.7	69.3	68.9	79.9	84.6
Manure Management	37.8	50.5	55.4	55.6	60.4	58.8	58.9
Petroleum Systems	42.1	37.5	35.0	34.9	35.7	36.0	36.8
Wastewater Treatment	28.0	30.0	29.0	29.2	29.1	29.2	29.2
Forest Land Remaining Forest Land	3.8	17.0	11.7	25.7	23.8	14.2	9.3
Rice Cultivation	8.5	8.9	8.2	7.0	7.4	8.6	8.7
Stationary Combustion	8.8	7.9	7.8	7.3	7.7	7.7	7.3
Abandoned Underground Coal Mines	7.2	8.8	6.6	6.5	6.7	7.0	6.6
Mobile Combustion	5.6	4.0	3.0	2.8	2.6	2.4	2.3
Composting	0.4	1.5	1.9	1.9	2.0	2.0	2.0
Petrochemical Production	1.0	1.5	1.3	1.2	1.2	1.1	1.0
Iron and Steel Production & Metallurgical Coke Production	1.1	1.1	0.9	0.9	0.8	0.8	0.4
Field Burning of Agricultural Residues	0.3	0.3	0.2	0.3	0.3	0.3	0.3
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[c]	*0.2*	*0.1*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*
N₂O	**303.0**	**327.8**	**310.4**	**313.8**	**312.5**	**298.7**	**284.2**
Agricultural Soil Management	190.1	198.8	203.2	200.8	201.3	202.6	196.7
Mobile Combustion	42.2	51.1	35.5	32.3	29.1	25.1	23.0
Manure Management	13.9	16.4	16.6	17.3	17.4	17.2	17.2
Nitric Acid Production	17.0	18.7	15.9	15.5	18.5	15.8	14.0
Stationary Combustion	12.3	14.0	14.1	13.9	14.0	13.6	12.3
Forest Land Remaining Forest Land	2.6	11.6	8.0	17.3	16.1	9.7	6.5
Wastewater Treatment	3.5	4.3	4.6	4.6	4.7	4.8	4.8
N2O from Product Uses	4.2	4.7	4.2	4.2	4.2	4.2	4.2
Adipic Acid Production	15.2	5.3	4.8	4.1	3.5	2.0	1.9
Composting	0.3	1.3	1.7	1.7	1.8	1.8	1.8
Settlements Remaining Settlements	0.9	1.1	1.4	1.4	1.5	1.5	1.5
Incineration of Waste	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wetlands Remaining Wetlands	+	+	+	+	+	+	+

Gas/Source	1990	2000	2005	2006	2007	2008	2009
International Bunker Fuels[c]	*1.0*	*0.9*	*1.0*	*1.1*	*1.1*	*1.2*	*1.1*
HFCs, PFCs, and SF6	**103.8**	**152.4**	**160.1**	**162.5**	**170.4**	**168.6**	**161.1**
HFCs	**46.6**	**116.9**	**134.0**	**137.4**	**144.9**	**144.5**	**139.5**
Substitution of Ozone Depleting Substances[d]	0.3	80.4	113.7	119.6	123.1	126.9	132.3
HCFC-22 Production	46.1	36.2	20.0	17.5	21.5	17.2	6.8
Semiconductor Manufacture	0.2	0.3	0.3	0.3	0.3	0.4	0.4
PFCs	**24.4**	**16.2**	**7.9**	**8.0**	**9.6**	**8.7**	**7.5**
Semiconductor Manufacture	2.9	6.3	4.5	5.1	5.1	5.5	5.6
Aluminum Production	21.6	9.9	3.4	2.9	4.5	3.2	1.9
SF6	**32.8**	**19.2**	**18.1**	**17.1**	**15.9**	**15.4**	**14.2**
Electrical Transmission and Distribution	27.1	15.3	14.4	13.4	12.6	12.7	12.2
Magnesium Production and Processing	5.2	2.9	2.8	2.7	2.5	1.8	1.0
Semiconductor Manufacture	0.5	1.0	0.9	0.9	0.8	0.8	0.9
Total	**6,309.9**	**7,240.7**	**7,336.0**	**7,297.5**	**7,394.1**	**7,194.4**	**6,767.5**

+ Does not exceed 0.05 Tg CO_2 Eq.

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

[b] Emissions from Wood Biomass and Ethanol Consumption are not included specifically in summing energy sector totals.

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

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

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

Table A-261: Change in U.S. Greenhouse Gas Emissions and Sinks Using SAR vs. AR4 GWPs (Tg CO_2 Eq.)

Gas/Source	1990	2000	2005	2006	2007	2008	2009	Percent Change in 2009
CO2	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**
CH4	**128.5**	**125.7**	**120.3**	**128.0**	**126.6**	**128.9**	**130.7**	**19%**
Natural Gas Systems	36.2	39.9	36.3	41.5	39.1	40.3	42.1	19%
Enteric Fermentation	25.2	26.0	26.0	26.4	26.9	26.8	26.6	19%
Landfills	28.1	21.3	21.4	21.3	21.2	22.1	22.4	19%
Coal Mining	16.0	11.5	10.8	11.1	11.0	12.8	13.5	19%
Manure Management	6.0	8.1	8.9	8.9	9.7	9.4	9.4	19%
Petroleum Systems	6.7	6.0	5.6	5.6	5.7	5.8	5.9	19%
Wastewater Treatment	4.5	4.8	4.6	4.7	4.7	4.7	4.7	19%
Forest Land Remaining Forest Land	0.6	2.7	1.9	4.1	3.8	2.3	1.5	19%
Rice Cultivation	1.4	1.4	1.3	1.1	1.2	1.4	1.4	19%
Stationary Combustion	1.4	1.3	1.2	1.2	1.2	1.2	1.2	19%
Abandoned Underground Coal Mines	1.2	1.4	1.1	1.0	1.1	1.1	1.0	19%
Mobile Combustion	0.9	0.6	0.5	0.4	0.4	0.4	0.4	19%
Composting	0.1	0.2	0.3	0.3	0.3	0.3	0.3	19%
Petrochemical Production	0.2	0.2	0.2	0.2	0.2	0.2	0.2	19%
Iron and Steel Production & Metallurgical Coke Production	0.2	0.2	0.1	0.1	0.1	0.1	0.1	19%
Field Burning of Agricultural Residues	0.1	+	+	+	+	0.1	+	19%
Ferroalloy Production	+	+	+	+	+	+	+	19%
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+	19%
Incineration of Waste	+	+	+	+	+	+	+	19%
International Bunker Fuels[a]	+	+	+	+	+	+	+	*19%*
N2O	**(12.2)**	**(13.2)**	**(12.5)**	**(12.6)**	**(12.6)**	**(12.0)**	**(11.4)**	**(4%)**

Agricultural Soil Management	(7.7)	(8.0)	(8.2)	(8.1)	(8.1)	(8.2)	(7.9)	(4%)
Mobile Combustion	(1.7)	(2.1)	(1.4)	(1.3)	(1.2)	(1.0)	(0.9)	(4%)
Manure Management	(0.6)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(4%)
Nitric Acid Production	(0.7)	(0.8)	(0.6)	(0.6)	(0.7)	(0.6)	(0.6)	(4%)
Stationary Combustion	(0.5)	(0.6)	(0.6)	(0.6)	(0.6)	(0.5)	(0.5)	(4%)
Forest Land Remaining Forest Land	(0.1)	(0.5)	(0.3)	(0.7)	(0.6)	(0.4)	(0.3)	(4%)
Wastewater Treatment	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(4%)
N2O from Product Uses	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(4%)
Adipic Acid Production	(0.6)	(0.2)	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(4%)
Composting	(+)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(4%)
Settlements Remaining Settlements	(+)	(+)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(4%)
Incineration of Waste	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(4%)
Field Burning of Agricultural Residues	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(4%)
Wetlands Remaining Wetlands	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(4%)
International Bunker Fuels[a]	*(+)*	*(+)*	*(+)*	*(+)*	*(+)*	*(+)*	*(+)*	*(4%)*
HFCs, PFCs, and SF$_6$	**11.8**	**15.6**	**14.6**	**15.1**	**16.7**	**16.4**	**15.0**	**10%**
HFCs	**9.7**	**13.7**	**13.8**	**14.0**	**15.4**	**15.1**	**13.8**	**11%**
Substitution of Ozone Depleting Substances	(+)	6.1	9.5	10.2	10.8	11.4	12.3	10%
HCFC-22 Production	9.7	7.6	4.2	3.7	4.5	3.6	1.4	26%
Semiconductor Manufacture	+	0.1	0.1	0.1	0.1	0.1	0.1	26%
PFCs	**3.7**	**2.8**	**1.8**	**2.0**	**2.1**	**2.0**	**1.9**	**33%**
Semiconductor Manufacture	0.6	1.4	1.3	1.6	1.5	1.6	1.6	40%
Aluminum Production	3.0	1.3	0.5	0.4	0.6	0.5	0.3	17%
SF$_6$	**(1.6)**	**(0.9)**	**(0.9)**	**(0.8)**	**(0.8)**	**(0.7)**	**(0.7)**	**(5%)**
Electrical Transmission and Distribution	(1.3)	(0.7)	(0.7)	(0.6)	(0.6)	(0.6)	(0.6)	(5%)
Magnesium Production and Processing	(0.3)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(+)	(5%)
Semiconductor Manufacture	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(5%)
Total	**128.1**	**128.1**	**122.4**	**130.5**	**130.7**	**133.3**	**134.3**	**2.0%**

NC (No change)

+ Does not exceed 0.05 Tg CO_2 Eq.

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

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

Table A-262 below shows a comparison of total emissions estimates by sector using both the IPCC SAR and AR4 GWP values. For most sectors, the change in emissions was minimal. The effect on emissions from waste was by far the greatest (18 percent in 2009), 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 A-262: Comparison of Emissions by Sector using IPCC SAR and AR4 GWP Values (Tg CO_2 Eq.)

Sector	1990	2000	2005	2006	2007	2008	2009
Energy							
SAR GWP (Used in Inventory)	5,287.8	6,168.0	6,282.8	6,210.2	6,290.7	6,116.6	5,751.1
AR4 GWP, Updated	5,347.9	6,226.1	6,336.3	6,269.1	6,347.5	6,176.7	5,813.8
Difference (%)	1.1%	0.9%	0.9%	0.9%	0.9%	1.0%	1.1%
Industrial Processes							
SAR GWP (Used in Inventory)	315.8	348.8	334.1	339.4	350.9	331.7	282.9
AR4 GWP, Updated	326.6	363.9	348.2	354.1	367.1	347.7	297.5
Difference (%)	3.4%	4.3%	4.2%	4.3%	4.6%	4.8%	5.2%
Solvent and Other Product Use							
SAR GWP (Used in Inventory)	4.4	4.9	4.4	4.4	4.4	4.4	4.4
AR4 GWP, Updated	4.2	4.7	4.2	4.2	4.2	4.2	4.2
Difference (%)	(3.9%)	(3.9%)	(3.9%)	(3.9%)	(3.9%)	(3.9%)	(3.9%)
Agriculture							
SAR GWP (Used in Inventory)	383.6	410.6	418.8	418.8	425.8	426.3	419.3
AR4 GWP, Updated	408.0	437.5	446.1	446.5	454.7	455.0	448.2
Difference (%)	6.4%	6.5%	6.5%	6.6%	6.8%	6.7%	6.9%
Land Use, Land-Use Change, and Forestry							

SAR GWP (Used in Inventory)	(846.6)	(540.3)	(1,027.9)	(1,014.5)	(1,013.4)	(1,007.3)	(990.1)
AR4 GWP, Updated	(846.1)	(539.3)	(1,027.5)	(1,012.1)	(1,011.3)	(1,006.4)	(990.0)
Difference (%)	(0.1%)	(0.2%)	0.0%	(0.2%)	(0.2%)	(0.1%)	(0.0%)
Waste							
SAR GWP (Used in Inventory)	175.2	143.9	144.9	144.4	144.1	149.0	150.5
AR4 GWP, Updated	207.7	170.0	171.0	170.4	170.0	175.8	177.6
Difference (%)	18.5%	18.1%	18.0%	18.0%	18.0%	18.0%	18.0%
Net Emissions (Sources and Sinks)							
SAR GWP (Used in Inventory)	**5,320.3**	**6,536.1**	**6,157.1**	**6,102.6**	**6,202.5**	**6,020.7**	**5,618.2**
AR4 GWP	**5,448.4**	**6,662.9**	**6,278.4**	**6,232.3**	**6,332.2**	**6,153.0**	**5,751.3**
Difference (%)	**2.4%**	**1.9%**	**2.0%**	**2.1%**	**2.1%**	**2.2%**	**2.4%**

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

Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends, as shown in Table A-263 and Table A-264.

Table A-263: Change in U.S. Greenhouse Gas Emissions and Sinks Using TAR vs. AR4 GWPs (Tg CO$_2$ Eq.)

Gas	1990	2000	2005	2006	2007	2008	2009
CO$_2$	NC	NC	NC	NC	NC	NC	NC
CH$_4$	64.3	62.8	60.1	64.0	63.3	64.4	65.4
N$_2$O	2.0	2.2	2.1	2.1	2.1	2.0	1.9
HFCs	8.8	13.4	12.5	12.2	13.0	12.2	10.3
PFCs*	4.5	2.7	1.2	1.2	1.5	1.2	1.0
SF$_6$	0.9	0.5	0.5	0.4	0.4	0.4	0.4
Total	**80.4**	**81.7**	**76.3**	**80.0**	**80.2**	**80.3**	**78.9**

NC (No change)
*Includes NF$_3$
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table A-264: Change in U.S. Greenhouse Gas Emissions Using TAR vs. AR4 GWPs (Percent)

Gas/Source	1990	2000	2005	2006	2007	2008	2009
CO$_2$	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**
CH$_4$	**8.7%**	**8.7%**	**8.7%**	**8.7%**	**8.7%**	**8.7%**	**8.7%**
N$_2$O	**0.7%**	**0.7%**	**0.7%**	**0.7%**	**0.7%**	**0.7%**	**0.7%**
HFCs	**23.2%**	**13.0%**	**10.2%**	**9.8%**	**9.8%**	**9.2%**	**7.9%**
Substitution of Ozone Depleting Substances	3.3%	8.8%	8.2%	8.0%	7.7%	7.5%	7.2%
HCFC-22 Production[b]	23.3%	23.3%	23.3%	23.3%	23.3%	23.3%	23.3%
Semiconductor Manufacture[c]	23.3%	23.3%	23.3%	23.3%	23.3%	23.3%	23.3%
PFCs	**22.4%**	**19.9%**	**17.7%**	**17.6%**	**17.8%**	**16.8%**	**15.8%**
Semiconductor Manufacture[c]	10.0%	11.3%	13.1%	14.2%	13.4%	13.6%	13.7%
Aluminum Production[a]	24.2%	26.0%	24.4%	24.2%	23.4%	22.9%	22.8%
SF$_6$	**2.7%**	**2.7%**	**2.7%**	**2.7%**	**2.7%**	**2.7%**	**2.7%**
Total	**1.3%**	**1.8%**	**1.7%**	**1.8%**	**1.8%**	**1.9%**	**2.0%**

NC (No change)
a PFC emissions from CF$_4$ and C$_2$F$_6$
b HFC-23 emitted
c Emissions from HFC-23, CF$_4$, C$_2$F$_6$, C$_3$F$_8$, SF$_6$, and the addition of NF$_3$
Note: Excludes Sinks. Parentheses indicate negative values.

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IPCC (2001) Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change, J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.). Cambridge University Press. Cambridge, United Kingdom.

6.2. Ozone Depleting Substance Emissions

Ozone is present in both the stratosphere,[81] where it shields the earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[82] 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.[83] 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,[84] and stockpiles of the ODSs, as well as material recovered from equipment being decommissioned, are used for maintaining the existing equipment. As a result, emissions of Class I compounds will continue, albeit in ever decreasing amounts, for many more years. Class II designated substances, all of which are hydrochlorofluorocarbons (HCFCs), have been, or are being, phased out at later dates than Class I compounds because they have lower ozone depletion potentials. These compounds served, and in some cases continue to 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 continue for several decades as equipment that use Class I as equipment that use Class I substances and Class II 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; overall, stratospheric ozone has a warming effect.

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 Global Warming Potential Values Annex 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 A- 265.

Table A- 265: Emissions of Ozone Depleting Substances (Gg)

Compound	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Class I												
CFC-11	29.0	12.1	12.7	12.7	12.6	12.7	12.4	12.2	12.2	11.1	9.9	8.6

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[81] 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.

[82] 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.

[83] 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.

[84] Older refrigeration and air-conditioning equipment, fire extinguishing systems, meter-dose inhalers, and foam products blown with CFCs/HCFCs may still contain ODS.

CFC-12	106.5		65.0		32.9	26.7	21.3	16.6	12.4	8.6	6.3	5.8	4.9	4.0
CFC-113	59.4		11.5		+	+	+	+	+	+	+	+	+	+
CFC-114	5.4		1.1		0.5	0.4	0.4	0.3	0.3	0.2	0.2	0.2	0.1	0.1
CFC-115	5.5		5.3		4.1	3.6	3.2	2.7	2.0	1.3	0.6	0.2	0.1	0.1
Carbon Tetrachloride	4.3		0.9		+	+	+	+	+	+	+	+	+	+
Methyl Chloroform	222.5		72.1		+	+	+	+	+	+	+	+	+	+
Halon-1211	1.6		1.6		1.1	0.9	0.8	0.7	0.7	0.7	0.7	0.6	0.6	0.6
Halon-1301	1.6		1.6		1.5	1.5	1.5	1.5	1.5	1.4	1.3	1.1	0.9	0.8
Class II														
HCFC-22	44.4		55.0		71.9	74.8	77.9	79.4	81.3	81.7	83.2	83.7	84.7	84.5
HCFC-123	+		0.3		0.6	0.6	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8
HCFC-124	+		1.2		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.6
HCFC-141b	1.0		4.0		7.0	6.7	5.6	4.0	4.1	4.2	4.3	5.5	6.9	8.4
HCFC-142b	2.1		3.6		2.7	2.8	2.9	3.0	3.2	3.3	3.4	3.5	3.7	2.5
HCFC-225ca/cb	+		0.1		0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3

+ Does not exceed 0.05 Gg.

Methodology and Data Sources

Emissions of ozone depleting substances were estimated using the EPA's Vintaging Model. 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. Please see HFC and PFC Emissions from Substitution of Ozone Depleting Substances Annex 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. Please see the ODS Substitutes section of this report for a more detailed description of the uncertainties that exist in the Vintaging Model.

References

IPCC (1996) Climate Change 1995: The Science of Climate Change. Intergovernmental Panel on Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell. (eds.). Cambridge University Press. Cambridge, United Kingdom.

6.3. 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 2007). 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 A-266.

The major source of SO_2 emissions in the United States is the burning of sulfur containing fuels, mainly coal. Metal smelting and other industrial processes also release significant quantities of SO_2. The largest contributor to U.S. emissions of SO_2 is electricity generation, accounting for 60 percent of total SO_2 emissions in 2009 (see Table A-267); coal combustion accounted for approximately 92 percent of that total. The second largest source was industrial fuel combustion, which produced 18 percent of 2009 SO_2 emissions. Overall, SO_2 emissions in the United States decreased by 59 percent from 1990 to 2009. The majority of this decline came from reductions from electricity generation, 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,[85] (2) New Source Performance Standards,[86] (3) the New Source Review/Prevention of Significant Deterioration Program,[87] and (4) the sulfur dioxide allowance program.[88]

Table A-266: SO₂ Emissions (Gg)

Sector/Source	1990	2000	2005	2006	2007	2008	2009
Energy	**19,628**	**13,797**	**12,634**	**11,568**	**10,991**	**9,573**	**7,800**
Stationary Combustion	18,407	12,849	11,541	10,612	10,172	8,891	7,167
Mobile Combustion	793	632	889	750	611	472	455
Oil and Gas Activities	390	287	181	182	184	187	154
Waste Combustion	38	29	24	24	24	23	24
Industrial Processes	**1,307**	**1,031**	**831**	**818**	**807**	**795**	**798**
Chemical Manufacturing	269	307	228	230	230	231	222
Metals Processing	659	284	159	167	176	184	158
Storage and Transport	6	5	3	3	4	4	2
Other Industrial Processes	362	372	327	318	308	298	324
Miscellaneous*	11	64	114	102	89	77	91
Solvent Use	**+**	**1**	**+**	**+**	**+**	**+**	**+**
Degreasing	+	+	+	+	+	+	+
Graphic Arts	+	+	+	+	+	+	+
Dry Cleaning	NA	+	+	+	+	+	+
Surface Coating	+	+	+	+	+	+	+
Other Industrial	+	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	**+**	**1**	**1**	**1**	**1**	**1**	**1**
Landfills	+	1	1	1	1	1	1
Wastewater Treatment	+	+	+	+	+	+	+
Miscellaneous Waste	+	+	+	+	+	+	+
Total	**20,935**	**14,830**	**13,466**	**12,388**	**11,799**	**10,368**	**8,599**

[85] [42 U.S.C § 7409, CAA § 109]

[86] [42 U.S.C § 7411, CAA § 111]

[87] [42 U.S.C § 7473, CAA § 163]

[88] [42 U.S.C § 7651, CAA § 401]

Source: Data taken from EPA (2005) and disaggregated based on EPA (2003).
* Miscellaneous includes other combustion and fugitive dust categories.
+ Does not exceed 0.5 Gg
NA (Not Available)
Note: Totals may not sum due to independent rounding.

Table A-267: SO$_2$ Emissions from Electricity Generation (Gg)

Fuel Type	1990		2000		2005	2006	2007	2008	2009
Coal	13,808		9,620		8,680	7,846	7,459	6,300	4,718
Petroleum	580		428		458	414	393	332	249
Natural Gas	1		157		174	157	149	126	94
Misc. Internal Combustion	45		54		57	52	49	41	31
Other	NA		78		71	64	61	51	38
Total	**14,433**		**10,338**		**9,439**	**8,532**	**8,111**	**6,851**	**5,131**

Source: Data taken from EPA (2009 and 2010) and disaggregated based on EPA (2003).
Note: Totals may not sum due to independent rounding.

References

EPA (2010). "2009 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards.

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IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon , D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom.

6.4. Complete List of Source Categories

Chapter/Source	Gas(es)
Energy	
Fossil Fuel Combustion	CO_2
Non-Energy Use 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
Abandoned Underground Coal Mines	CH_4
Natural Gas Systems	CH_4
Petroleum Systems	CH_4
Incineration of Waste	CO_2, CH_4, N_2O
Industrial Processes	
Titanium Dioxide Production	CO_2
Aluminum Production	CO_2, CF_4, C_2F_6
Iron and Steel Production	CO_2, CH_4
Ferroalloy Production	CO_2, CH_4
Ammonia Production and Urea Consumption	CO_2
Cement Production	CO_2
Lime Production	CO_2
Limestone and Dolomite Use	CO_2
Soda Ash Production and Consumption	CO_2
Carbon Dioxide Consumption	CO_2
Phosphoric Acid Production	CO_2
Petrochemical Production	CH_4, CO_2
Silicon Carbide Production and Consumption	CH_4, CO_2
Lead Production	CO_2
Zinc Production	CO_2
Adipic Acid Production	N_2O
Nitric Acid Production	N_2O
Substitution of Ozone Depleting Substances	HFCs, PFCs[a]
HCFC-22 Production	HFC-23
Semiconductor Manufacture	HFCs, PFCs, SF_6[b]
Electrical Transmission and Distributing	SF_6
Magnesium Production and Processing	SF_6
Solvent and Other Product Use	CO, NO_x, NMVOC
N_2O Product Usage	N_2O
Agriculture	
Enteric Fermentation	CH_4
Manure Management	CH_4, N_2O
Rice Cultivation	CH_4
Field Burning of Agricultural Residues	CH_4, N_2O
Agricultural Soil Management	N_2O, CO, NO_x
Land Use, Land-Use Change, and Forestry	
CO_2 Flux	CO_2 (sink)
Cropland Remaining Cropland	CO_2
Settlements Remaining Settlements	N_2O
Forestland Remaining Forestland	CH_4, N_2O
Wetlands Remaining Wetlands	CO_2, N_2O
Waste	
Landfills	CH_4
Wastewater Treatment	CH_4, N_2O
Composting	CH_4, N_2O

[a] Includes HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-236fa, CF_4, HFC-152a, HFC-227ea, HFC-245fa, HFC-4310mee, and PFC/PFPEs.

[b] Includes such gases as HFC-23, CF_4, C_2F_6, SF_6.

6.5. 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. Table A- 268 provides a guide for determining the magnitude of metric units.

Table A- 268: 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	=	0.001 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[89]

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 =
2.388×10^{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 conversion factors in Table A-269 can be used as default factors, if local data are not available. See Appendix A of EIA's *Annual Energy Review 2009* (EIA 2010) for more detailed information on the energy content of various fuels.

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[89] Reference: EIA (2007)

Table A-269: 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)	
Motor gasoline	5.150
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 2009* (EIA 2010). For coal ranks, *State Energy Data Report 1992* (EIA 1993). All values are given in higher heating values (gross calorific values).

References

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EIA (1993) *State Energy Data Report 1992*, DOE/EIA-0214(93), Energy Information Administration, U.S. Department of Energy. Washington, DC. December.

6.6.   Abbreviations

AAPFCO	American Association of Plant Food Control Officials
ABS	Acrylonitrile Butadiene Styrene
AFEAS	Alternative Fluorocarbon Environmental Acceptability Study
AFV	Alternative Fuel Vehicle
AGA	American Gas Association
AHEF	Atmospheric and Health Effect Framework
AISI	American Iron and Steel Institute
ANL	Argonne National Laboratory
APC	American Plastics Council
API	American Petroleum Institute
ASAE	American Society of Agricultural Engineers
ASTM	American Society for Testing and Materials
BCEF	Biomass conversion and expansion factors
BEA	Bureau of Economic Analysis, U.S. Department of Commerce
BoC	Bureau of Census
BOD5	Biochemical oxygen demand over a 5-day period
BOF	Basic Oxygen Furnace
BRS	Biennial Reporting System
BTS	Bureau of Transportation Statistics, U.S. Department of Transportation
Btu	British thermal unit
C&EN	Chemical and Engineering News
CAAA	Clean Air Act Amendments of 1990
CAPP	Canadian Association of Petroleum Producers
CARB	California Air Resources Board
CBI	Confidential Business Information
CEFM	Cattle Enteric Fermentation Model
CFC	Chlorofluorocarbon
CFR	Code of Federal Regulations
CKD	Cement Kiln Dust
CMA	Chemical Manufacturer's Association
CMOP	Coalbed Methane Outreach Program
CNG	Compressed Natural Gas
CRF	Common Reporting Format
CRP	Conservation Reserve Program
CTIC	Conservation Technology Information Center
CVD	Chemical vapor deposition
DE	Digestible Energy
DESC	Defense Energy Support Center-DoD's defense logistics agency
DFAMS	Defense Fuels Automated Management System
DM	Dry Matter
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
EAF	Electric Arc Furnace
EF	Emission Factor
EFMA	European Fertilizer Manufacturers Association
EJ	Exajoule
EGR	Exhaust Gas Recirculation
EIA	Energy Information Administration, U.S. Department of Energy
EIIP	Emissions Inventory Improvement Program
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
ERS	Economic Research Service
FAA	Federal Aviation Administration
FAO	Food and Agricultural Organization
FCCC	Framework Convention on Climate Change
FEB	Fiber Economics Bureau
FGD	Flue Gas Desulphurization
FHWA	Federal Highway Administration
FIA	Forest Inventory and Analysis
FIPR	Florida Institute of Phosphate Research

FTP	Federal Test Procedure
GCV	Gross calorific value
GDP	Gross domestic product
Gg	Gigagram
GHG	Greenhouse gas
GRI	Gas Research Institute
GSAM	Gas Systems Analysis Model
GWP	Global warming potential
HBFC	Hydrobromofluorocarbon
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HDDV	Heavy duty diesel vehicle
HDGV	Heavy duty gas vehicle
HDPE	High density polyethylene
HFC	Hydrofluorocarbon
HFE	Hydrofluoroethers
HHV	Higher Heating Value
HMA	Hot Mix Asphalt
HTF	Heat Transfer Fluid
HTS	Harmonized Tariff Schedule
HWP	Harvested wood product
ICAO	International Civil Aviation Organization
IEA	International Energy Association
IFO	Intermediate Fuel Oil
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
JWR	Jim Walters Resources
LDDT	Light duty diesel truck
LDDV	Light duty diesel vehicle
LDGT	Light duty gas truck
LDGV	Light duty gas vehicle
LDPE	Low density polyethylene
LEV	Low emission vehicles
LFG	Landfill gas
LFGTE	Landfill gas-to-energy
LHV	Lower Heating Value
LLDPE	Linear low density polyethylene
LMOP	EPA's Landfill Methane Outreach Program
LNG	Liquefied Natural Gas
LPG	Liquefied petroleum gas(es)
LTO	Landing and take-off
LULUCF	Land use, land-use change, and forestry
MC	Motorcycle
MCF	Methane conversion factor
MCFD	Thousand Cubic Feet Per Day
MGO	Marine Gas Oil
MLRA	Major Land Resource Area
MMCFD	Million Cubic Feet Per Day
MMS	Minerals Management Service
MMTCE	Million metric tons carbon equivalent
MSHA	Mine Safety and Health Administration
MSW	Municipal solid waste
MTBE	Methyl Tertiary Butyl Ether
NAHMS	National Animal Health Monitoring System
NAICS	North American Industry Classification System
NAPAP	National Acid Precipitation and Assessment Program
NASS	USDA's National Agriculture Statistics Service
NCV	Net calorific value
NEU	Non-Energy Use
NEV	Neighborhood Electric Vehicle
NGL	Natural Gas Liquids
NIR	National Inventory Report
NMVOC	Non-methane volatile organic compound

NOx	Nitrogen Oxides
NPRA	National Petroleum and Refiners Association
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NRI	National Resources Inventory
NSCEP	National Service Center for Environmental Publications
NSCR	Non-selective catalytic reduction
NWS	National Weather Service
OAP	EPA Office of Atmospheric Programs
OAQPS	EPA Office of Air Quality Planning and Standards
ODP	Ozone Depleting Potential
ODS	Ozone depleting substances
OECD	Organization of Economic Co-operation and Development
OEM	Original equipment manufacturers
OMS	EPA Office of Mobile Sources
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
OTA	Office of Technology Assessment
OTAQ	EPA Office of Transportation and Air-Quality
PAH	Polycyclic Aromatic Hydrocarbons
PCC	Precipitate calcium carbonate
PDF	Probability Density Function
PECVD	Plasma enhanced chemical vapor deposition
PET	Polyethylene Terephthalate
PEVM	PFC Emissions Vintage Model
PFC	Perfluorocarbon
PFPE	Perfluoropolyether
POTW	Publicly Owned Treatment Works
Ppbv	Parts per billion (10^9) by volume
Ppmv	Parts per million(10^6) by volume
Pptv	Parts per trillion (10^{12}) by volume
PRP	Pasture/Range/Paddock
PS	Polystyrene
PSU	Primary Sample Unit
PU	Polyurethane
PVC	Polyvinyl chloride
QA/QC	Quality Assurance and Quality Control
QBtu	Quadrillion Btu
RCRA	Resource Conservation and Recovery Act
SAE	Society of Automotive Engineers
SAGE	System for assessing Aviation's Global Emissions
SAN	Styrene Acrylonitrile
SAR	IPCC Second Assessment Report
SCR	Selective catalytic reduction
SNAP	Significant New Alternative Policy Program
SNG	Synthetic natural gas
SOC	Soil Organic Carbon
STMC	Scrap Tire Management Council
SULEV	Super Ultra Low Emissions Vehicle
SWANA	Solid Waste Association of North America
TAM	Typical Animal Mass
TAME	Tertiary Amyl Methyl Ether
TAR	IPCC Third Assessment Report
TBtu	Trillion Btu
TDN	Total Digestible Nutrients
TFI	The Fertilizer Institute
Tg CO$_2$ Eq.	Teragrams carbon dioxide equivalent
TJ	Terajoule
TLEV	Traditional Low Emissions Vehicle
TMLA	Total Manufactured Layer Area
TRI	Toxic Release Inventory
TSDF	Hazardous waste treatment, storage, and disposal facility
TVA	Tennessee Valley Authority
UDA	Utility Data Institute
U.S.	United States
U.S. ITC	United States International Trade Commission

UEP	United Egg Producers
ULEV	Ultra Low Emission Vehicle
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
USAF	United States Air Force
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Survey
VAIP	EPA's Voluntary Aluminum Industrial Partnership
VKT	Vehicle kilometers traveled
VMT	Vehicle miles traveled
VOCs	Volatile Organic Compounds
VS	Volatile Solids
WIP	Waste In Place
WMO	World Meteorological Organization
WMS	Waste Management Systems
ZEVs	Zero Emissions Vehicles

6.7. Chemical Formulas

Table A-270: 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 7 Uncertainty

The annual U.S. Inventory presents the best effort to produce estimates for greenhouse gas source and sink categories in the United States. These estimates were generated according to the UNFCCC reporting guidelines, following the recommendations set forth in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997), the *IPCC Good Practice Guidance* (IPCC 2000), the Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003), and the *2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). This Annex provides an overview of the uncertainty analysis conducted to support the U.S. Inventory, describes the sources of uncertainty characterized throughout the Inventory associated with various source categories (including emissions and sinks), and describes the methods through which uncertainty information was collected, quantified, and presented.

7.1. Overview

The current inventory emission estimates for some source categories, such as for CO_2 Emissions from Fossil Fuel Combustion, have relatively low level of uncertainty associated with them. However, for some other source categories, the inventory emission estimates are considered less certain. The two major types of uncertainty associated with these emission estimates are (1) model uncertainty, which arises when the emission and/or removal estimation models used in developing the inventory estimates do not fully and accurately characterize the respective emission and/or removal processes (due to a lack of technical details or other resources), resulting in the use of incorrect or incomplete estimation methodologies and (2) parameter uncertainty, which arises due to a lack of precise input data such as emission factors and activity data.

The model uncertainty can be partially analyzed by comparing the model results with those of other models developed to characterize the same emission (or removal) process, after taking into account the differences in their conceptual framework, capabilities, data and assumptions. However, it would be very difficult—if not impossible—to quantify the model uncertainty associated with the emission estimates (primarily because, in most cases, only a single model has been developed to estimate emissions from any one source). Therefore, model uncertainty was not quantified in this report. Nonetheless, it has been discussed qualitatively, where appropriate, along with the individual source category description and inventory estimation methodology.

Parameter uncertainty is, therefore, the principal type and source of uncertainty associated with the national inventory emission estimates and is the main focus of the quantitative uncertainty analyses in this report. Parameter uncertainty has been quantified for all of the emission sources and sinks in the U.S. Inventory, with the exception of one very small emission source category, CH_4 emissions from Incineration of Waste, which was included in the 1990-2008 National GHG Inventory for the first time, and two other source categories International Bunker Fuels and biomass energy consumption) whose emissions are not included in the Inventory totals.

The primary purpose of the uncertainty analysis conducted in support of the U.S. Inventory is (i) to determine the quantitative uncertainty associated with the emission (and removal) estimates presented in the main body of this report [based on the uncertainty associated with the input parameters used in the emission (and removal) estimation methodologies] and (ii) to evaluate the relative importance of the input parameters in contributing to uncertainty in the associated source category inventory estimate and in the overall inventory estimate. Thus, the U.S. Inventory uncertainty analysis provides a strong foundation for developing future improvements and revisions to the Inventory estimation process. For each source category, the analysis highlights opportunities for changes to data measurement, data collection, and calculation methodologies. These are presented in the "Planned Improvements" sections of each source category's discussion in the main body of the report.

7.2. Methodology and Results

The United States has developed a quality assurance and quality control (QA/QC) and uncertainty management plan (EPA 2002) in accordance with the IPCC *Good Practice Guidance* (IPCC 2000). Like the QA/QC plan, the uncertainty management plan is part of a continually evolving process. The uncertainty management plan provides for a quantitative assessment of the inventory analysis itself, thereby contributing to continuing efforts to understand both what causes uncertainty and how to improve inventory quality. Although the plan provides both general and specific guidelines for implementing quantitative uncertainty analysis, its components are intended to evolve over time, consistent with the

inventory estimation process. The U.S. plan includes procedures and guidelines, and forms and templates, for developing quantitative assessments of uncertainty in the national Inventory estimates (EPA 2002).

The IPCC *Good Practice Guidance* recommends two approaches—Tier 1 and Tier 2—for developing quantitative estimates of uncertainty in the inventory estimate of individual source categories and the overall inventory. Of these, the Tier 2 approach is both more flexible and reliable than Tier 1; both methods are described in the next section. The United States is in the process of implementing a multi-year strategy to develop quantitative estimates of uncertainty for all source categories using the Tier 2 approach. For the current Inventory, a Tier 2 approach was implemented for all source categories with the exception of Composting and parts of Agricultural Soil Management source categories.

The current Inventory reflects significant improvements over the previous publication in the extent to which the Tier 2 approach to uncertainty analysis was adopted. Each of the new Tier 2 analyses reflects additional detail and characterization of input parameters using statistical data collection, expert elicitation methods and more informed judgment. In following the UNFCCC requirement under Article 4.1, emissions from International Bunker Fuels and Indirect Greenhouse Gas Emissions are not included in the total emissions estimated for the U.S. Inventory; therefore, no quantitative uncertainty estimates have been developed for these source categories.[90] Emissions from biomass combustion are accounted for implicitly in the LULUCF chapter through the calculation of changes in carbon stocks. The Energy sector does provide an estimate of CO_2 emissions from bioenergy consumption provided as a memo item for informational purposes in line with the UNFCCC reporting requirements.

Tier 1 and Tier 2 Approach

The Tier 1 method for estimating uncertainty is based on the error propagation equation. This equation combines the uncertainty associated with the activity data and the uncertainty associated with the emission (or the other) factors. The Tier 1 approach is applicable where emissions (or removals) are usually estimated as the product of an activity value and an emission factor or as the sum of individual sub-source category values. Inherent in employing the Tier 1 method are the assumptions that, for each source category, (i) both the activity data and the emission factor values are approximately normally distributed, (ii) the coefficient of variation (i.e., the ratio of the standard deviation to the mean) associated with each input variable is less than 30 percent, and (iii) the input variables within and across (sub-) source categories are not correlated (i.e., value of each variable is independent of the values of other variables).

The Tier 2 method is preferred (i) if the uncertainty associated with the input variables is significantly large, (ii) if the distributions underlying the input variables are not normal, (iii) if the estimates of uncertainty associated with the input variables are correlated, and/or (iv) if a sophisticated estimation methodology and/or several input variables are used to characterize the emission (or removal) process correctly. In practice, the Tier 2 is the preferred method of uncertainty analysis for all source categories where sufficient and reliable data are available to characterize the uncertainty of the input variables.

The Tier 2 method employs the Monte Carlo Stochastic Simulation technique (also referred to as the Monte Carlo method). Under this method, estimates of emissions (or removals) for a particular source category are generated many times (equal to the number of simulations specified) using an uncertainty model, which is an emission (or removal) estimation equation that imitates or is the same as the inventory estimation model for a particular source category. These estimates are generated using the respective, randomly-selected values for the constituent input variables using commercially available simulation software such as *@RISK* or *Crystal Ball*.

Characterization of Uncertainty in Input Variables

Both Tier 1 and Tier 2 uncertainty analyses require that all the input variables are well-characterized in terms of their Probability Density Functions (PDFs). In the absence of particularly convincing data measurements, sufficient data samples, or expert judgments that determined otherwise, the PDFs incorporated in the current source category uncertainty analyses were limited to normal, lognormal, uniform, triangular, and beta distributions. The choice among these five PDFs depended largely on the observed or measured data and expert judgment.

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[90] However, because the input variables that determine the emissions from the Fossil Fuel Combustion and the International Bunker Fuels source categories are correlated, uncertainty associated with the activity variables in the International Bunker Fuels was taken into account in estimating the uncertainty associated with the Fossil Fuel Combustion.

Source Category Inventory Uncertainty Estimates

Discussion surrounding the input parameters and sources of uncertainty for each source category appears in the body of this report. Table A-271 summarizes results based on assessments of source category-level uncertainty. The table presents base year (1990 or 1995) and current year (2009) emissions for each source category. The combined uncertainty (at the 95 percent confidence interval) for each source category is expressed as the percentage deviation above and below the total 2009 emissions estimated for that source category. Source category trend uncertainty is described subsequently in this Appendix.

Table A-271: Summary Results of Source Category Uncertainty Analyses

Source Category	Base Year Emissions[*,a]	2009 Emissions [a]	2009 Uncertainty[b]	
	Tg CO$_2$ Eq.	Tg CO$_2$ Eq.	Low	High
CO$_2$	**5,099.3**	**5,504.8**	**-1%**	**6%**
Fossil Fuel Combustion[c]	4,738.0	5,208.6	-1%	6%
Non-Energy Use of Fuels	118.6	123.4	-	10%
Natural Gas Systems	37.6	32.2	-	30%
Cement Production	33.3	29.0	-	14%
Lime Production	11.5	11.2	-7%	10%
Limestone and Dolomite Use	5.1	7.6	-	19%
Soda Ash Production and Consumption	4.1	4.3	-7%	7%
Carbon Dioxide Consumption	1.4	1.8	-	30%
Incineration of Waste	8.0	12.3	-	24%
Titanium Dioxide Production	1.2	1.5	-	13%
Aluminum Production	6.8	3.0	-4%	4%
Iron and Steel Production and Metallurgical Coke Production	99.5	41.9	- 16%	16%
Ferroalloy Production	2.2	1.5	-	13%
Ammonia Production and Urea Consumption	16.8	11.8	-7%	8%
Phosphoric Acid Production	1.5	1.0	-	19%
Petrochemical Production	3.3	2.7	-	31%
Silicon Carbide Production and Consumption	0.4	0.1	-9%	9%
Lead Production	0.5	0.5	-	15%
Zinc Production	0.7	1.0	-	18%
Cropland Remaining Cropland	7.1	7.8	-	50%
Wetlands Remaining Wetlands	1.0	1.1	-	34%
Petroleum Systems	0.6	0.5	-	149%
Land Use, Land-Use Change, and Forestry (Sink)[d]	*(861.5)*	*(1,015.1)*	*15%*	*-15%*
Biomass - Wood[f]	*215.2*	*183.8*	*NE*	*NE*
International Bunker Fuels[e]	*111.8*	*123.1*	*NE*	*NE*
Biomass – Ethanol[f]	*4.2*	*61.2*	*NE*	*NE*
CH$_4$	**674.9**	**686.3**	**-9%**	**17%**
Stationary Combustion	7.4	6.2	-	127%
Mobile Combustion	4.7	2.0	-9%	15%
Coal Mining	84.1	71.0	-	16%
Abandoned Underground Coal Mines	6.0	5.5	-	32%
Natural Gas Systems	189.8	221.2	-	30%
Petroleum Systems	35.4	30.9	-	149%
Petrochemical Production	0.9	0.8	-	27%
Silicon Carbide Production and Consumption	+	+	-9%	9%
Iron and Steel Production and Metallurgical Coke Production	1.0	0.4	- 21%	23%
Ferroalloy Production	+	+	-	12%
Enteric Fermentation	132.1	139.8	-	18%
Manure Management	31.7	49.5	-	20%
Rice Cultivation	7.1	7.3	-	146%
Field Burning of Agricultural Residues	0.3	0.2	-	42%
Forest Land Remaining Forest Land	3.2	7.8	-	145%
Landfills	147.4	117.5	-	40%
Wastewater Treatment	23.5	24.5	-	47%

Composting	0.3	1.7	-	50%
Incineration of Waste	+	+	NE	NE
International Bunker Fuels[e]	*0.2*	*0.1*	*NE*	*NE*
N₂O	**315.2**	**295.6**	**-**	**44%**
Stationary Combustion	12.8	12.8	-	187%
Mobile Combustion	43.9	23.9	-	17%
Adipic Acid Production	15.8	1.9	-	42%
Nitric Acid Production	17.7	14.6	-	42%
Manure Management	14.5	17.9	-	24%
Agricultural Soil Management	197.8	204.6	-	54%
Field Burning of Agricultural Residues	0.1	0.1	-	31%
Wastewater Treatment	3.7	5.0	-	93%
N2O from Product Uses	4.4	4.4	-8%	8%
Incineration of Waste	0.5	0.4	-	320%
Settlements Remaining Settlements	1.0	1.5	-	163%
Forest Land Remaining Forest Land	2.7	6.7	-	139%
Composting	0.4	1.8	-	50%
Wetlands Remaining Wetlands	+	+	-	41%
International Bunker Fuels[e]	*1.1*	*1.1*	*NE*	*NE*
HFCs, PFCs, and SF₆	**120.7**	**143.3**	**-6%**	**7%**
Substitution of Ozone Depleting Substances[g]	29.0	117.1	-7%	8%
HCFC-22 Production	36.4	5.4	-7%	10%
Semiconductor Manufacture	2.9	5.3	-	11%
Aluminum Production	18.5	1.6	-	11%
Electrical Transmission and Distribution	28.4	12.8	-	22%
Magnesium Production and Processing	5.4	1.1	-3%	4%
Total[h]	**6,210.0**	**6,630.0**	**-1%**	**6%**
Net Emissions (Sources and Sinks) [h]	**5,348.5**	**5,614.9**	**-2%**	**8%**

Notes:

Totals may not sum due to independent rounding.

*Base Year is 1990 for all sources except Substitution of Ozone Depleting Substances, for which the United States has chosen 1995.

+ Does not exceed 0.05 Tg CO₂ Eq.

NE Not Estimated

[a] Emission estimates reported in this table correspond to emissions from only those source categories for which quantitative uncertainty was performed this year. Thus the totals reported for 2009 in this table exclude approximately 3.2 Tg CO₂ Eq. of emissions for which quantitative uncertainty was not assessed. Hence, these emission estimates do not match the final total U.S. greenhouse gas emission estimates presented in this Inventory. All uncertainty estimates correspond only to the totals reported in this table.

[b] The uncertainty estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5[th] percentile and the upper bound corresponding to 97.5[th] percentile.

[c] This source category's inventory estimates exclude CO₂ emissions from geothermal sources, as quantitative uncertainty analysis was not performed for that sub-source category. Hence, for this source category, the emissions reported in this table do not match the emission estimates presented in the Energy chapter of the Inventory.

[d] Sinks are only included in Net Emissions.

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

[f] Emissions from Wood Biomass and Ethanol Consumption are not included specifically in summing energy sector totals.

[g] This source category's inventory estimate for 2009 excludes 2.9 Tg of CO₂ Eq. from several very small emission sources, as uncertainty associated with those sources was not assessed. Hence, for this source category, the emissions reported in this table do not match the emission estimates presented in the Industrial Processes chapter of the Inventory.

[h] Totals exclude emissions for which uncertainty was not quantified. The Base Year emissions correspond to 1990 estimates for all source categories, with the exception of Substitution of ODS, for which the estimates correspond to 1995. Similarly, the total for HFCs, PFCs, and SF₆ for the Base Year includes 1995 emission estimates for Substitution of ODS and 1990 emission estimates for all other source categories.

Overall (Aggregate) Inventory Level Uncertainty Estimates

The overall level uncertainty estimate for the U.S. greenhouse gas emissions inventory was developed using the IPCC Tier 2 uncertainty estimation methodology. The uncertainty models of all the emission source categories could not be directly integrated to develop the overall uncertainty estimates due to software constraints in integrating multiple, large uncertainty models. Therefore, an alternative approach was adopted to develop the overall uncertainty estimates. The Monte Carlo simulation output data for each emission source category uncertainty analysis were combined by type of gas and the probability distributions were fitted to the combined simulation output data, where such simulated output data were available. If such detailed output data were not available for particular emissions sources, individual probability

distributions were assigned to those source category emission estimates based on the most detailed data available from the quantitative uncertainty analysis performed.

For the Composting and for parts of Agricultural Soil Management source categories, Tier 1 uncertainty results were used in the overall uncertainty analysis estimation. However, for all other emission sources (excluding international bunker fuels, CO_2 from biomass combustion, and CH_4 from incineration of waste), Tier 2 uncertainty results were used in the overall uncertainty estimation.

The overall uncertainty model results indicate that the 2009 U.S. greenhouse gas emissions are estimated to be within the range of approximately 6,584 to 7,034 Tg CO_2 Eq., reflecting a relative 95 percent confidence interval uncertainty range of -1 percent to 6 percent with respect to the total U.S. greenhouse gas emission estimate of approximately 6,630 Tg CO_2 Eq. The uncertainty interval associated with total CO_2 emissions, which constitute about 83 percent of the total U.S. greenhouse gas emissions in 2009, ranges from -1 percent to 6 percent of total CO_2 emissions estimated. The results indicate that the uncertainty associated with the inventory estimate of the total CH_4 emissions ranges from -9 percent to 17 percent, uncertainty associated with the total inventory N_2O emission estimate ranges from -11 percent to 44 percent, and uncertainty associated with high GWP gas emissions ranges from -6 percent to 7 percent.

A summary of the overall quantitative uncertainty estimates is shown below.

Table A-272. Quantitative Uncertainty Assessment of Overall National Inventory Emissions (Tg CO_2 Eq. and Percent)

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

Notes:
[a] Emission estimates reported in this table correspond to emissions from only those source categories for which quantitative uncertainty was performed this year. Thus the totals reported in this table exclude approximately 3.2 Tg CO_2 Eq. of emissions for which quantitative uncertainty was not assessed. Hence, these emission estimates do not match the final total U.S. greenhouse gas emission estimates presented in this Inventory.
[b] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5[th] percentile and the upper bound corresponding to 97.5[th] percentile.
[c] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.
[d] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.
[e] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the inventory emission calculations for 2009.

Trend Uncertainty

In addition to the estimates of uncertainty associated with the current year's emission estimates, this Annex also presents the estimates of trend uncertainty. The *IPCC Good Practice Guidance* defines trend as the difference in emissions between the base year (i.e., 1990) and the current year (i.e., 2009) inventory estimates. However, for purposes of understanding the concept of trend uncertainty, the emission trend is defined in this Inventory as the percentage change in the emissions (or removal) estimated for the current year, relative to the emission (or removal) estimated for the base year. The uncertainty associated with this emission trend is referred to as trend uncertainty.

Under the Tier 1 approach, the trend uncertainty for a source category is estimated using the sensitivity of the calculated difference between the base year and the current year (i.e., 2009) emissions to an incremental (i.e., 1 percent) increase in one or both of these values for that source category. The two sensitivities are expressed as percentages: Type A sensitivity highlights the effect on the difference between the base and the current year emissions caused by a 1 percent change in both, while Type B sensitivity highlights the effect caused by a change to only the current year's emissions. Both sensitivities are simplifications introduced in order to analyze the correlation between the base and the current year estimates. Once calculated, the two sensitivities are combined using the error propagation equation to estimate the overall trend uncertainty.

Under the Tier 2 approach, the trend uncertainty is estimated using Monte Carlo Stochastic Simulation technique. The trend uncertainty analysis takes into account the fact that the base and the current year estimates often share input variables. For purposes of the current Inventory, a simple approach has been adopted, under which the base year source category emissions (or removals) are assumed to exhibit the same uncertainty characteristics as the current year emissions (or removals). Source category-specific PDFs for base year estimates were developed using current year (i.e., 2009) uncertainty output data. These were adjusted to account for differences in magnitude between the two years' inventory estimates. Then, for each source category, a trend uncertainty estimate was developed using the Monte Carlo method. The overall inventory trend uncertainty estimate was developed by combining all source category-specific trend uncertainty estimates. These preliminary trend uncertainty estimates present the range of likely change from base year to 2009, and are shown in Table A- 273.

Table A- 273. Quantitative Assessment of Trend Uncertainty (Tg CO₂ Eq. and Percent)

Gas/Source	Base Year Emissions[*,a]	2009 Emissions [a]	Emissions Trend [a]	Trend Range[a,b]	
	(Tg CO₂ Eq.)		(%)	(%)	
				Lower Bound	Upper Bound
CO₂	**5,099.3**	**5,504.8**	**8%**	**3%**	**13%**
Fossil Fuel Combustion[c]	4,738.0	5,208.6	10%	5%	16%
Non-Energy Use of Fuels	118.6	123.4	4%	-17%	31%
Iron and Steel Production and Metallurgical Coke Production	99.5	41.9	-58%	-67%	-47%
Natural Gas Systems	37.6	32.2	-14%	-39%	20%
Cement Production	33.3	29.0	-13%	-28%	5%
Incineration of Waste	8.0	12.3	54%	12%	111%
Ammonia Production and Urea Consumption	16.8	11.8	-30%	-37%	-22%
Lime Production	11.5	11.2	-3%	-14%	10%
Cropland Remaining Cropland	7.1	7.8	11%	-56%	181%
Limestone and Dolomite Use	5.1	7.6	49%	20%	85%
Soda Ash Production and Consumption	4.1	4.3	3%	-7%	14%
Aluminum Production	6.8	3.0	-56%	-58%	-53%
Petrochemical Production	3.3	2.7	-17%	-46%	27%
Carbon Dioxide Consumption	1.4	1.8	24%	-17%	88%
Ferroalloy Production	2.2	1.5	-32%	-43%	-18%
Titanium Dioxide Production	1.2	1.5	29%	7%	55%
Wetlands Remaining Wetlands	1.0	1.1	5%	-33%	67%
Phosphoric Acid Production	1.5	1.0	-32%	-48%	-11%
Zinc Production	0.7	1.0	45%	12%	86%
Petroleum Systems	0.6	0.5	-17%	-64%	90%
Lead Production	0.5	0.5	2%	-18%	25%
Silicon Carbide Production and Consumption	0.4	0.1	-61%	-66%	-56%
Land Use, Land-Use Change, and Forestry (Sink)[d]	*(861.5)*	*(1,015.1)*	*18%*	*-5%*	*46%*
Biomass - Wood[f]	*215.2*	*183.8*	*-15%*	*NE*	*NE*
International Bunker Fuels[e]	*111.8*	*123.1*	*10%*	*NE*	*NE*
Biomass – Ethanol[f]	*4.2*	*61.2*	*1348%*	*NE*	*NE*
CH₄	**674.9**	**686.3**	**2%**	**-15%**	**22%**
Natural Gas Systems	189.8	221.2	17%	-17%	64%
Enteric Fermentation	132.1	139.8	6%	-14%	30%
Landfills	147.4	117.5	-20%	-61%	63%
Coal Mining	84.1	71.0	-16%	-32%	4%
Manure Management	31.7	49.5	56%	19%	105%
Petroleum Systems	35.4	30.9	-13%	-62%	98%
Wastewater Treatment	23.5	24.5	4%	-42%	91%
Forest Land Remaining Forest Land	3.2	7.8	144%	-50%	1110%
Rice Cultivation	7.1	7.3	3%	-75%	317%
Stationary Combustion	7.4	6.2	-17%	-67%	109%
Abandoned Underground Coal Mines	6.0	5.5	-9%	-40%	38%
Mobile Combustion	4.7	2.0	-58%	-65%	-51%
Composting	0.3	1.7	421%	131%	1061%
Petrochemical Production	0.9	0.8	-2%	-34%	44%
Iron and Steel Production and Metallurgical Coke Production	1.0	0.4	-62%	-72%	-48%
Field Burning of Agricultural Residues	0.3	0.2	-8%	-51%	72%
Ferroalloy Production	+	+	-40%	-99%	-99%
Silicon Carbide Production and Consumption	+	+	-67%	-71%	-62%

Incineration of Waste	+	+	-23%	NE	NE
International Bunker Fuels[e]	*0.2*	*0.1*	*-14%*	*NE*	*NE*
N₂O[g]	**315.2**	**295.6**	**-6%**	**-32%**	**31%**
Agricultural Soil Management	197.8	204.6	3%	-36%	65%
Mobile Combustion	43.9	23.9	-46%	-56%	-32%
Manure Management	14.5	17.9	23%	-7%	63%
Nitric Acid Production	17.7	14.6	-18%	-56%	50%
Stationary Combustion	12.8	12.8	0%	-65%	183%
Forest Land Remaining Forest Land	2.7	6.7	152%	-40%	977%
Wastewater Treatment	3.7	5.0	36%	-72%	499%
N2O from Product Uses	4.4	4.4	0%	-12%	12%
Adipic Acid Production	15.8	1.9	-88%	-93%	-77%
Composting	0.4	1.8	421%	135%	1042%
Settlements Remaining Settlements	1.0	1.5	55%	-51%	392%
Incineration of Waste	0.5	0.4	-23%	-83%	245%
Field Burning of Agricultural Residues	0.1	0.1	3%	-33%	60%
Wetlands Remaining Wetlands	+	+	-7%	-72%	225%
International Bunker Fuels[e]	*1.1*	*1.1*	*4%*	*NE*	*NE*
HFCs, PFCs, and SF₆	**120.7**	**143.3**	**19%**	**9%**	**29%**
Substitution of Ozone Depleting Substances[g]	29.0	117.1	304%	264%	349%
Electrical Transmission and Distribution	28.4	12.8	-55%	-66%	-39%
HCFC-22 Production	36.4	5.4	-85%	-87%	-83%
Semiconductor Manufacture	2.9	5.3	83%	58%	111%
Aluminum Production	18.5	1.6	-91%	-93%	-90%
Magnesium Production and Processing	5.4	1.1	-81%	-82%	-80%
Total[h]	**6,210.0**	**6,630.0**	**7%**	**2%**	**12%**
Net Emissions (Sources and Sinks)[h]	**5,348.5**	**5,614.9**	**5%**	**-2%**	**12%**

Notes:

Totals may not sum due to independent rounding.

*Base Year is 1990 for all sources except Substitution of Ozone Depleting Substances, for which the United States has chosen to use 1995.

+ Does not exceed 0.05 Tg CO₂ Eq.

NE Not Estimated

[a] Emission estimates reported in this table correspond to emissions from only those source categories for which quantitative uncertainty was performed this year. Thus the totals reported in this table for 2009 exclude approximately 3.2 Tg CO₂ Eq. of emissions for which quantitative uncertainty was not assessed. Hence, these emission estimates do not match the final total U.S. greenhouse gas emission estimates presented in this Inventory. Emissions trends and the emission range were calculated based on the emissions estimates reported in this table and, therefore, may differ from the emissions trends reported elsewhere in this Inventory.

[b] The trend range represents a 95 percent confidence interval for the emission trend, with the lower bound corresponding to 2.5th percentile value and the upper bound corresponding to 97.5th percentile value.

[c] This source category's inventory estimates exclude CO₂ emissions from geothermal sources, as quantitative uncertainty analysis was not performed for that sub-source category. Hence, for this source category, the emissions reported in this table do not match the emission estimates presented in the Energy chapter of the Inventory.

[d] Sinks are only included in Net Emissions.

[e] Emissions from International Bunker Fuels are not included in the emission totals and emission trend estimates.

[f] Emissions from Wood Biomass and Ethanol Consumption are not included specifically in summing energy sector totals.

[g] This source category's inventory estimate for 2009 excludes about 2.9 Tg of CO₂ Eq. from several very small emission sources, as uncertainty associated with those sources was not assessed. Hence, for this source category, the emissions reported in this table do not match the emission estimates presented in the Industrial Processes chapter of the Inventory.

[h] Totals exclude emissions for which uncertainty was not quantified. The Base Year emissions correspond to 1990 estimates for all source categories, with the exception of Substitution of ODS, for which the estimates correspond to 1995. Similarly, the total for HFCs, PFCs, and SF₆ for the Base Year includes 1995 emission estimates for Substitution of ODS and 1990 emission estimates for all other source categories.

7.3. Planned Improvements

Identifying the sources of uncertainty in the emission and sink estimates of the Inventory and quantifying the magnitude of the associated uncertainty is the crucial first step towards improving those estimates. Quantitative assessment of the parameter uncertainty may also provide information about the relative importance of input parameters (such as activity data and emission factors), based on their relative contribution to the uncertainty within the source category estimates. Such information can be used to prioritize resources with a goal of reducing uncertainty over time within or among inventory source categories and their input parameters. In the current Inventory, potential sources of model uncertainty have been identified for some emission source categories, and uncertainty estimates based on their parameters' uncertainty have been developed for all the emission source categories, with the exception of CH₄ from incineration of waste, which is a minor emission source category newly added to the Inventory starting with the 2008 business year, and the international bunker fuels and wood biomass and ethanol combustion source categories, which are

not included in the energy sector totals. Emissions from biomass and ethanol combustion however are accounted for implicitly in the LULUCF chapter through the calculation of changes in carbon stocks. The Energy sector does provide an estimate of CO_2 emissions from bioenergy consumption provided as a memo item for informational purposes.

Specific areas that require further research include:

- *Incorporating excluded emission sources.* Quantitative estimates for some of the sources and sinks of greenhouse gas emissions, such as from some land-use activities, industrial processes, and parts of mobile sources, could not be developed at this time either because data are incomplete or because methodologies do not exist for estimating emissions from these source categories. See Annex 5 of this report for a discussion of the sources of greenhouse gas emissions and sinks excluded from this report. In the future, efforts will focus on estimating emissions from excluded emission sources and developing uncertainty estimates for all source categories for which emissions are estimated.

- *Improving the accuracy of emission factors.* Further research is needed in some cases to improve the accuracy of emission factors used to calculate emissions from a variety of sources. For example, the accuracy of current emission factors applied to CH_4 and N_2O emissions from stationary and mobile combustion are 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.

In improving the quality of uncertainty estimates the following include areas that deserve further attention:

- *Refine Source Category and Overall Uncertainty Estimates.* For many individual source categories, further research is needed to more accurately characterize PDFs that surround emissions modeling input variables. This might involve using measured or published statistics or implementing rigorous elicitation protocol to elicit expert judgments, if published or measured data are not available.

- *Include GWP uncertainty in the estimation of Overall level and trend uncertainty.* The current year's Inventory does not include the uncertainty associated with the GWP values in the estimation of the overall uncertainty for the Inventory. Including this source would contribute to a better characterization of overall uncertainty and help assess the level of attention that this source of uncertainty warrants in the future.

- *Improve characterization of trend uncertainty associated with base year Inventory estimates.* The characterization of base year uncertainty estimates could be improved, by developing explicit uncertainty models for the base year. This would then improve the analysis of trend uncertainty. However, not all of the simplifying assumptions described in the "Trend Uncertainty" section above may be eliminated through this process due to a lack of availability of more appropriate data.

7.4. Additional Information on Uncertainty Analyses by Source

The quantitative uncertainty estimates associated with each emission and sink source category are reported in each chapter of this Inventory following the discussions of inventory estimates and their estimation methodology. This section provides additional descriptions of the uncertainty analyses performed for some of the sources, including the models and methods used to calculate the emission estimates and the potential sources of uncertainty surrounding them. These sources are organized below in the same order as the sources in each chapter of the main section of this Inventory. To avoid repetition, the following uncertainty analysis discussions of individual source categories do not include descriptions of these source categories. Hence, to better understand the details provided below, refer to the respective chapters and sections in the main section of this Inventory, as needed. All uncertainty estimates are reported relative to the 2009 Inventory estimates for the 95 percent confidence interval, unless otherwise specified.

Energy

The uncertainty analysis descriptions in this section correspond to some source categories included in the Energy Chapter of the Inventory.

Mobile Combustion (excluding CO_2)

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

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

The estimates of VMT for on-road vehicles by vehicle type in the U.S. were provided by the FHWA (1996 through 2009), and were generated through a cooperative process between the FHWA and the state and the local governments. These estimates are subject to several possible sources of error, such as unregistered vehicles, and measurement and estimation errors. These VMT were apportioned by fuel type, based on data from DOE (1993 through 2009), and then allocated to individual model years using temporal profiles of both the vehicle fleet by age and vehicle usage by model year in the U.S. provided by EPA (2007c) and EPA (2000). While the uncertainty associated with the total national VMT is believed to be low, the uncertainty within individual source categories was considered to be higher due to the uncertainty associated with apportioning total VMT into individual vehicle categories, by fuel type, technology type, and by equipment age. It was assumed that smaller sources had greater percentage uncertainty and vice-versa. Another source of uncertainty in the estimates occurs due to differences in the FHWA and the EPA data sources. For example, the FHWA data are used for defining vehicle types and for developing the estimates of VMT by vehicle type; whereas, the estimates of VMT by fuel types are calculated using EPA's definition of vehicle categories (which differ from those of the FHWA).

The emission factors for on-road vehicles used in the Inventory were obtained from ICF (2006b) and ICF (2004). These factors were based on laboratory testing of vehicles. While the controlled testing environment simulates real driving conditions, emission results from such testing can only approximate real world conditions and emissions. For some vehicle and control technology types, because the testing did not yield statistically significant results within the 95 percent confidence interval, expert judgment was adopted in developing the emission factors. In those cases, the missing emission factors were extrapolated based on the data available on the other emission factors and the emissions factors available for similar vehicle and control technology type. For example, if light duty trucks with an oxidation catalyst has no testing (or not significant testing) results and if light duty cars with an oxidation catalyst had testing results, the CH_4 and the N_2O emission factors for the trucks were calculated from the corresponding emissions factors for the car based upon the ratio of CO_2 emissions per mile for the car to the truck.

A total of 111 highway data input variables were simulated through Monte Carlo Simulation technique using @RISK software. Variables included VMT and emission factors for individual conventional and alternative fuel vehicle categories and technologies. In developing the uncertainty estimation model, a normal distribution was assumed for all but two activity-related input variables (e.g., VMT); in the case of the two input variables, buses and percent of diesel combination trucks, triangular distributions were assumed. The dependencies and other correlations among the activity data were incorporated into the model to ensure consistency in the model specification and simulation. Emission factors were assigned uniform distributions, with the upper and the lower bounds assigned based on 95 percent confidence intervals of laboratory test data. In cases where data did not yield statistically significant results within the 95 percent confidence interval, estimates of upper and lower bounds were determined using expert judgments. For biodiesel vehicles, because no test data were available, consistent with the assumptions underlying the ANL GREET model, their N_2O and CH_4 emissions were assumed to be same as those for diesel vehicles of similar types. For other alternative fuel vehicles (AFVs), uncertainty estimates were developed based on conventional fuel vehicle emission factors and applicable multipliers, as described in the ICF's AFV emission factors memorandum to EPA (ICF 2006a). The results of the quantitative uncertainty analysis are reported as *quantitative uncertainty estimates* following the mobile source category emissions description in the Energy Chapter of this Inventory.

Emissions from non-road vehicles account for 23 percent of CH_4 emissions from mobile sources and 13 percent of N_2O emissions from mobile sources in 2009. A quantitative analysis of uncertainty in the inventory estimates of emissions from non-road vehicles was performed for the first time for the 2009 inventory. Sources of uncertainty for non-road vehicles were investigated by examining the underlying uncertainty of emission factors and fuel consumption data. A non-road uncertainty assessment module was developed independently and integrated with the highway mobile uncertainty model to facilitate a more comprehensive quantitative analysis of uncertainty for all mobile sources.

The fuel consumption data for non-road vehicles were obtained from several sources. Estimates of fuel consumption for non-road vehicles (i.e., equipment used for agriculture, construction, lawn and garden, railroad, airport ground support, etc., as well as recreational vehicles) were generated by the EPA's NONROAD model (EPA 2009). This model estimates fuel consumption based on estimated equipment/vehicle use (in hours) and average fuel consumed per hour of use. Since the fuel estimates are not based upon documented fuel sales or consumption, a fair degree of uncertainty accompanies these estimates. Estimates of distillate fuel sales for ships and boats were obtained from EIA's *Fuel Oil and Kerosene Sales* (EIA 1991 through 20010). These estimates have a moderate level of uncertainty since

EIA's estimates are based on survey data and reflect sales to economic sectors, which may include use by both mobile and non-mobile sources within a sector. Domestic consumption of residual fuel by ships and boats is obtained from EIA (20010a). These estimates fluctuate widely from year to year, and are believed to be highly uncertain. In addition, estimates of distillate and residual fuel sales for ships and boats are adjusted for bunker fuel consumption, which introduces an additional (and much higher) level of uncertainty. Jet fuel and aviation gasoline consumption data are obtained from DOT (1991 through 20010), EIA (2007a), FAA (20010), and FAA (2006). Additionally, all jet fuel consumption in the transportation sector is assumed to be consumed by aircraft. Some jet fuel may also be used for other purposes such as blending with diesel fuel or heating oil. In calculating CH_4 emissions from aircraft, an average emission factor is applied to total jet fuel consumption. This average emission factor takes into account the fact that CH_4 emissions occur only during the landing and take-off (LTO) cycles, with no CH_4 being emitted during the cruise cycle. However, a better approach would be to apply emission factors based on the number of LTO cycles.

Emission factors for non-road modes were taken from IPCC/UNEP/OECD/IEA (1997) and Browning (2009). These emission factors are based on laboratory test data and expert judgment, and have similar sources of uncertainty as the on-road emission factors for uncontrolled vehicles.

A total of 79 non-road data input variables were simulated in the non-road uncertainty assessment module using @RISK software. To determine the uncertainty associated with the non-road fuel consumption data, the agencies and experts that supply the data were contacted. Since few of these sources were able to provide quantitative estimates of uncertainty, expert judgment was used to assess the quantitative uncertainty associated with the fuel consumption data. A normal distribution was assumed for all non-road activity-related input (fuel use) variables, and the activity variables were assumed to be independent of each other. Uncertainty estimates for non-road emissions factors were developed based on laboratory test data and expert judgement. Beta-PERT distributions were assumed for the emissions factor variables, and correlations among the data were incorporated into the model to ensure consistency in model specification.

The results of the quantitative uncertainty analysis are reported as *quantitative uncertainty estimates* following the mobile source category emissions description in the Energy Chapter of this Inventory.

Incineration of Waste

The upper and lower bounds of uncertainty in the CO_2 emissions estimate for Incineration of Waste are 24 percent and -21 percent respectively, and in the N_2O emission estimates are 320 percent and -51 percent respectively, relative to the respective 2009 emission estimates, at the 95 percent confidence interval. The uncertainties in the waste combustion emission estimates arise from both the assumptions applied to the data and from the quality of the data. Key factors include MSW combustion rate, fraction oxidized, missing data on MSW composition, average carbon content of MSW components, assumptions on the synthetic/biogenic carbon ratio, and combustion conditions affecting N_2O emissions. For more information on emission estimates from MSW combustion, please refer to the Incineration of Waste section of the Energy chapter. The highest levels of uncertainty surround the variables, whose estimates were developed based on assumptions (e.g., percent of clothing and footwear composed of synthetic rubber); the lowest levels of uncertainty surround variables that were determined by quantitative measurements (e.g., combustion efficiency, carbon content of carbon black). Important sources of uncertainty are as follows:

- *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 *BioCycle* (Glenn 1999, Goldstein and Matdes 2000, Goldstein and Matdes 2001, Kaufman et al. 2004a, Kaufman et al. 2004b, Simmons et al. 2006, Arsova et al. 2008, van Haaren et al. 2010) estimate of total waste combustion, used for the N_2O and CH_4 emissions estimates, and waste incineration rate, used for the CO_2 emissions estimate are 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. The survey methodology changed significantly in 2003 and thus the results reported for 2002 are not directly comparable to the earlier results (Kaufman et al. 2004a, 2004b), introducing further uncertainty.

- *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. A value of 98 percent was assumed for this analysis.

- *Missing Data on Municipal Solid Waste Composition.* Disposal rates have been interpolated when there is an incomplete interval within a time series. Where data are not available for years at the end of a time series, they are set equal to the most recent years for which estimates are available.

- *Average Carbon Contents.* Average carbon contents were applied to the mass of "Other" plastics combusted, synthetic rubber in tires and municipal solid waste, and synthetic fibers. These average values were estimated from the average carbon content of the known products recently produced. The actual carbon content of the

combusted waste may differ from this estimate depending on differences in the chemical formulation between the known and unspecified materials, and differences between the composition of the material disposed and that produced. For rubber, this uncertainty ranges from 51 to 91 percent; for plastics, it may be more significant, as their carbon contents range from 38 to 92 percent. However, overall, this is a small source of uncertainty.

- *Synthetic/Biogenic Assumptions.* A portion of the fiber and rubber in municipal solid waste 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 exhibit high uncertainty. The emission factor for N_2O from municipal solid waste combustion facilities used in the analysis corresponds to the default emission factor for continuously fed stoker units found in IPCC (2006). Using this emission factor assumes that all waste combustors in the United States use continuously fed stoker technology, which is uncertain. 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 also exhibits uncertainty.

Industrial Processes

The uncertainty analysis descriptions in this section correspond to some source categories included in the Industrial Processes Chapter of the Inventory.

Ammonia Manufacture and Urea Consumption

The uncertainty upper and lower bounds of the emission estimate for Ammonia Manufacture and Urea Consumption were 8 percent and -7 percent, respectively, at the 95 percent confidence interval. The European Fertilizer Manufacturer's Association (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 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, as CO_2 emissions from fuel use and non-energy use are calculated separately.[91]

Natural gas feedstock consumption data for the U.S. ammonia industry as a whole are available from the Energy Information Administration (EIA) *Manufacturers Energy Consumption Survey* (MECS) for the years 1985, 1988, 1991, 1994 and 1998 (EIA 1994, 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. 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

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[91] It appears that the IPCC emission factor for ammonia production of 1.5 ton CO_2 per ton 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 tons CO_2 per ton ammonia, respectively) and it is likely that if one value does not include fuel use, the other value also does not. For the conventional steam reforming process, however, the EFMA reports an emission factor range for feedstock CO_2 of 1.15 to 1.30 ton per ton (with a typical value of 1.2 ton per ton) and an emission factor for fuel CO_2 of 0.5 tons per ton. 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 ton per ton, 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 ton CO_2 per ton ammonia reported by the EFMA. Because it appears that the emission factors cited in the *IPCC Guidelines* may actually include natural gas used as fuel, we use the 1.2 tons/ton emission factor developed by the EFMA.

years may underestimate feedstock natural gas consumption, and therefore the EFMA emission factor was used to estimate CO_2 emissions from ammonia production, rather than EIA data.

Research indicates that there is only one U.S. plant that manufactures ammonia from petroleum coke. CO_2 emissions from this plant are explicitly accounted for in the Inventory estimates. No data for ammonia plants using naphtha or other feedstocks other than natural gas have been identified. Therefore, all other CO_2 emissions from ammonia plants are calculated using the emission factor for natural gas feedstock. However, actual emissions may differ because processes other than catalytic steam reformation and feedstocks other than natural gas may have been used for ammonia production. Urea is also used for other purposes than as a nitrogenous fertilizer. Currently, urea used as a nitrogenous fertilizer is accounted for in the LULUCF chapter. Research has identified one ammonia production plant that is recovering byproduct CO_2 for use in EOR. Such CO_2 is currently assumed to remain sequestered (see the section of this chapter on CO_2 Consumption); however, time series data for the amount of CO_2 recovered from this plant are not available and therefore all of the CO_2 produced by this plant is assumed to be emitted to the atmosphere and allocated to Ammonia Manufacture.

Phosphoric Acid Production

The uncertainty upper and lower bounds of the emissions estimate for Phosphoric Acid Production were 19 percent and -18 percent, respectively, at the 95 percent confidence interval. Factors such as the composition of phosphate rock affect CO_2 emissions from phosphoric acid production. For more information on how emissions estimates were calculated, please refer to the Phosphoric Acid Production section of the Industrial Processes chapter. Only one set of data from the Florida Institute of Phosphate Research (FIPR) was available for the composition of phosphate rock mined domestically and imported, and data for uncalcined phosphate rock mined in North Carolina and Idaho were unavailable. Inorganic carbon content (as CO_2) of phosphate rock could vary ±1 percent, resulting in a variation in CO_2 emissions of ±20 percent.

Organic C is not included in the calculation of CO_2 emissions from phosphoric acid production. However, if, for example, 50 percent of the organic carbon content of the phosphate rock were to be emitted as CO_2 in the phosphoric acid production process, the CO_2 emission estimate would increase by approximately 50 percent. If it is assumed that 100 percent of the reported domestic production of phosphate rock for Idaho and Utah was first calcined, and it is assumed that 50 percent of the organic carbon content of the total production for Idaho and Utah was converted to CO_2 in the calcination process, the CO_2 emission estimate would increase on the order of 10 percent. If it were assumed that there are zero emissions from other uses of phosphate rock, CO_2 emissions would fall 10 percent.

Iron and Steel & Metallurgical Coke Production

The uncertainty upper and lower bounds of the CO_2 emission estimate for Iron and Steel & Metallurgical Coke Production were 16 percent and -16 percent, respectively, at the 95 percent confidence interval. Factors such as the composition of C anodes and the C content of pig iron and crude steel affect CO_2 emissions from Iron and Steel Production. For more information on emission estimates, please refer to the Iron and Steel Production section of the Industrial Processes chapter. Simplifying assumptions were made concerning the composition of C 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. It was also assumed that the C contents of all pig iron and crude steel have carbon contents of 4 percent and 1 percent, respectively. The carbon content of pig iron can vary between 3.6 and 4.4 percent, while crude steel can have a carbon content of up to 2 percent, although it is typically less than 1 percent (IPCC 2000).

Aluminum Production

The uncertainty upper and lower bounds of the PFCs emission estimate for Aluminum Production were 11 percent and -11 percent, respectively, at the 95 percent confidence interval. The uncertainties associated with three variables were estimated for each smelter: (1) the quantity of aluminum produced, (2) the anode effect minutes per cell day (which may be reported directly or calculated as the product of anode effect frequency and anode effect duration), and (3) the smelter- or technology-specific slope coefficient (or weight fraction). For more information on the effect of these variables on PFC emissions, please refer the Aluminum Production section of the Industrial Processes chapter. All three types of data are assumed to be characterized by a normal distribution. The uncertainty in aluminum production estimates was assumed to be 1 percent for reported data (IPCC 2006). For reported anode effect frequency and duration data, the uncertainties were assumed to be 2 percent and 5 percent, respectively (Kantamaneni et al. 2001). For calculated smelter-specific CF_4 and C_2F_6 slope coefficients the uncertainties were assumed to be 15 percent (IPCC 2006). For smelters applying technology-specific slope coefficients or weight fractions, the uncertainty in the coefficients was based on the standard deviation of the individual measurements used to determine the average value given by the IPCC guidance for

technology-specific (Tier 2) slope coefficients. Consequently, the uncertainty value assigned to the technology-specific slope coefficients for CF_4 for CWPB was 0.036, and for C_2F_6 for CWPB was 0.060. (The uncertainty in the technology-specific CF_4 slope coefficent for CWPB is reported as 6 percent in IPCC (2006), but was increased to 50 percent in this analysis to better account for measurement uncertainty for an individual facility. The uncertainty in PFC emissions for CWPB facilities (the best behaved of the technology types) is about 50 percent for any given facility using the Tier 2 calculation.) In general, where precise quantitative information was not available on the uncertainty of a parameter, an upper-bound value was used.

Magnesium Production

The uncertainty information below pertains to the emission estimates presented in the Magnesium Production section of the Industrial Processes chapter. Please refer to that section for more information about this source. The uncertainty upper and lower bounds of the emissions estimate for Magnesium Production were 4 percent and -4 percent, respectively, at the 95 percent confidence interval. An uncertainty of 5 percent was assigned to the data reported by each participant in the Partnership. If Partners did not report emissions data during the current reporting year, SF_6 emissions data were estimated using available emission factor and production information reported in prior years; the extrapolation was based on the average trend for Partners reporting in the current reporting year and the year prior. The uncertainty associated with the SF_6 usage estimate generated from the extrapolated emission factor and production information was determined using a sum of squares method. A 5 percent uncertainty for the year the Partner last reported was assumed and a 30% uncertainty for each subsequent year was assumed. For those industry processes that are not represented in Partnership, such as permanent mold and wrought casting, SF_6 emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-73). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. Emissions associated with sand casting activities not entirely captured by the Partnership utilized a Partner-reported emission factor with an uncertainty of 75 percent. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Electrical Transmission and Distribution

The uncertainty upper and lower bounds of the emissions estimate for Electrical Transmission and Distribution at the 95 percent confidence interval were 22 percent and -21 percent, respectively. Uncertainty associated with emissions of SF_6 from electrical transmission and distribution stem from the following three quantities: (1) emissions from partners, (2) emissions from non-partners, and (3) emissions from manufacturers of electrical equipment. The uncertainty of partner emissions is related to whether the partner emissions are reported or estimated. For reported partner emissions, individual partner submitted SF_6 data was assumed to have an uncertainty of 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of the total partner reported data was estimated to be 5.3 percent. For partner-estimated emissions, the uncertainty associated with emissions extrapolated or interpolated from reported emissions data was assumed to be 20 percent. There are two sources of uncertainty that contribute to the non-partner emissions uncertainty. The first is the uncertainty in the coefficients of the regression equations used to estimate emissions from non-partners, and the second is the uncertainty in the total transmission miles for non-partners—the independent variable in the regression equation. The uncertainty in the coefficients (as defined by the regression standard error estimate) is estimated to be ±20 percent for small utilities and ±64 percent for large utilities, while the uncertainty in the transmission miles is assumed to be 10 percent. For equipment manufacturers, the quantity of SF_6 charged into equipment by equipment manufacturers is estimated using partner reported new nameplate capacity data and the estimate for the total industry nameplate capacity. The quantity of SF_6 charged into equipment in 2009 is estimated to have an uncertainty of 70.2 percent, and is derived from the uncertainty in partner reported new nameplate capacity (estimated as 4.2 percent using error propagation) and the uncertainty in the estimate for U.S. total nameplate capacity (assumed to be 70 percent).

A Monte Carlo analysis was applied to estimate the overall uncertainty of the 2009 emission estimate for SF_6 from electrical transmission and distribution. For each defined parameter (i.e., regression coefficient, transmission mileage, partner-reported and partner-estimated SF_6 emissions data for electric power systems; and SF_6 emission rate and statistics for manufacturers), random variables were selected from probability density functions, all assumed to have normal distributions about the mean.

Agriculture

The uncertainty analysis descriptions in this section correspond to some source categories included in the Agriculture Chapter of the Inventory.

Manure Management

The uncertainty information below pertains to the emission estimates presented in the Manure Management section of the Agriculture chapter. Please refer to that section for information about various manure management systems and their effect on emissions from this source. The uncertainty upper and lower bounds of the CH_4 emissions estimate for Manure Management were 20 percent and -18 percent, respectively, at the 95 percent confidence interval. The primary factors that contribute to the uncertainty in the emission estimates are a lack of information on the usage of various manure management systems in each regional location and the exact CH_4 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 1992, 1997, and 2002 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.

Previously, IPCC published a default range of MCFs for anaerobic lagoon systems of 0 to 100 percent, reflecting the wide range in performance that may be achieved with these systems (IPCC 2000). 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 CH_4 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, a MCF methodology utilizing the van't Hoff-Arrhenius equation was developed to more closely match observed system performance and account for the affect of temperature on system performance.

The MCF methodology used in the inventory includes a factor to account for management and design practices that result in the loss of VS 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.

Uncertainty also exists with the maximum CH_4 producing potential of VS 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 CH_4 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.

Rice Cultivation

The uncertainty upper and lower bounds of the emission estimate for Rice Cultivation were 146 percent and -65 percent, respectively, at the 95 percent confidence interval. Factors such as primary rice-cropped area, ratooning, and flooding affect greenhouse gas emissions from this source. For more information on emissions estimates for Rice Cultivation, please refer to that section in the Agriculture Chapter. Uncertainty associated with primary rice-cropped area for each state was assumed to range from 1 percent to 5 percent of the mean area based on expert judgment. A normal distribution of uncertainty, truncated to avoid negative values, was assumed about the mean for areas.

Ratooned area data are an additional source of uncertainty. Although ratooning accounts for only 5 to 10 percent of the total rice-cropped area, it is responsible for about 15 to 30 percent of total emissions. For states that have never reported any ratooning, it is assumed with complete certainty that no ratooning occurred in 2009. For states that regularly report ratooning, uncertainty is estimated to be between 3 percent and 5 percent (based on expert judgment) and is assumed to have a normal distribution, truncated to avoid negative values. For Arkansas, which reported significant ratooning in 1998 and 1999 only, a triangular distribution was assumed, with a lower boundary of 0 percent ratooning and an upper boundary of 0.034 percent ratooning based on the maximum ratooned area reported in 1998 and 1999.

The practice of flooding outside of the normal rice season is also an uncertainty. According to agricultural 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 68 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, however, CH_4 flux

measurements have not been undertaken over a sufficient geographic range or under a broad enough range of representative conditions to account for this source in the emission estimates or its associated uncertainty.

Agricultural Soil Management

The uncertainty information below pertains to the emission estimates presented in the Agricultural Soil Management section of the Agriculture chapter. Please refer to that section for information about this source. For direct emissions calculated using DAYCENT, uncertainty in the results was attributed to model inputs (i.e., activity data, weather and soil conditions) and the structure of the model (i.e., underlying model equations and parameterization). A Monte Carlo analysis was implemented to address these uncertainties and propagate errors through the modeling process (Del Grosso et al., 2010). The analysis was conducted using probability distribution functions (PDFs) for weather, soil characteristics, and N inputs to simulate direct N_2O emissions for each crop- or grassland type in a county. A joint PDF was used to address the structural uncertainty for direct N_2O emissions from crops, which was derived using an empirically-based method (Ogle et al. 2007). This same Monte Carlo analysis was used to derive uncertainty for the volatilization, runoff, and leaching of N that had been estimated with DAYCENT. County-scale PDFs for weather were based on the variation in temperature and precipitation as represented in DAYMET weather data grid cells (1x1 km) occurring in croplands and grasslands in a county. The National Land Cover Dataset (Vogelman et al. 2001) provided the data on distribution of croplands and grasslands. Similarly, county-scale PDFs for soil characteristics were based on STATSGO Soil Map Units (Soil Survey Staff 2005), that occurred in croplands and grasslands. PDFs for fertilizer were derived from survey data for major U.S. crops, both irrigated and rainfed (ERS 1997; NASS 2004, 1999, 1992; Grant and Krenz 1985). State-level PDFs were developed for each crop if a minimum of 15 data points existed for each of the two categories (irrigated and rainfed). Where data were insufficient at the state-level, PDFs were developed for multi-state Farm Production Regions. Uncertainty in manure application for specific crops was incorporated into the analysis based on total manure available for application in each county, a weighted average application rate, and the crop-specific land area amended with manure for 1997 (compiled from USDA data on animal numbers, manure production, storage practices, application rates and associated land areas receiving manure amendments; see Edmonds et al. 2003). Together with the total area for each crop within a county, the result yielded a probability that a given crop in a specific county would either receive manure or not in the Monte Carlo analysis. A ratio of manure N available for application in each year of the inventory relative to 1997 was used to adjust the amount of area amended with manure, under the assumption that changing the amount of manure N available for application would lead to a proportional change in amended area (see the section on Major Crop Types on Mineral Soils for data sources on manure N availability). If soils were amended with manure, a reduction factor was applied to the N fertilization rate accounting for the interaction between fertilization and manure N amendments (i.e., producers reduce mineral fertilization rates if applying manure). Reduction factors were randomly selected from probability distribution factors based on relationships between manure N application and fertilizer rates from USDA cropping survey data (ERS 1997).

An empirically-based uncertainty estimator was developed to assess the uncertainty in model structure associated with its' algorithms and parameterization, using a method described by Ogle et al. (2007). This estimator was based on a linear mixed-effect modeling analysis comparing N_2O emission estimates from eight agricultural experiments with 50 treatments. Although the dataset was relatively small, modeled emissions were significantly related to measurements with a p-value of less than 0.01. Random effects were included to capture the dependence in time series and data collected from the same experimental site, which were needed to estimate appropriate standard deviations for parameter coefficients. The model structural uncertainty estimator, accounted for bias and prediction error in the DAYCENT model results, as well as random error associated with fine-scale emission predictions in counties over a time series from 1990 to 2009. Note that the current application only addresses structural uncertainty in cropland estimates; further development will be needed to address this uncertainty in model estimates for grasslands, which is a planned improvement as more soil N_2O measurement data become available for grassland sites. In general, DAYCENT tended to underestimate emissions if the rates were above 6 g N_2O/ha/day (Del Grosso et al., 2010). Model structural uncertainty was not assessed for N volatilization and leaching/runoff, because sufficient data from field experiments were not available.

A simple error propagation method (IPCC 2006) was used to estimate uncertainties for direct emissions estimated with Tier 1 methods, including management of non-major crops (mineral fertilization, crop residues, organic fertilizers) and N inputs that were not addressed in the DAYCENT simulations (i.e., sewage sludge N, PRP manure N excreted on federal grasslands). Similarly, indirect emissions from N inputs that were not simulated with DAYCENT were calculated according to the IPCC methodology using the simple error propagation method (IPCC 2006). PDFs for the proportion of N subject to volatilization, leaching and runoff, as well as indirect N_2O emission factors were based on IPCC (2006), and PDFs for the activity data were based on the uncertainties associated underlying survey information and

calculations.[92] For lands simulated by DAYCENT, uncertainty in indirect emissions was derived using the simple error propagation approach, combining uncertainty from the DAYCENT outputs for N volatilization and leaching/runoff with uncertainty in the indirect N_2O emission factors (IPCC 2006).

Field Burning of Agricultural Residues

The uncertainty upper and lower bounds of the CH_4 emission estimate for Field Burning of Agricultural Residues were 42 percent and -40 percent, respectively, and of the N_2O emissions estimate were 31 percent and -30 percent respectively, at the 95 percent confidence interval. Variables such as crop production, residue/crop product ratios, and burning and combustion efficiencies affect greenhouse gas emission estimates for Field Burning of Agricultural Residues. For more information on emission estimates, please refer to the Field Burning of Agricultural Residues section of the Agriculture Chapter. The uncertainty in production for all crops considered here is estimated to be 5 percent, based on expert judgment. The uncertainty in area burned was 7 percent, based on McCarty (2009). Residue/crop product ratios can vary among cultivars. Generic residue/crop product ratios, rather than ratios specific to the United States, have been used for all crops except sugarcane. An uncertainty of 10 percent was applied to the residue/crop product ratios for all crops except for cotton, which was 55 percent. Based on the range given for measurements of soybean dry matter fraction (Strehler and Stützle 1987), residue dry matter contents were assigned an uncertainty of 3.1 percent for all crop types, except for cotton and lentils, which were 10 and 4.4 percent, respectively. Burning and combustion efficiencies were assigned an uncertainty of 5 percent based on expert judgment.

The N_2O emission ratio was estimated to have an uncertainty of 28.6 percent based on the range reported in IPCC/UNEP/OECD/IEA (1997). The uncertainty estimated for the CH_4 emission ratio was 40 percent based on the range of ratios reported in IPCC/UNEP/OECD/IEA (1997).

Land Use, Land-Use Change, and Forestry

Forest Land Remaining Forest Land

Changes in Forest Carbon Stocks

Forest area data from the USDA Forest Service and C density data affect total net flux of forest C estimates. For more information on net forest C flux, please refer to the Changes in Forest Carbon Stocks section of the Land Use, Land-Use Change, and Forestry (LULUCF) chapter. The USDA Forest Service inventories are designed to be accurate within 3 percent at the 67 percent confidence level (one standard error) per 405,000 ha (1 million acres) of timberland (USDA Forest Service 2006c). For larger areas, the uncertainty in area is concomitantly less, and precision at plot levels is greater. An analysis of uncertainty in growing stock volume data for timber producing land in the Southeast by Phillips et al. (2000) found that nearly all of the uncertainty in their analysis was due to sampling rather than the regression equations used to estimate volume from tree height and diameter. The quantitative uncertainty analysis summarized here primarily focuses on uncertainties associated with the estimates of specific C stocks at the plot level and does not address error in tree diameters or volumes.

Estimates for stand-level C pools are derived from extrapolations of site-specific studies to all forest land, because survey data on these pools are not generally available. Such extrapolation introduces uncertainty because available studies may not adequately represent regional or national averages. Uncertainty may also arise due to: (1) modeling errors (e.g., relying on coefficients or relationships that are not well known); and (2) errors in converting estimates from one reporting unit to another (Birdsey and Heath 1995). An important source of uncertainty is that there is little consensus from available data sets on the effect of land-use change and forest management activities (such as harvest) on soil C stocks. For example, while Johnson and Curtis (2001) found little or no net change in soil C following harvest, on average, across a number of studies, many of the individual studies did show differences. Heath and Smith (2000) noted that the experimental design in a number of soil studies limited their usefulness for determining effects of harvesting on soil C. Because soil C stocks are large, estimates need to be very precise, since even small relative changes in soil C sum to large differences when integrated over large areas. The soil C stock and stock change estimates presented here are based on the assumption that soil C density for each broad forest type group stays constant over time. The state of information and modeling are improving in this regard (Woodbury et al. 2006, 2007); the effects of land use and of changes in land use and forest management will be better accounted for in future estimates of soil C.

Uncertainty in estimates about the HWP Contribution is based on Monte Carlo simulation of the production approach. The uncertainty analysis is based on Skog et al. (2004), with later revisions made in conjunction with overall revisions in the HWP model (Skog in preparation). The uncertainty analysis for HWP includes an evaluation of the effect

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[92] With the exception of organic fertilizers and crop yields, which were assumed to have a default ±50 percent uncertainty.

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of uncertainty in 13 sources including production and trade data, factors to convert products to quantities of C, rates at which wood and paper are discarded, and rates and limits for decay of wood and paper in SWDS.

Direct N_2O fluxes from Forest Soils

The uncertainty upper and lower bounds of the emissions estimate for Direct N_2O Fluxes from Forest Soils were 211 percent and -59 percent, respectively, at the 95 percent confidence interval. Variables such as the emission factor for synthetic fertilizer applied to soil, and the area of forest land receiving fertilizer affect Direct N_2O fluxes from Forest Soils. For more information, please refer to that section of the LULUCF chapter. The uncertainty range of the IPCC (2006) default emission factor for synthetic fertilizer applied to soil, ranges from 0.3 to 3 percent. Because IPCC does not provide further information on whether this range represents the 95 percent confidence interval or the absolute minimum and maximum values, a triangular distribution was used to represent the uncertainty of the emission factor. The uncertainty in the area of forest land receiving fertilizer was conservatively estimated at ±20 percent and in fertilization rates at ±50 percent (Binkley 2004).

Cropland Remaining Cropland

The uncertainty information below pertains to the emission estimates presented in the Cropland Remaining Cropland section of the LULUCF chapter. Please refer to that section for information about this source. The uncertainty upper and lower bounds of the emissions estimate for Cropland Remaining Cropland were -172 percent and 167 percent, respectively, at the 95 percent confidence interval. Probability Distribution Functions (PDFs) for fertilizer were based on survey data for major U.S. crops, both irrigated and rainfed (ERS 1997; NASS 2004, 1999, 1992; Grant and Krenz 1985). State-level PDFs were developed for each crop if a minimum of 15 data points existed for each of the two categories (irrigated and rainfed). Where data were insufficient at the state-level, PDFs were developed for multi-state Farm Production Regions. Uncertainty in manure applications for specific crops was incorporated in the analysis based on total manure available for use in each county, a weighted average application rate, and the crop-specific land area amended with manure (compiled from USDA data on animal numbers, manure production, storage practices, application rates and associated land areas receiving manure amendments; see Edmonds et al. 2003). Together with the total area for each crop within a county, this yielded a probability that a given crop at a specific NRI point would either receive manure or not. A ratio of managed manure N production in each year of the inventory relative to 1997 was used to adjust the probability of an area receiving an amendment, under the assumption that greater or less managed manure N production would lead to a proportional change in amended area (see Tier 3 Methods Section for data sources on manure N production). Manure amendment areas were averaged across decades to produce the PDF for the Monte Carlo Analysis (i.e., 1980-1989, 1990-2000). If soils were amended with manure, a reduction factor was applied to the N fertilization rate accounting for the interaction between fertilization and manure N amendments (i.e., producers often reduce mineral fertilization rates if applying manure). Reduction factors were randomly selected from probability distribution factors based on relationships between manure N application and fertilizer rates (ERS 1997). For tillage uncertainty, transition matrices were constructed from CTIC data to represent tillage changes for two time periods, combining the first two and the second two management blocks (i.e., 1980-1989, 1990-2000). A Monte Carlo analysis was conducted with 100 iterations in which inputs values were randomly drawn from the PDFs to simulate the soil C stocks for each NRI cluster of points (i.e., inventory points in the same county were grouped into clusters if they had the same land-use/management history and soil type) using the Century model.

An empirically-based uncertainty estimator was developed to assess uncertainty in model structure associated with the algorithms and parameterization. The estimator was based on a linear mixed effect modeling analysis comparing modeled soil C stocks with field measurements from 45 long-term agricultural experiments with over 800 treatments, representing a variety of tillage, cropping, and fertilizer management practices (Ogle et al. 2006b). The final model included variables for organic matter amendments, N fertilizer rates, inclusion of hay/pasture in cropping rotations, use of no-till, setting-aside cropland from production and inclusion of bare fallow in the rotation. Each of these variables were found to be significant at a 95 percent probability level, and accounted for statistically significant biases in the modeled estimates from Century. For example, Century tended to under-estimate the influence of organic amendments on soil C storage, so a variable was added to adjust the estimate from Century. Random effects captured the dependence in time series and data collected from the same long-term experimental site, which were needed to estimate appropriate standard deviations for parameter coefficients. For each C stock estimate from the Monte Carlo analysis, the structural uncertainty estimator was applied to adjust the value accounting for bias and prediction error in the modeled values. The structural uncertainty estimator was applied by randomly drawing parameter coefficients from their joint probability distribution, in addition to random draws from PDFs representing the uncertainty due to site and site by year random effects. Finally, uncertainty in the land-use and management statistics from the NRI were incorporated into the analysis based on the sampling variance for the clusters of NRI points.

The NRI has a two-stage sampling design that allowed PDFs to be constructed assuming a multivariate normal distribution accounting for dependencies in activity data. PDFs for the tillage activity data, as provided by the CTIC, were constructed on a bivariate normal distribution with a log-ratio scale, accounting for the negative dependence among the proportions of land under conventional and conservation tillage practices. PDFs for the agricultural areas receiving manure were derived assuming a normal distribution from county-scale area amendment estimates derived from the USDA Census of Agriculture (Edmonds et al. 2003). Lastly, enrollment in wetland restoration programs was estimated from contract agreements, but due to a lack of information on the margin of error, PDFs were constructed assuming a nominal ±50 percent uncertainty range.

Mineral Soil Carbon Stock Changes

Tier 3 Approach

The uncertainty information below pertains to the emission estimates presented in the Mineral Soil Carbon Stock Changes section of the LULUCF chapter. Please refer to that section for information about this source. The uncertainty analysis for the Tier 3 Century inventory had three components: 1) a Monte Carlo approach to address uncertainties in model inputs, 2) an empirically-based approach for quantifying uncertainty inherent in the structure of the Century model, and 3) scaling uncertainty associated with the NRI survey (i.e., scaling from the individual NRI points to the entire U.S. agricultural land base using the expansion factors).

For the model input uncertainty, probability distribution functions (PDFs) were developed for fertilizer rates, manure application and tillage practices. An empirically-based uncertainty estimator was developed to assess uncertainty in model structure associated with the algorithms and parameterization. The estimator was based on a linear mixed effect modeling analysis comparing modeled soil C stocks with field measurements from 45 long-term agricultural experiments with over 800 treatments, representing a variety of tillage, cropping, and fertilizer management practices (Ogle et al. 2007). The final model included variables for organic matter amendments, N fertilizer rates, inclusion of hay/pasture in cropping rotations, use of no-till, setting-aside cropland from production, and inclusion of bare fallow in the rotation. Each of these variables were found to be significant at a 0.05 alpha level, and accounted for statistically significant biases in modeled estimates from the Century model. Uncertainty in land-use and management statistics from the NRI were incorporated into the analysis based on the sampling variance for the clusters of NRI points.

Tier 2 Approach

For the Tier 2 IPCC method, a Monte Carlo approach was used (Ogle et al. 2003). PDFs for stock change factors were derived from a synthesis of 91 published studies, which addressed the impact of management on SOC storage. Uncertainties in land-use and management activity data were also derived from a statistical analysis.

Additional Mineral C Stock Change Calculations

A ±50 percent uncertainty was assumed for additional adjustments to the mineral soil C stocks between 1990 and 2006, accounting for additional C stock changes associated gains or losses in C sequestration after 1997 due to changes in Conservation Reserve Program enrollment.

Organic Soil Carbon Stock Changes

Uncertainty in C emissions from organic soils was estimated in the same manner described for mineral soil using the Tier 2 method and Monte Carlo analysis. PDFs for emission factors were derived from a synthesis of 10 studies, and combined with uncertainties in the NRI land use and management data for organic soils in the Monte Carlo analysis. Please refer to the Organic Soil C Stock Changes section of the LULUCF chapter for more information on C emissions from organic soils.

CO_2 Emissions from Liming

The uncertainty information below pertains to the emission estimates presented in the Mineral Soil Carbon Stock Changes section of the LULUCF chapter. Please refer to that section for information about liming activity data and the emission factors used for this source. A Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the uncertainty of CO_2 emissions from liming. Uncertainties in the estimates of emissions from liming result from both the emission factors and the activity data. The emission factors used for limestone and dolomite take into account the fate of C following application to soils, including: dissolution of liming constituents; leaching of bicarbonates into the soil and transport to the ocean; and emissions to the atmosphere (West and McBride 2005). The C accounting behind these emission factors entails assumptions about several uncertain factors. First, it is uncertain what fraction of agricultural lime is dissolved by nitric acid (HNO_3)—a process that releases CO_2—and what portion reacts with carbonic acid (H_2CO_3), resulting in the uptake of CO_2. The fractions can vary depending on soil pH and N fertilizer use. The second major source of uncertainty is the fraction of bicarbonate (HCO_3^-) that leaches through the soil profile and *is transported into*

groundwater, which can eventually be transferred into rivers and into the ocean. This fraction can vary depending on the soil pH and whether calcium (Ca^{2+}) and magnesium (Mg^{2+}) liming constituents that might otherwise accompany HCO_3^-, are taken up by crops, remain in the upper soil profile, or are transported through or out of the soil profile. Finally, the emission factors do not account for the time that is needed for leaching and transport processes to occur.

There are several sources of uncertainty in the limestone and dolomite activity data. When reporting data to the USGS (or U.S. Bureau of Mines), some producers do not distinguish between limestone and dolomite. In these cases, data are reported as limestone, so this reporting could lead to an overestimation of limestone and an underestimation of dolomite. In addition, the total quantity of crushed stone listed each year in the *Minerals Yearbook* excludes American Samoa, Guam, Puerto Rico, and the U.S. Virgin Islands.

Land Converted to Cropland

Tier 2 Approach

The uncertainty upper and lower bounds of the emissions estimate for Land Converted to Cropland were 36 percent and -40 percent, respectively, at the 95 percent confidence interval. The uncertainty analysis for *Land Converted to Cropland* using the Tier 2 approach was based on the same method described for *Cropland Remaining Cropland*.

Mineral and Organic Soil Carbon Stock Changes

The quantitative estimates of uncertainty presented above are missing several components. This section qualitatively describes these contributors to overall uncertainty. The agricultural soil C inventory has undergone several improvements during the past few years, such as the development of the Tier 3 inventory method to estimate mineral soil C stock changes for the majority of U.S. cropland. However, some limitations remain in the analysis. First, the current agricultural soil C inventory includes some points designated as non-agricultural land-uses in the NRI if the points were categorized as cropland in either 1992 or 1997, but were urban, water, or miscellaneous non-cropland (e.g., roads and barren areas) in another year. The impact on soil organic C storage that results from converting non-agricultural uses to cropland is not well-understood, and therefore, those points were not included in the calculations for mineral soils (emissions from organic soils, however, were computed for those points in the years that they were designated as an agricultural use). Similarly, the effect of aquaculture (e.g., rice cultivation followed by crayfish production in flooded fields) on soil C stocks has not been estimated due to a lack of experimental data. Second, the current estimates may underestimate losses of C from organic soils because the *1997 National Resources Inventory* was not designed as a soil survey and organic soils frequently occur as relatively small inclusions within major soil types. Lastly, the IPCC Tier 2 methodology does not take into account changes in SOC stocks due to pre-1982 land use and land-use change.

Grassland Remaining Grassland

Tier 2 Approach

The uncertainty upper and lower bounds of the emissions estimate for Grassland Remaining Grassland were -32 percent and 25 percent, respectively, at the 95 percent confidence interval. The uncertainty analysis for *Grassland Remaining Grassland* using the Tier 2 approach was based on the same method described for *Cropland Remaining Cropland*.

Additional Uncertainties in Mineral and Organic Soil C Stock Changes

The quantitative estimates of uncertainty presented above are missing several components. This section qualitatively describes these contributors to overall uncertainty. Minimal data exist on where and how much sewage sludge has been applied to U.S. agricultural land and the accounting of this activity appears to be much more difficult than the related-activity of using manure to amend agricultural soils. Consequently, there is considerable uncertainty in the application of sewage sludge, which is assumed to be applied to *Grassland Remaining Grassland*. However, some sludge may be applied to other agricultural land, but there is not sufficient information to further subdivide application among the agricultural land use/land-use change categories. Another limitation is that the current estimates may underestimate losses of C from organic soils because the *1997 National Resources Inventory* was not designed as a soil survey and organic soils frequently occur as relatively small inclusions within major soil types. Lastly, the IPCC Tier 2 methodology does not take into account changes in SOC stocks due to pre-1982 land use and land-use change.

Land Converted to Grassland

Tier 2 Approach

The uncertainty upper and lower bounds of the emissions estimate for Land Converted to Grassland were -15 percent and 15 percent, respectively, at the 95 percent confidence interval, The uncertainty analysis for *Land Converted to Grassland* using the Tier 2 approach was based on the same method described for *Cropland Remaining Cropland*. See the Tier 2 section under minerals soils in the *Cropland Remaining Cropland* section for additional discussion.

Additional Uncertainties in Mineral and Organic Soil Carbon Stock Changes

The quantitative estimates of uncertainty presented above are missing several components. This section qualitatively describes these contributors to overall uncertainty. The agricultural soil C inventory has undergone several improvements during the past few years, such as the development of the Tier 3 inventory method to estimate mineral soil C stock changes for the majority of U.S. grassland. However, some limitations remain in the analysis. First, the current agricultural soil C inventory includes some points designated as non-agricultural land-uses in the NRI if the points were categorized as agricultural land use in either 1992 or 1997, but were urban, water, or miscellaneous non-cropland (e.g., roads and barren areas) in another year. The impact on SOC storage that results from converting non-agricultural uses to grassland is not well-understood, and therefore, those points were not included in the calculations for mineral soils (emissions from organic soils, however, were computed for those points in the years that they were designated as grassland). Second, the current estimates may underestimate losses of C from organic soils because the *1997 National Resources Inventory* was not designed as a soil survey and organic soils frequently occur as relatively small inclusions within major soil types. Lastly, this IPCC Tier 2 methodology does not take into account changes in SOC stocks due to pre-1982 land use and land-use change.

Settlements Remaining Settlements

N₂O Fluxes from Settlement Soil

The uncertainty information below pertains to the emission estimates presented in the N_2O Fluxes from Settlement Soils section of the LULUCF chapter. Please refer to that section for information about synthetic fertilizer N, the amounts of sewage sludge applied to non-agricultural lands, and other variables that affect this source. The uncertainty upper and lower bounds of the emissions estimate for N_2O fluxes from Settlement Soil were 163 percent and -49 percent, respectively, at the 95 percent confidence interval. The uncertainty range for the IPCC's default emission factor for mineral and organic N additions applied to soil ranges from 0.3 to 3 percent (IPCC 2006). Because the IPCC does not provide further information on whether this range represents the 95 percent confidence interval or the absolute minimum and maximum values, a triangular distribution was used to represent the uncertainty of the emission factor.

The uncertainty in the total amount of synthetic fertilizer N applied in the United States was estimated to be ±3 percent (Terry 2005). The uncertainty in the amount of synthetic fertilizer N applied to settlement soils was conservatively estimated to be ±50 percent, since no uncertainty was provided in Ruddy et al. (2006). The uncertainty in the amounts of sewage sludge applied to non-agricultural lands and used in surface disposal was based on the uncertainty of the following data points: (1) N content of sewage sludge; (2) total sludge applied in 2000; (3) wastewater existing flow in 1996, 2000, and 2004; and (4) the sewage sludge disposal practice distributions to non-agricultural land application and surface disposal**.**

(1) The value assumed for N content of sewage sludge could range from around 0.1 percent to around 17 percent (McFarland 2001). Because information was not available on the distribution, a triangular distribution was assumed based on IPCC guidelines.

(2) The uncertainty in the total amount of sludge applied in 2000 was based on a comparison with similar data available from other publications, which were all within 3 percent of the value used in the Inventory calculations (BioCycle 2000, NRC 2002, WEF 1997, Bastian 1997). The distribution was estimated to be normal based on expert opinion (Boucher 2006).

(3) The uncertainty in the wastewater existing flow values for 1996 and 2000 was estimated at 0.0625 percent with a lognormal distribution (Plastino 2006).

(4) The uncertainty in the sewage sludge disposal practice distributions was based on a comparison with similar data available from other publications, which were at most 12 percent different than the distribution for non-agricultural land application used in the Inventory calculations and at most 69 percent different than the distribution for surface disposal used in the Inventory calculations (Biocycle 2000, NRC 2002).

Other

   The uncertainty analysis descriptions in this section correspond to Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills source category included in the Other Chapter of the Inventory.

   Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills

   The uncertainty ranges were assigned based on expert judgment and are assumed to be normally distributed around the inventory estimate, except for the values for decomposition rate, proportion of C stored, and the decay rates. The uncertainty ranges associated with these values are highlighted separately in this section.

   The uncertainty range selected for input variables for the proportions of both grass and leaves in yard trimmings was 20 to 60 percent. The initial C content for grass, leaves, and food scraps (all expressed as percentages in the calculations for the inventory) were plus or minus 10 percent. For the moisture content of branches (where the inventory estimate is 10 percent), the uncertainty range was assumed to be 5 to 30 percent, within a lognormal distribution.

   The uncertainty ranges associated with the disposal of grass, leaves, branches, and food scraps were bound at 50 percent to 150 percent of the inventory estimates. The proportion of C stored in grass, leaves, branches, and food scraps was assumed to vary plus or minus 20 percent from the best estimate, with a uniform distribution. The proportion of C stored in food scraps was truncated at a lower bound of 2 percent.

   Finally, the uncertainty ranges assigned to the decay rates of grass, leaves, branches, and food scraps were developed based on De la Cruz, 2010. The minimum value corresponds to projected conditions if all landfills are in a dry environment; the maximum value corresponds to bioreactor conditions. A triangular distribution is applied to each of these variables.

References

EPA (2002). *Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory: Procedures Manual for Quality Assurance/Quality Control and Uncertainty Analysis*, U.S. Greenhouse Gas Inventory Program, U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-02-007B, June 2002.

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