DRAFT Annexes to the Inventory of U.S. GHG Emissions and Sinks

The following eight 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* (UNFCCC 2003). Annex I 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. Annex 7 provides data on the uncertainty of the emission estimates included in this report. Finally, Annex 8 provides information on the QA/QC methods and procedures used in the development of the Inventory.

ANNEX 1 Key Category Analysis

The United States has identified national key categories based on the estimates presented in this report. The *2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) 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 greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals." 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 the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006), includes:

- Approach 1 (including both level and trend assessments);
- Approach 2 (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 Land Use, Land-Use Change and Forestry [LULUCF]); discusses Approach 1, Approach 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 (GWP)-weighted emissions in 2015. The table also indicates the criteria used in identifying these categories (i.e., level, trend, Approach 1, Approach 2, and/or qualitative assessments).

Table A-1: Key Source Categories for the United States (1990-2015)

IPCC Source Categories	Gas	Approach 1				Approach 2				Qual[a]	2015 Emissions (MMT 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 Mobile Combustion: Road	CO_2	•	•	•	•	•	•	•	•		1,460.9
CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	•	•	•	•	•	•	•	•		1,350.5
CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	•	•	•	•	•	•	•	•		526.1
CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	•	•	•	•	•	•	•	•		467.5
CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	•	•	•	•	•		•			295.5
CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	•	•	•	•	•		•			252.8
CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	•	•	•	•	•	•	•			175.4
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	•	•	•	•	•	•	•			159.2
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	•		•	•	•	•	•			127.0
CO_2 Emissions from Mobile Combustion: Other	CO_2	•	•	•	•						81.6
CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	•	•	•	•						66.8
CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	•	•	•	•	•	•	•	•		65.9
CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	•	•	•	•						47.3
CO_2 Emissions from Natural Gas Systems	CO_2	•		•		•		•			42.4
CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	•	•	•	•						34.6
CO_2 Emissions from Mobile Combustion: Marine	CO_2	•	•	•	•						31.6
CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	•	•	•	•	•	•		•		23.7

CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2						•				3.2
CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2		•		•						2.9
CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2						•		•		0.0
CH_4 Emissions from Natural Gas Systems	CH_4	•	•	•	•	•	•	•	•		160.0
Fugitive Emissions from Coal Mining	CH_4	•	•	•	•	•	•	•	•		60.9
CH_4 Emissions from Petroleum Systems	CH_4	•	•	•	•	•	•	•	•		41.5
Non-CO_2 Emissions from Stationary Combustion - Residential	CH_4					•	•	•	•		3.9
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	N_2O		•		•	•	•	•	•		19.5
N_2O Emissions from Mobile Combustion: Road	N_2O	•	•	•	•		•		•		11.3
International Bunker Fuels[c]	Several									•	111.8
Industrial Processes											
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	•	•	•	•	•	•	•	•		47.9
CO_2 Emissions from Cement Production	CO_2	•		•							39.6
CO_2 Emissions from Petrochemical Production	CO_2		•								28.1
N_2O Emissions from Adipic Acid Production	N_2O		•		•						4.3
Emissions from Substitutes for Ozone Depleting Substances	HiGWP	•	•	•	•	•	•	•	•		168.6
HFC-23 Emissions from HCFC-22 Production	HiGWP		•		•		•		•		5.0
PFC Emissions from Aluminum Production	HiGWP	•	•	•	•		•		•		4.2
SF_6 Emissions from Electrical Transmission and Distribution	HiGWP		•		•						2.0
Agriculture											
CH_4 Emissions from Enteric Fermentation	CH_4	•		•		•		•			166.5
CH_4 Emissions from Manure Management	CH_4	•	•	•	•	•	•	•	•		66.3
Direct N_2O Emissions from Agricultural Soil Management	N_2O	•	•	•		•		•			213.3
Indirect N_2O Emissions from Applied Nitrogen	N_2O	•	•	•	•	•	•	•	•		38.0
Waste											
CH_4 Emissions from Landfills	CH_4	•	•	•	•	•	•	•	•		115.7
Land Use, Land Use Change, and Forestry											

CO_2 Emissions from Land Converted to Grassland	CO_2		•	•		•	•		294.2
CO_2 Emissions from Land Converted to Settlements	CO_2		•	•					150.2
CO_2 Emissions from Land Converted to Cropland	CO_2		•	•		•	•		28.6
CO_2 Emissions from Grassland Remaining Grassland	CO_2					•	•		7.3
CO_2 Emissions from Cropland Remaining Cropland	CO_2		•	•		•	•		(14.0)
CO_2 Emissions from Land Converted to Forest Land	CO_2		•	•					(75.2)
CO_2 Emissions from Settlements Remaining Settlements	CO_2		•	•		•	•		(102.1)
CO_2 Emissions from Forest Land Remaining Forest Land	CO_2		•	•		•	•		(667.0)
CH_4 Emissions from Forest Fires	CH_4					•	•		7.3
N_2O Emissions from Forest Fires	N_2O						•		4.8
Subtotal Without LULUCF									**6,411.3**
Total Emissions Without LULUCF									**6,586.2**
Percent of Total Without LULUCF									**97%**
Subtotal With LULUCF									**6,014.0**
Total Emissions With LULUCF									**6,219.8**
Percent of Total With LULUCF									**97%**

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

Notes: 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 2015) in which each source category reached the threshold for being a key category based on either an Approach 1 or Approach 2 level assessment.

In addition to conducting Approach 1 and 2 level and trend assessments, a qualitative assessment of the source categories, as described in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006), 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 Approach 1. 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 Approach 2.

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

IPCC Source Categories	Direct Greenhouse Gas	2015 Emissions (MMT CO_2 Eq.)	Key Category?	ID Criteria[a]	Level in which year(s)?[b]
Energy					
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,460.9	•	L_1 T_1 L_2 T_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,350.5	•	L_1 T_1 L_2 T_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	526.1	•	L_1 T_1 L_2 T_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	467.5	•	L_1 T_1 L_2 T_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	295.5	•	L_1 T_1 L_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	252.8	•	L_1 T_1 L_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	175.4	•	L_1 T_1 L_2 T_2	1990, 2015
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	159.2	•	L_1 T_1 L_2 T_2	1990, 2015
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	127.0	•	L_1 L_2 T_2	1990, 2015
CO_2 Emissions from Mobile Combustion: Other	CO_2	81.6	•	L_1 T_1	1990_1, 2015_1
CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	66.8	•	L_1 T_1	1990_1, 2015_1
CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	65.9	•	L_1 T_1 L_2 T_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	47.3	•	L_1 T_1	1990_1, 2015_1
CO_2 Emissions from Natural Gas Systems	CO_2	42.4	•	L_1 L_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	34.6	•	L_1 T_1	2015_1
CO_2 Emissions from Mobile Combustion: Marine	CO_2	31.6	•	L_1 T_1	1990_1
CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	23.7	•	L_1 T_1 L_2 T_2	1990
CO_2 Emissions from Incineration of Waste	CO_2	10.7			
CO_2 Emissions from Petroleum Systems	CO_2	3.6			
CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	3.4			
CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	3.2	•	T_2	
CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	2.9	•	T_1	
CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4			
CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	0.0	•	T_2	
CH_4 Emissions from Natural Gas Systems	CH_4	160.0	•	L_1 T_1 L_2 T_2	1990, 2015
Fugitive Emissions from Coal Mining	CH_4	60.9	•	L_1 T_1 L_2 T_2	1990, 2015
CH_4 Emissions from Petroleum Systems	CH_4	41.5	•	L_1 T_1 L_2 T_2	1990, 2015

Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	6.4			
Non-CO_2 Emissions from Stationary Combustion - Residential	CH_4	3.9	•	L_2 T_2	1990_2
Non-CO_2 Emissions from Stationary Combustion - Industrial	CH_4	1.5			
CH_4 Emissions from Mobile Combustion: Road	CH_4	1.5			
Non-CO_2 Emissions from Stationary Combustion - Commercial	CH_4	1.1			
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.5			
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	CH_4	0.4			
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	CH_4	0.1			
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	+			
CH_4 Emissions from Mobile Combustion: Marine	CH_4	+			
CH_4 Emissions from Incineration of Waste	CH_4	+			
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	N_2O	19.5	•	T_1 L_2 T_2	1990_2, 2015_2
N_2O Emissions from Mobile Combustion: Road	N_2O	11.3	•	L_1 T_1 T_2	1990_1
Non-CO_2 Emissions from Stationary Combustion - Industrial	N_2O	2.4			
N_2O Emissions from Mobile Combustion: Other	N_2O	2.0			
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.5			
Non-CO_2 Emissions from Stationary Combustion - Residential	N_2O	0.8			
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6			
Non-CO_2 Emissions from Stationary Combustion - Commercial	N_2O	0.3			
N_2O Emissions from Incineration of Waste	N_2O	0.3			
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1			
International Bunker Fuels[c]	Several	111.8	•	Q	
Industrial Processes and Product Use					
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	47.9	•	L_1 T_1 L_2 T_2	1990, 2015_1
CO_2 Emissions from Cement Production	CO_2	39.6	•	L_1	1990_1, 2015_1
CO_2 Emissions from Petrochemical Production	CO_2	28.1	•	T_1	
CO_2 Emissions from Lime Production	CO_2	13.3			
CO_2 Emissions from Other Process Uses of Carbonates	CO_2	10.8			
CO_2 Emissions from Ammonia Production	CO_2	10.8			
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	4.3			
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	2.8			
CO_2 Emissions from Aluminum Production	CO_2	2.8			
CO_2 Emissions from Ferroalloy Production	CO_2	2.0			
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.6			
CO_2 Emissions from Glass Production	CO_2	1.3			
CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	1.1			
CO_2 Emissions from Phosphoric Acid Production	CO_2	1.0			
CO_2 Emissions from Zinc Production	CO_2	0.9			
CO_2 Emissions from Lead Production	CO_2	0.5			
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.2			

CO_2 Emissions from Magnesium Production and Processing	CO_2	+			
CH_4 Emissions from Petrochemical Production	CH_4	0.2			
CH_4 Emissions from Ferroalloy Production	CH_4	+			
CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+			
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+			
N_2O Emissions from Nitric Acid Production	N_2O	11.6			
N_2O Emissions from Adipic Acid Production	N_2O	4.3	•	T_1	
N_2O Emissions from Product Uses	N_2O	4.2			
N_2O Emissions from Semiconductor Manufacture	N_2O	0.2			
Emissions from Substitutes for Ozone Depleting Substances	HiGWP	168.6	•	L_1 T_1 L_2 T_2	2015
HFC-23 Emissions from HCFC-22 Production	HiGWP	5.0	•	T_1 T_2	
PFC, HFC, SF_6, and NF_3 Emissions from Semiconductor Manufacture	HiGWP	4.8			
SF_6 Emissions from Electrical Transmission and Distribution	HiGWP	4.2	•	L_1 T_1 T_2	1990_1
PFC Emissions from Aluminum Production	HiGWP	2.0	•	T_1	
SF_6 Emissions from Magnesium Production and Processing	HiGWP	0.9			
HFC-134A Emissions from Magnesium Production and Processing	HiGWP	0.1			
Agriculture					
CO_2 Emissions from Urea Fertilization	CO_2	5.0			
CO_2 Emissions from Liming	CO_2	3.8			
CH_4 Emissions from Enteric Fermentation	CH_4	166.5	•	L_1 L_2	1990, 2015
CH_4 Emissions from Manure Management	CH_4	66.3	•	L_1 T_1 L_2 T_2	1990_1, 2015
CH_4 Emissions from Rice Cultivation	CH_4	11.2			
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.3			
Direct N_2O Emissions from Agricultural Soil Management	N_2O	213.3	•	L_1 T_1 L_2	1990, 2015
Indirect N_2O Emissions from Applied Nitrogen	N_2O	38.0	•	L_1 T_1 L_2 T_2	1990, 2015
N_2O Emissions from Manure Management	N_2O	17.7			
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1			
Waste					
CH_4 Emissions from Landfills	CH_4	115.7	•	L_1 T_1 L_2 T_2	1990, 2015
CH_4 Emissions from Wastewater Treatment	CH_4	14.8			
CH_4 Emissions from Composting	CH_4	2.1			
N_2O Emissions from Wastewater Treatment	N_2O	5.0			
N_2O Emissions from Composting	N_2O	1.9			

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] For the ID criteria, Q refers to "Qualitative", 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 an Approach 1 or Approach 2 assessment (e.g., L_2 designates a source is a key category for an Approach 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 Approach 2 assessment only in 1990).

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

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	Direct Greenhouse Gas	2015 Emissions (MMT CO_2 Eq.)	Key Category?	ID Criteria[a]	Level in which year(s)?[b]
Energy					
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,460.9	•	L_1 T_1 L_2 T_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,350.5	•	L_1 T_1 L_2 T_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	526.1	•	L_1 T_1 L_2 T_2	1990_1, 2015
CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	467.5	•	L_1 T_1 L_2 T_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	295.5	•	L_1 T_1 L_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	252.8	•	L_1 T_1 L_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	175.4	•	L_1 T_1 L_2	1990_1, 2015
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	159.2	•	L_1 T_1 L_2	1990, 2015_1
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	127.0	•	L_1 T_1 L_2	1990, 2015
CO_2 Emissions from Mobile Combustion: Other	CO_2	81.6	•	L_1 T_1	1990_1, 2015_1
CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	66.8	•	L_1 T_1	1990_1, 2015_1
CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	65.9	•	L_1 T_1 L_2 T_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	47.3	•	L_1 T_1	1990_1, 2015_1
CO_2 Emissions from Natural Gas Systems	CO_2	42.4	•	L_1 L_2	1990, 2015
CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	34.6	•	L_1 T_1	2015_1
CO_2 Emissions from Mobile Combustion: Marine	CO_2	31.6	•	L_1 T_1	1990_1, 2015_1
CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	23.7	•	L_1 T_1 T_2	1990_1
CO_2 Emissions from Incineration of Waste	CO_2	10.7			
CO_2 Emissions from Petroleum Systems	CO_2	3.6			
CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	3.4			
CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	3.2			
CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	2.9	•	T_1	
CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4			
CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	0.0	•	T_2	
CH_4 Emissions from Natural Gas Systems	CH_4	160.0	•	L_1 T_1 L_2 T_2	1990, 2015
Fugitive Emissions from Coal Mining	CH_4	60.9	•	L_1 T_1 L_2 T_2	1990, 2015_1
CH_4 Emissions from Petroleum Systems	CH_4	41.5	•	L_1 T_1 L_2 T_2	1990, 2015
Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	6.4			
Non-CO_2 Emissions from Stationary Combustion - Residential	CH_4	3.9	•	L_2 T_2	1990_2
Non-CO_2 Emissions from Stationary Combustion - Industrial	CH_4	1.5			
CH_4 Emissions from Mobile Combustion: Road	CH_4	1.5			
Non-CO_2 Emissions from Stationary Combustion - Commercial	CH_4	1.1			
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.5			

Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	CH_4	0.4			
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	CH_4	0.1			
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	+			
CH_4 Emissions from Mobile Combustion: Marine	CH_4	+			
CH_4 Emissions from Incineration of Waste	CH_4	+			
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	N_2O	19.5	•	T_1 L_2 T_2	1990_2, 2015_2
N_2O Emissions from Mobile Combustion: Road	N_2O	11.3	•	L_1 T_1 T_2	1990_1
Non-CO_2 Emissions from Stationary Combustion - Industrial	N_2O	2.4			
N_2O Emissions from Mobile Combustion: Other	N_2O	2.0			
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.5			
Non-CO_2 Emissions from Stationary Combustion - Residential	N_2O	0.8			
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6			
Non-CO_2 Emissions from Stationary Combustion - Commercial	N_2O	0.3			
N_2O Emissions from Incineration of Waste	N_2O	0.3			
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1			
International Bunker Fuels[c]	Several	111.8	•	Q	
Industrial Processes and Product Use					
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	47.9	•	L_1 T_1 L_2 T_2	1990, 2015_1
CO_2 Emissions from Cement Production	CO_2	39.6	•	L_1	2015_1
CO_2 Emissions from Petrochemical Production	CO_2	28.1			
CO_2 Emissions from Lime Production	CO_2	13.3			
CO_2 Emissions from Other Process Uses of Carbonates	CO_2	10.8			
CO_2 Emissions from Ammonia Production	CO_2	10.8			
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	4.3			
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	2.8			
CO_2 Emissions from Aluminum Production	CO_2	2.8			
CO_2 Emissions from Ferroalloy Production	CO_2	2.0			
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.6			
CO_2 Emissions from Glass Production	CO_2	1.3			
CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	1.1			
CO_2 Emissions from Phosphoric Acid Production	CO_2	1.0			
CO_2 Emissions from Zinc Production	CO_2	0.9			
CO_2 Emissions from Lead Production	CO_2	0.5			
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.2			
CO_2 Emissions from Magnesium Production and Processing	CO_2	+			
CH_4 Emissions from Petrochemical Production	CH_4	0.2			
CH_4 Emissions from Ferroalloy Production	CH_4	+			
CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+			
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+			
N_2O Emissions from Nitric Acid Production	N_2O	11.6			
N_2O Emissions from Adipic Acid Production	N_2O	4.3	•	T_1	
N_2O Emissions from Product Uses	N_2O	4.2			
N_2O Emissions from Semiconductor Manufacture	N_2O	0.2			

Emissions from Substitutes for Ozone Depleting Substances	HiGWP	168.6	•	L_1 T_1 L_2 T_2	2015
HFC-23 Emissions from HCFC-22 Production	HiGWP	5.0	•	T_1 T_2	
PFC, HFC, SF_6, and NF_3 Emissions from Semiconductor Manufacture	HiGWP	4.8			
SF_6 Emissions from Electrical Transmission and Distribution	HiGWP	4.2	•	L_1 T_1 T_2	1990_1
PFC Emissions from Aluminum Production	HiGWP	2.0	•	T_1	
SF_6 Emissions from Magnesium Production and Processing	HiGWP	0.9			
HFC-134a Emissions from Magnesium Production and Processing	HiGWP	0.1			
Agriculture					
CO_2 Emissions from Urea Fertilization	CO_2	5.0			
CO_2 Emissions from Liming	CO_2	3.8			
CH_4 Emissions from Enteric Fermentation	CH_4	166.5	•	L_1 L_2	1990, 2015
CH_4 Emissions from Manure Management	CH_4	66.3	•	L_1 T_1 L_2 T_2	1990_1, 2015
CH_4 Emissions from Rice Cultivation	CH_4	11.2			
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.3			
Direct N_2O Emissions from Agricultural Soil Management	N_2O	213.3	•	L_1 L_2	1990, 2015
Indirect N_2O Emissions from Applied Nitrogen	N_2O	38.0	•	L_1 T_1 L_2 T_2	1990, 2015
N_2O Emissions from Manure Management	N_2O	17.7			
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1			
Waste					
CH_4 Emissions from Landfills	CH_4	115.7	•	L_1 T_1 L_2 T_2	1990, 2015
CH_4 Emissions from Wastewater Treatment	CH_4	14.8			
CH_4 Emissions from Composting	CH_4	2.1			
N_2O Emissions from Wastewater Treatment	N_2O	5.0			
N_2O Emissions from Composting	N_2O	1.9			
Land Use, Land Use Change, and Forestry					
CO_2 Emissions from Land Converted to Grassland	CO_2	294.2	•	L_1 T_1 L_2 T_2	1990, 2015
CO_2 Emissions from Land Converted to Settlements	CO_2	150.2	•	L_1 T_1	1990_1, 2015_1
CO_2 Emissions from Land Converted to Cropland	CO_2	28.6	•	L_1 T_1 L_2 T_2	1990, 2015_2
CO_2 Emissions from Grassland Remaining Grassland	CO_2	7.3	•	L_2 T_2	1990_2, 2015_2
CO_2 Emissions from Peatlands Remaining Peatlands	CO_2	0.8			
CO_2 Emissions from Land Converted to Wetlands	CO_2	(0.0)			
CO_2 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CO_2	(8.7)			
CO_2 Emissions from Cropland Remaining Cropland	CO_2	(14.0)	•	L_1 T_1 L_2 T_2	1990, 2015_2
CO_2 Emissions from Land Converted to Forest Land	CO_2	(75.2)	•	L_1 T_1	1990_1, 2015_1
CO_2 Emissions from Settlements Remaining Settlements	CO_2	(102.1)	•	L_1 T_1 L_2 T_2	1990, 2015
CO_2 Emissions from Forest Land Remaining Forest Land	CO_2	(667.0)	•	L_1 T_1 L_2 T_2	1990, 2015
CH_4 Emissions from Forest Fires	CH_4	7.3	•	L_2 T_2	2015_2
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CH_4	3.5			
CH_4 Emissions from Grass Fires	CH_4	0.4			
CH_4 Emissions from Land Converted to Coastal Wetlands	CH_4	0.0			
CH_4 Emissions from Peatlands Remaining Peatlands	CH_4	0.0			
N_2O Emissions from Forest Fires	N_2O	4.8	•	T_2	

N_2O Emissions from Settlement Soils	N_2O	2.6
N_2O Emissions from Forest Soils	N_2O	0.5
N_2O Emissions from Grass Fires	N_2O	0.4
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	N_2O	0.1
N_2O Emissions from Peatlands Remaining Peatlands	N_2O	+

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] For the ID criteria, Q refers to "Qualitative", 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 an Approach 1 or Approach 2 assessment (e.g., L_2 designates a source is a key category for an Approach 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 Approach 2 assessment only in 1990).

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

Note: Parentheses indicate negative values (or sequestration).

Evaluation of Key Categories

Level Assessment

When using an Approach 1 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 *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) was designed to establish a general level where the key category analysis covers approximately 75 to 92 percent of inventory uncertainty.

Including the Approach 2 provides additional insight into why certain source categories are considered key, and how to prioritize inventory improvements. In the Approach 2, the level assessment for each category from the Approach 1 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 kt 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 Approach 2 level assessment may differ from those identified by the Approach 1 assessment. The final set of key categories includes all source and sink categories identified as key by either the Approach 1 or the Approach 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 2015 level assessments for both with and without LULUCF sources and sinks, and contain further detail on where each source falls within the analysis. Approach 1 key categories are shaded dark gray. Additional key categories identified by the Approach 2 assessment are shaded light gray.

Trend Assessment

Approach 1 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 Approach 2, the trend assessment for each category from Approach 1 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 Approach 2 trend assessment may differ from those identified by the Approach 1 assessment. The final set of key categories includes all source and sink categories identified as key by either the Approach 1 or the Approach 2 assessment, keeping in mind that the two assessments are not mutually exclusive.

Table A-8 and Table A-9 contain the 1990 through 2015 trend assessment for both with and without LULUCF sources and sinks, and contain further detail on where each source falls within the analysis. Approach 1 key categories are shaded dark gray. Additional key categories identified by the Approach 2 assessment are shaded light gray.

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

IPCC Source Categories	Direct Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,547.6	0.24	0.24	10%	0.023
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,188.9	0.19	0.43	6%	0.012
CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	408.9	0.06	0.49	7%	0.005
CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	278.3	0.04	0.54	19%	0.008
CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	238.0	0.04	0.58	7%	0.003
Direct N_2O Emissions from Agricultural Soil Management	N_2O	212.0	0.03	0.61	26%	0.009
CH_4 Emissions from Natural Gas Systems	CH_4	196.5	0.03	0.64	30%	0.009
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	187.4	0.03	0.67	6%	0.002
CH_4 Emissions from Landfills	CH_4	179.6	0.03	0.70	61%	0.017
CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	175.3	0.03	0.72	5%	0.001
CH_4 Emissions from Enteric Fermentation	CH_4	164.2	0.03	0.75	18%	0.005
CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	155.3	0.02	0.77	16%	0.004
CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	142.1	0.02	0.80	7%	0.002
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	117.7	0.02	0.82	42%	0.008
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	99.7	0.02	0.83	15%	0.002
CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	97.5	0.02	0.85	8%	0.001
CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	97.4	0.02	0.86	5%	0.001
Fugitive Emissions from Coal Mining	CH_4	96.5	0.02	0.88	16%	0.002

CO_2 Emissions from Mobile Combustion: Other	CO_2	73.3	0.01	0.89	6%	0.001
CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	63.3	0.01	0.90	5%	0.001
CH_4 Emissions from Petroleum Systems	CH_4	58.3	0.01	0.91	149%	0.014
HFC-23 Emissions from HCFC-22 Production	HFCs	46.1	0.01	0.91	10%	0.001
Indirect N_2O Emissions from Applied Nitrogen	N_2O	44.6	0.01	0.92	155%	0.011
CO_2 Emissions from Mobile Combustion: Marine	CO_2	44.3	0.01	0.93	6%	<0.001
CO_2 Emissions from Natural Gas Systems	CO_2	37.7	0.01	0.93	30%	0.002
N_2O Emissions from Mobile Combustion: Road	N_2O	37.7	0.01	0.94	18%	0.001
CH_4 Emissions from Manure Management	CH_4	37.2	0.01	0.95	20%	0.001
CO_2 Emissions from Cement Production	CO_2	33.3	0.01	0.95	6%	<0.001
CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	27.2	<0.01	0.96	11%	<0.001
SF_6 Emissions from Electrical Transmission and Distribution	SF_6	23.1	<0.01	0.96	23%	0.001
PFC Emissions from Aluminum Production	PFCs	21.5	<0.01	0.96	6%	<0.001
CO_2 Emissions from Petrochemical Production	CO_2	21.3	<0.01	0.97	5%	<0.001
CH_4 Emissions from Rice Cultivation	CH_4	16.0	<0.01	0.97	28%	0.001
CH_4 Emissions from Wastewater Treatment	CH_4	15.7	<0.01	0.97	26%	0.001
N_2O Emissions from Adipic Acid Production	N_2O	15.2	<0.01	0.97	4%	<0.001
N_2O Emissions from Manure Management	N_2O	14.0	<0.01	0.98	24%	0.001
CO_2 Emissions from Ammonia Production	CO_2	13.0	<0.01	0.98	8%	<0.001
N_2O Emissions from Nitric Acid Production	N_2O	12.1	<0.01	0.98	5%	<0.001
CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	12.0	<0.01	0.98	15%	<0.001
CO_2 Emissions from Lime Production	CO_2	11.7	<0.01	0.98	3%	<0.001
CO_2 Emissions from Incineration of Waste	CO_2	8.0	<0.01	0.98	14%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	N_2O	7.4	<0.01	0.99	173%	0.002
Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	7.2	<0.01	0.99	23%	<0.001
CO_2 Emissions from Aluminum Production	CO_2	6.8	<0.01	0.99	2%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Residential	CH_4	5.2	<0.01	0.99	234%	0.002
CH_4 Emissions from Mobile Combustion: Road	CH_4	5.2	<0.01	0.99	25%	<0.001
SF_6 Emissions from Magnesium Production and Processing	SF_6	5.2	<0.01	0.99	7%	<0.001
CO_2 Emissions from Other Process Uses of Carbonates	CO_2	4.9	<0.01	0.99	15%	<0.001
CO_2 Emissions from Liming	CO_2	4.7	<0.01	0.99	111%	0.001
N_2O Emissions from Product Uses	N_2O	4.2	<0.01	0.99	24%	<0.001
CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	3.8	<0.01	0.99	12%	<0.001
PFC, HFC, SF_6, and NF_3 Emissions from Semiconductor Manufacture	Several	3.6	<0.01	0.99	5%	<0.001
CO_2 Emissions from Petroleum Systems	CO_2	3.6	<0.01	0.99	149%	0.001
N_2O Emissions from Wastewater Treatment	N_2O	3.4	<0.01	0.99	107%	0.001
Non-CO_2 Emissions from Stationary Combustion - Industrial	N_2O	3.1	<0.01	1.00	222%	0.001
CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	3.0	<0.01	1.00	NE	<0.001
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	2.8	<0.01	1.00	7%	<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	12%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Industrial	CH_4	1.8	<0.01	1.00	50%	<0.001
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.7	<0.01	1.00	68%	<0.001

CO_2 Emissions from Glass Production	CO_2	1.5	<0.01	1.00	5%	<0.001
CO_2 Emissions from Phosphoric Acid Production	CO_2	1.5	<0.01	1.00	20%	<0.001
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.5	<0.01	1.00	13%	<0.001
N_2O Emissions from Mobile Combustion: Other	N_2O	1.2	<0.01	1.00	48%	<0.001
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.2	<0.01	1.00	13%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Residential	N_2O	1.0	<0.01	1.00	206%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Commercial	CH_4	1.0	<0.01	1.00	140%	<0.001
CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	0.6	<0.01	1.00	19%	<0.001
CO_2 Emissions from Zinc Production	CO_2	0.6	<0.01	1.00	21%	<0.001
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6	<0.01	1.00	45%	<0.001
CO_2 Emissions from Lead Production	CO_2	0.5	<0.01	1.00	16%	<0.001
N_2O Emissions from Incineration of Waste	N_2O	0.5	<0.01	1.00	163%	<0.001
CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4	<0.01	1.00	NA	<0.001
CH_4 Emissions from Composting	CH_4	0.4	<0.01	1.00	50%	<0.001
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.4	<0.01	1.00	9%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Commercial	N_2O	0.4	<0.01	1.00	42%	<0.001
N_2O Emissions from Composting	N_2O	0.3	<0.01	1.00	50%	<0.001
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.3	<0.01	1.00	48%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	CH_4	0.3	<0.01	1.00	22%	<0.001
Emissions from Substitutes for Ozone Depleting Substances	Several	0.3	<0.01	1.00	10%	<0.001
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.2	<0.01	1.00	41%	<0.001
CH_4 Emissions from Petrochemical Production	CH_4	0.2	<0.01	1.00	55%	<0.001
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1	<0.01	1.00	30%	<0.001
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1	<0.01	1.00	200%	<0.001
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.1	<0.01	1.00	90%	<0.001
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	CH_4	+	<0.01	1.00	56%	<0.001
N_2O Emissions from Semiconductor Manufacture	N_2O	+	<0.01	1.00	13%	<0.001
CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+	<0.01	1.00	10%	<0.001
CH_4 Emissions from Mobile Combustion: Marine	CH_4	+	<0.01	1.00	73%	<0.001
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+	<0.01	1.00	19%	<0.001
CH_4 Emissions from Ferroalloy Production	CH_4	+	<0.01	1.00	12%	<0.001
CO_2 Emissions from Magnesium Production and Processing	CO_2	+	<0.01	1.00	3%	<0.001
CH_4 Emissions from Incineration of Waste	CH_4	+	<0.01	1.00	NE	<0.001
HFC-134A Emissions from Magnesium Production and Processing	HFCs	0.0	<0.01	1.00	4%	<0.001
CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	0.0	<0.01	1.00	17%	<0.001

+ Does not exceed 0.05 MMT CO_2 Eq.
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 (Not Estimated)
NA (Not Available)

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

IPCC Source Categories	Direct Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,547.6	0.20	0.20	10%	0.019
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,188.9	0.15	0.35	6%	0.010
CO_2 Emissions from Forest Land Remaining Forest Land	CO_2	698.4	0.09	0.44	38%	0.034
CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	408.9	0.05	0.49	7%	0.004
CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	278.3	0.04	0.53	19%	0.007
CO_2 Emissions from Land Converted to Grassland	CO_2	245.2	0.03	0.56	20%	0.006
CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	238.0	0.03	0.59	7%	0.002
Direct N_2O Emissions from Agricultural Soil Management	N_2O	212.0	0.03	0.62	26%	0.007
CH_4 Emissions from Natural Gas Systems	CH_4	196.5	0.03	0.64	30%	0.008
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	187.4	0.02	0.67	6%	0.002
CH_4 Emissions from Landfills	CH_4	179.6	0.02	0.69	61%	0.014
CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	175.3	0.02	0.71	5%	0.001
CH_4 Emissions from Enteric Fermentation	CH_4	164.2	0.02	0.74	18%	0.004
CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	155.3	0.02	0.76	16%	0.003
CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	142.1	0.02	0.77	7%	0.001
CO_2 Emissions from Land Converted to Settlements	CO_2	123.8	0.02	0.79	4%	0.001
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	117.7	0.02	0.80	42%	0.006
CO_2 Emissions from Land Converted to Cropland	CO_2	100.7	0.01	0.82	42%	0.005
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	99.7	0.01	0.83	15%	0.002
CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	97.5	0.01	0.84	8%	0.001
CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	97.4	0.01	0.86	5%	0.001
Fugitive Emissions from Coal Mining	CH_4	96.5	0.01	0.87	16%	0.002
CO_2 Emissions from Land Converted to Forest Land	CO_2	92.0	0.01	0.88	11%	0.001
CO_2 Emissions from Settlements Remaining Settlements	CO_2	86.2	0.01	0.89	67%	0.007
CO_2 Emissions from Mobile Combustion: Other	CO_2	73.3	0.01	0.90	6%	0.001
CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	63.3	0.01	0.91	5%	<0.001
CH_4 Emissions from Petroleum Systems	CH_4	58.3	0.01	0.92	149%	0.011
HFC-23 Emissions from HCFC-22 Production	HFCs	46.1	0.01	0.92	10%	0.001
Indirect N_2O Emissions from Applied Nitrogen	N_2O	44.6	0.01	0.93	155%	0.009
CO_2 Emissions from Mobile Combustion: Marine	CO_2	44.3	0.01	0.93	6%	<0.001
CO_2 Emissions from Cropland Remaining Cropland	CO_2	40.9	0.01	0.94	237%	0.012
CO_2 Emissions from Natural Gas Systems	CO_2	37.7	<0.01	0.94	30%	0.001
N_2O Emissions from Mobile Combustion: Road	N_2O	37.7	<0.01	0.95	18%	0.001
CH_4 Emissions from Manure Management	CH_4	37.2	<0.01	0.95	20%	0.001
CO_2 Emissions from Cement Production	CO_2	33.3	<0.01	0.96	6%	<0.001
CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	27.2	<0.01	0.96	11%	<0.001
SF_6 Emissions from Electrical Transmission and Distribution	SF_6	23.1	<0.01	0.96	23%	0.001
PFC Emissions from Aluminum Production	PFCs	21.5	<0.01	0.97	6%	<0.001

CO_2 Emissions from Petrochemical Production	CO_2	21.3	<0.01	0.97	5%	<0.001
CH_4 Emissions from Rice Cultivation	CH_4	16.0	<0.01	0.97	28%	0.001
CH_4 Emissions from Wastewater Treatment	CH_4	15.7	<0.01	0.97	26%	0.001
N_2O Emissions from Adipic Acid Production	N_2O	15.2	<0.01	0.98	4%	<0.001
N_2O Emissions from Manure Management	N_2O	14.0	<0.01	0.98	24%	<0.001
CO_2 Emissions from Ammonia Production	CO_2	13.0	<0.01	0.98	8%	<0.001
N_2O Emissions from Nitric Acid Production	N_2O	12.1	<0.01	0.98	5%	<0.001
CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	12.0	<0.01	0.98	15%	<0.001
CO_2 Emissions from Lime Production	CO_2	11.7	<0.01	0.98	3%	<0.001
CO_2 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CO_2	8.6	<0.01	0.98	59%	0.001
CO_2 Emissions from Incineration of Waste	CO_2	8.0	<0.01	0.99	14%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	N_2O	7.4	<0.01	0.99	173%	0.002
Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	7.2	<0.01	0.99	23%	<0.001
CO_2 Emissions from Aluminum Production	CO_2	6.8	<0.01	0.99	2%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Residential	CH_4	5.2	<0.01	0.99	234%	0.002
CH_4 Emissions from Mobile Combustion: Road	CH_4	5.2	<0.01	0.99	25%	<0.001
SF_6 Emissions from Magnesium Production and Processing	SF_6	5.2	<0.01	0.99	7%	<0.001
CO_2 Emissions from Other Process Uses of Carbonates	CO_2	4.9	<0.01	0.99	15%	<0.001
CO_2 Emissions from Liming	CO_2	4.7	<0.01	0.99	111%	0.001
N_2O Emissions from Product Uses	N_2O	4.2	<0.01	0.99	24%	<0.001
CO_2 Emissions from Grassland Remaining Grassland	CO_2	4.2	<0.01	0.99	465%	0.003
CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	3.8	<0.01	0.99	12%	<0.001
PFC, HFC, SF_6, and NF_3 Emissions from Semiconductor Manufacture	Several	3.6	<0.01	0.99	5%	<0.001
CO_2 Emissions from Petroleum Systems	CO_2	3.6	<0.01	0.99	149%	0.001
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CH_4	3.4	<0.01	0.99	30%	<0.001
N_2O Emissions from Wastewater Treatment	N_2O	3.4	<0.01	0.99	107%	<0.001
CH_4 Emissions from Forest Fires	CH_4	3.2	<0.01	1.00	174%	0.001
Non-CO_2 Emissions from Stationary Combustion - Industrial	N_2O	3.1	<0.01	1.00	222%	0.001
CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	3.0	<0.01	1.00	NE	<0.001
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	2.8	<0.01	1.00	7%	<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	12%	<0.001
N_2O Emissions from Forest Fires	N_2O	2.1	<0.01	1.00	157%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Industrial	CH_4	1.8	<0.01	1.00	50%	<0.001
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.7	<0.01	1.00	68%	<0.001
CO_2 Emissions from Glass Production	CO_2	1.5	<0.01	1.00	5%	<0.001
CO_2 Emissions from Phosphoric Acid Production	CO_2	1.5	<0.01	1.00	20%	<0.001
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.5	<0.01	1.00	13%	<0.001
N_2O Emissions from Settlement Soils	N_2O	1.4	<0.01	1.00	268%	<0.001
N_2O Emissions from Mobile Combustion: Other	N_2O	1.2	<0.01	1.00	48%	<0.001
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.2	<0.01	1.00	13%	<0.001
CO_2 Emissions from Peatlands Remaining Peatlands	CO_2	1.1	<0.01	1.00	19%	<0.001

Non-CO_2 Emissions from Stationary Combustion - Residential	N_2O	1.0	<0.01	1.00	206%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Commercial	CH_4	1.0	<0.01	1.00	140%	<0.001
CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	0.6	<0.01	1.00	19%	<0.001
CO_2 Emissions from Zinc Production	CO_2	0.6	<0.01	1.00	21%	<0.001
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6	<0.01	1.00	45%	<0.001
CO_2 Emissions from Lead Production	CO_2	0.5	<0.01	1.00	16%	<0.001
N_2O Emissions from Incineration of Waste	N_2O	0.5	<0.01	1.00	163%	<0.001
CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4	<0.01	1.00	NA	<0.001
CH_4 Emissions from Composting	CH_4	0.4	<0.01	1.00	50%	<0.001
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.4	<0.01	1.00	9%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Commercial	N_2O	0.4	<0.01	1.00	42%	<0.001
N_2O Emissions from Composting	N_2O	0.3	<0.01	1.00	50%	<0.001
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.3	<0.01	1.00	48%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	CH_4	0.3	<0.01	1.00	22%	<0.001
Emissions from Substitutes for Ozone Depleting Substances	Several	0.3	<0.01	1.00	10%	<0.001
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.2	<0.01	1.00	41%	<0.001
CH_4 Emissions from Petrochemical Production	CH_4	0.2	<0.01	1.00	55%	<0.001
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	N_2O	0.1	<0.01	1.00	116%	<0.001
N_2O Emissions from Forest Soils	N_2O	0.1	<0.01	1.00	318%	<0.001
N_2O Emissions from Grass Fires	N_2O	0.1	<0.01	1.00	229%	<0.001
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1	<0.01	1.00	30%	<0.001
CH_4 Emissions from Grass Fires	CH_4	0.1	<0.01	1.00	209%	<0.001
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1	<0.01	1.00	200%	<0.001
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.1	<0.01	1.00	90%	<0.001
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	CH_4	+	<0.01	1.00	56%	<0.001
N_2O Emissions from Semiconductor Manufacture	N_2O	+	<0.01	1.00	13%	<0.001
CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+	<0.01	1.00	10%	<0.001
CH_4 Emissions from Mobile Combustion: Marine	CH_4	+	<0.01	1.00	73%	<0.001
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+	<0.01	1.00	19%	<0.001
CO_2 Emissions from Land Converted to Wetlands	CO_2	+	<0.01	1.00	30%	<0.001
CH_4 Emissions from Ferroalloy Production	CH_4	+	<0.01	1.00	12%	<0.001
CH_4 Emissions from Land Converted to Coastal Wetlands	CH_4	+	<0.01	1.00	30%	<0.001
CH_4 Emissions from Peatlands Remaining Peatlands	CH_4	+	<0.01	1.00	62%	<0.001
CO_2 Emissions from Magnesium Production and Processing	CO_2	+	<0.01	1.00	3%	<0.001
N_2O Emissions from Peatlands Remaining Peatlands	N_2O	+	<0.01	1.00	61%	<0.001

+ Does not exceed 0.05 MMT CO_2 Eq.
[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.
NE (Not Estimated)
NA (Not Available)

Table A-6: 2015 Key Source Category Approach 1 and Approach 2 Analysis—Level Assessment, without LULUCF

IPCC Source Categories	Direct GHG	2015 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,460.9	0.22	0.22	6%	0.014
CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,350.5	0.21	0.43	10%	0.020
CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	526.1	0.08	0.51	5%	0.004
CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	467.5	0.07	0.58	7%	0.005
CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	295.5	0.04	0.62	19%	0.009
CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	252.8	0.04	0.66	7%	0.003
Direct N_2O Emissions from Agricultural Soil Management	N_2O	213.3	0.03	0.69	26%	0.008
CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	175.4	0.03	0.72	7%	0.002
Emissions from Substitutes for Ozone Depleting Substances	Several	168.6	0.03	0.75	10%	0.003
CH_4 Emissions from Enteric Fermentation	CH_4	166.5	0.03	0.77	18%	0.005
CH_4 Emissions from Natural Gas Systems	CH_4	160.0	0.02	0.80	30%	0.007
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	159.2	0.02	0.82	6%	0.002
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	127.0	0.02	0.84	42%	0.008
CH_4 Emissions from Landfills	CH_4	115.7	0.02	0.86	61%	0.011
CO_2 Emissions from Mobile Combustion: Other	CO_2	81.6	0.01	0.87	6%	0.001
CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	66.8	0.01	0.88	5%	0.001
CH_4 Emissions from Manure Management	CH_4	66.3	0.01	0.89	20%	0.002
CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	65.9	0.01	0.90	16%	0.002
Fugitive Emissions from Coal Mining	CH_4	60.9	0.01	0.91	16%	0.001
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	47.9	0.01	0.92	15%	0.001
CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	47.3	0.01	0.92	5%	<0.001
CO_2 Emissions from Natural Gas Systems	CO_2	42.4	0.01	0.93	30%	0.002
CH_4 Emissions from Petroleum Systems	CH_4	41.5	0.01	0.94	149%	0.009
CO_2 Emissions from Cement Production	CO_2	39.6	0.01	0.94	6%	<0.001
Indirect N_2O Emissions from Applied Nitrogen	N_2O	38.0	0.01	0.95	155%	0.009
CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	34.6	0.01	0.95	11%	0.001
CO_2 Emissions from Mobile Combustion: Marine	CO_2	31.6	<0.01	0.96	6%	<0.001
CO_2 Emissions from Petrochemical Production	CO_2	28.1	<0.01	0.96	5%	<0.001
CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	23.7	<0.01	0.96	8%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	N_2O	19.5	<0.01	0.97	173%	0.005
N_2O Emissions from Manure Management	N_2O	17.7	<0.01	0.97	24%	0.001
CH_4 Emissions from Wastewater Treatment	CH_4	14.8	<0.01	0.97	26%	0.001
CO_2 Emissions from Lime Production	CO_2	13.3	<0.01	0.97	3%	<0.001
N_2O Emissions from Nitric Acid Production	N_2O	11.6	<0.01	0.98	5%	<0.001
N_2O Emissions from Mobile Combustion: Road	N_2O	11.3	<0.01	0.98	18%	<0.001
CH_4 Emissions from Rice Cultivation	CH_4	11.2	<0.01	0.98	28%	<0.001

CO_2 Emissions from Other Process Uses of Carbonates	CO_2	10.8	<0.01	0.98	15%	<0.001
CO_2 Emissions from Ammonia Production	CO_2	10.8	<0.01	0.98	8%	<0.001
CO_2 Emissions from Incineration of Waste	CO_2	10.7	<0.01	0.98	14%	<0.001
Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	6.4	<0.01	0.99	23%	<0.001
CO_2 Emissions from Urea Fertilization	CO_2	5.0	<0.01	0.99	43%	<0.001
HFC-23 Emissions from HCFC-22 Production	HFCs	5.0	<0.01	0.99	10%	<0.001
N_2O Emissions from Wastewater Treatment	N_2O	5.0	<0.01	0.99	107%	0.001
PFC, HFC, SF_6, and NF_3 Emissions from Semiconductor Manufacture	Several	4.8	<0.01	0.99	5%	<0.001
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	4.3	<0.01	0.99	13%	<0.001
N_2O Emissions from Adipic Acid Production	N_2O	4.3	<0.01	0.99	4%	<0.001
N_2O Emissions from Product Uses	N_2O	4.2	<0.01	0.99	24%	<0.001
SF_6 Emissions from Electrical Transmission and Distribution	SF_6	4.2	<0.01	0.99	23%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Residential	CH_4	3.9	<0.01	0.99	234%	0.001
CO_2 Emissions from Liming	CO_2	3.8	<0.01	0.99	111%	0.001
CO_2 Emissions from Petroleum Systems	CO_2	3.6	<0.01	0.99	149%	0.001
CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	3.4	<0.01	0.99	19%	<0.001
CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	3.2	<0.01	0.99	17%	<0.001
CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	2.9	<0.01	0.99	15%	<0.001
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	2.8	<0.01	1.00	7%	<0.001
CO_2 Emissions from Aluminum Production	CO_2	2.8	<0.01	1.00	2%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Industrial	N_2O	2.4	<0.01	1.00	222%	0.001
CH_4 Emissions from Composting	CH_4	2.1	<0.01	1.00	50%	<0.001
PFC Emissions from Aluminum Production	PFCs	2.0	<0.01	1.00	6%	<0.001
N_2O Emissions from Mobile Combustion: Other	N_2O	2.0	<0.01	1.00	48%	<0.001
CO_2 Emissions from Ferroalloy Production	CO_2	2.0	<0.01	1.00	12%	<0.001
N_2O Emissions from Composting	N_2O	1.9	<0.01	1.00	50%	<0.001
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.6	<0.01	1.00	13%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Industrial	CH_4	1.5	<0.01	1.00	50%	<0.001
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.5	<0.01	1.00	68%	<0.001
CH_4 Emissions from Mobile Combustion: Road	CH_4	1.5	<0.01	1.00	25%	<0.001
CO_2 Emissions from Glass Production	CO_2	1.3	<0.01	1.00	5%	<0.001
CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	1.1	<0.01	1.00	12%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Commercial	CH_4	1.1	<0.01	1.00	140%	<0.001
CO_2 Emissions from Phosphoric Acid Production	CO_2	1.0	<0.01	1.00	20%	<0.001
CO_2 Emissions from Zinc Production	CO_2	0.9	<0.01	1.00	21%	<0.001
SF_6 Emissions from Magnesium Production and Processing	SF_6	0.9	<0.01	1.00	7%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Residential	N_2O	0.8	<0.01	1.00	206%	<0.001
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6	<0.01	1.00	45%	<0.001
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.5	<0.01	1.00	48%	<0.001
CO_2 Emissions from Lead Production	CO_2	0.5	<0.01	1.00	16%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	CH_4	0.4	<0.01	1.00	22%	<0.001

CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4	<0.01	1.00	NA	<0.001
Non-CO_2 Emissions from Stationary Combustion - Commercial	N_2O	0.3	<0.01	1.00	42%	<0.001
N_2O Emissions from Incineration of Waste	N_2O	0.3	<0.01	1.00	163%	<0.001
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.3	<0.01	1.00	41%	<0.001
N_2O Emissions from Semiconductor Manufacture	N_2O	0.2	<0.01	1.00	13%	<0.001
CH_4 Emissions from Petrochemical Production	CH_4	0.2	<0.01	1.00	55%	<0.001
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.2	<0.01	1.00	9%	<0.001
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1	<0.01	1.00	200%	<0.001
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1	<0.01	1.00	30%	<0.001
HFC-134A Emissions from Magnesium Production and Processing	HFCs	0.1	<0.01	1.00	4%	<0.001
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	CH_4	0.1	<0.01	1.00	56%	<0.001
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	+	<0.01	1.00	90%	<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	10%	<0.001
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+	<0.01	1.00	19%	<0.001
CO_2 Emissions from Magnesium Production and Processing	CO_2	+	<0.01	1.00	3%	<0.001
CH_4 Emissions from Incineration of Waste	CH_4	+	<0.01	1.00	NE	<0.001
CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	0.0	<0.01	1.00	NE	<0.001

+ Does not exceed 0.05 MMT CO_2 Eq.
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 (Not Estimated)
NA (Not Available)

Table A-7: 2015 Key Source Category Approach 1 and Approach 2 Analysis—Level Assessment with LULUCF

IPCC Source Categories	Direct GHG	2015 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,460.9	0.18	0.18	6%	0.012
CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,350.5	0.17	0.35	10%	0.016
CO_2 Emissions from Forest Land Remaining Forest Land	CO_2	667.0	0.08	0.44	38%	0.031
CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	526.1	0.07	0.50	5%	0.003
CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	467.5	0.06	0.56	7%	0.004
CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	295.5	0.04	0.60	19%	0.007
CO_2 Emissions from Land Converted to Grassland	CO_2	294.2	0.04	0.64	20%	0.007
CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	252.8	0.03	0.67	7%	0.002
Direct N_2O Emissions from Agricultural Soil Management	N_2O	213.3	0.03	0.69	26%	0.007

CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	175.4	0.02	0.72	7%	0.002
Emissions from Substitutes for Ozone Depleting Substances	Several	168.6	0.02	0.74	10%	0.002
CH_4 Emissions from Enteric Fermentation	CH_4	166.5	0.02	0.76	18%	0.004
CH_4 Emissions from Natural Gas Systems	CH_4	160.0	0.02	0.78	30%	0.006
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	159.2	0.02	0.80	6%	0.001
CO_2 Emissions from Land Converted to Settlements	CO_2	150.2	0.02	0.82	4%	0.001
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	127.0	0.02	0.83	42%	0.007
CH_4 Emissions from Landfills	CH_4	115.7	0.01	0.85	61%	0.009
CO_2 Emissions from Settlements Remaining Settlements	CO_2	102.1	0.01	0.86	67%	0.009
CO_2 Emissions from Mobile Combustion: Other	CO_2	81.6	0.01	0.87	6%	0.001
CO_2 Emissions from Land Converted to Forest Land	CO_2	75.2	0.01	0.88	11%	0.001
CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	66.8	0.01	0.89	5%	<0.001
CH_4 Emissions from Manure Management	CH_4	66.3	0.01	0.90	20%	0.002
CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	65.9	0.01	0.91	16%	0.001
Fugitive Emissions from Coal Mining	CH_4	60.9	0.01	0.91	16%	0.001
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	47.9	0.01	0.92	15%	0.001
CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	47.3	0.01	0.93	5%	<0.001
CO_2 Emissions from Natural Gas Systems	CO_2	42.4	0.01	0.93	30%	0.002
CH_4 Emissions from Petroleum Systems	CH_4	41.5	0.01	0.94	149%	0.008
CO_2 Emissions from Cement Production	CO_2	39.6	<0.01	0.94	6%	<0.001
Indirect N_2O Emissions from Applied Nitrogen	N_2O	38.0	<0.01	0.95	155%	0.007
CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	34.6	<0.01	0.95	11%	<0.001
CO_2 Emissions from Mobile Combustion: Marine	CO_2	31.6	<0.01	0.95	6%	<0.001
CO_2 Emissions from Land Converted to Cropland	CO_2	28.6	<0.01	0.96	42%	0.001
CO_2 Emissions from Petrochemical Production	CO_2	28.1	<0.01	0.96	5%	<0.001
CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	23.7	<0.01	0.96	8%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	N_2O	19.5	<0.01	0.97	173%	0.004
N_2O Emissions from Manure Management	N_2O	17.7	<0.01	0.97	24%	0.001
CH_4 Emissions from Wastewater Treatment	CH_4	14.8	<0.01	0.97	26%	<0.001
CO_2 Emissions from Cropland Remaining Cropland	CO_2	14.0	<0.01	0.97	237%	0.004
CO_2 Emissions from Lime Production	CO_2	13.3	<0.01	0.97	3%	<0.001
N_2O Emissions from Nitric Acid Production	N_2O	11.6	<0.01	0.98	5%	<0.001
N_2O Emissions from Mobile Combustion: Road	N_2O	11.3	<0.01	0.98	18%	<0.001
CH_4 Emissions from Rice Cultivation	CH_4	11.2	<0.01	0.98	28%	<0.001
CO_2 Emissions from Other Process Uses of Carbonates	CO_2	10.8	<0.01	0.98	15%	<0.001
CO_2 Emissions from Ammonia Production	CO_2	10.8	<0.01	0.98	8%	<0.001
CO_2 Emissions from Incineration of Waste	CO_2	10.7	<0.01	0.98	14%	<0.001
CO_2 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CO_2	8.7	<0.01	0.98	59%	0.001
CH_4 Emissions from Forest Fires	CH_4	7.3	<0.01	0.98	174%	0.002
CO_2 Emissions from Grassland Remaining Grassland	CO_2	7.3	<0.01	0.99	465%	0.004
Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	6.4	<0.01	0.99	23%	<0.001
CO_2 Emissions from Urea Fertilization	CO_2	5.0	<0.01	0.99	43%	<0.001
HFC-23 Emissions from HCFC-22 Production	HFCs	5.0	<0.01	0.99	10%	<0.001
N_2O Emissions from Wastewater Treatment	N_2O	5.0	<0.01	0.99	107%	0.001

N_2O Emissions from Forest Fires	N_2O	4.8	<0.01	0.99	157%	0.001
PFC, HFC, SF_6, and NF_3 Emissions from Semiconductor Manufacture	Several	4.8	<0.01	0.99	5%	<0.001
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	4.3	<0.01	0.99	13%	<0.001
N_2O Emissions from Adipic Acid Production	N_2O	4.3	<0.01	0.99	4%	<0.001
N_2O Emissions from Product Uses	N_2O	4.2	<0.01	0.99	24%	<0.001
SF_6 Emissions from Electrical Transmission and Distribution	SF_6	4.2	<0.01	0.99	23%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Residential	CH_4	3.9	<0.01	0.99	234%	0.001
CO_2 Emissions from Liming	CO_2	3.8	<0.01	0.99	111%	0.001
CO_2 Emissions from Petroleum Systems	CO_2	3.6	<0.01	0.99	149%	0.001
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CH_4	3.5	<0.01	0.99	30%	<0.001
CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	3.4	<0.01	0.99	19%	<0.001
CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	3.2	<0.01	0.99	17%	<0.001
CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	2.9	<0.01	0.99	15%	<0.001
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	2.8	<0.01	1.00	7%	<0.001
CO_2 Emissions from Aluminum Production	CO_2	2.8	<0.01	1.00	2%	<0.001
N_2O Emissions from Settlement Soils	N_2O	2.6	<0.01	1.00	268%	0.001
Non-CO_2 Emissions from Stationary Combustion - Industrial	N_2O	2.4	<0.01	1.00	222%	0.001
CH_4 Emissions from Composting	CH_4	2.1	<0.01	1.00	50%	<0.001
PFC Emissions from Aluminum Production	PFCs	2.0	<0.01	1.00	6%	<0.001
N_2O Emissions from Mobile Combustion: Other	N_2O	2.0	<0.01	1.00	48%	<0.001
CO_2 Emissions from Ferroalloy Production	CO_2	2.0	<0.01	1.00	12%	<0.001
N_2O Emissions from Composting	N_2O	1.9	<0.01	1.00	50%	<0.001
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.6	<0.01	1.00	13%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Industrial	CH_4	1.5	<0.01	1.00	50%	<0.001
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.5	<0.01	1.00	68%	<0.001
CH_4 Emissions from Mobile Combustion: Road	CH_4	1.5	<0.01	1.00	25%	<0.001
CO_2 Emissions from Glass Production	CO_2	1.3	<0.01	1.00	5%	<0.001
CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	1.1	<0.01	1.00	12%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Commercial	CH_4	1.1	<0.01	1.00	140%	<0.001
CO_2 Emissions from Phosphoric Acid Production	CO_2	1.0	<0.01	1.00	20%	<0.001
CO_2 Emissions from Zinc Production	CO_2	0.9	<0.01	1.00	21%	<0.001
SF_6 Emissions from Magnesium Production and Processing	SF_6	0.9	<0.01	1.00	7%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Residential	N_2O	0.8	<0.01	1.00	206%	<0.001
CO_2 Emissions from Peatlands Remaining Peatlands	CO_2	0.8	<0.01	1.00	19%	<0.001
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6	<0.01	1.00	45%	<0.001
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.5	<0.01	1.00	48%	<0.001
CO_2 Emissions from Lead Production	CO_2	0.5	<0.01	1.00	16%	<0.001
N_2O Emissions from Forest Soils	N_2O	0.5	<0.01	1.00	318%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	CH_4	0.4	<0.01	1.00	22%	<0.001
N_2O Emissions from Grass Fires	N_2O	0.4	<0.01	1.00	229%	<0.001
CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4	<0.01	1.00	NA	<0.001

CH_4 Emissions from Grass Fires	CH_4	0.4	<0.01	1.00	209%	<0.001
Non-CO_2 Emissions from Stationary Combustion - Commercial	N_2O	0.3	<0.01	1.00	42%	<0.001
N_2O Emissions from Incineration of Waste	N_2O	0.3	<0.01	1.00	163%	<0.001
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.3	<0.01	1.00	41%	<0.001
N_2O Emissions from Semiconductor Manufacture	N_2O	0.2	<0.01	1.00	13%	<0.001
CH_4 Emissions from Petrochemical Production	CH_4	0.2	<0.01	1.00	55%	<0.001
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.2	<0.01	1.00	9%	<0.001
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	N_2O	0.1	<0.01	1.00	116%	<0.001
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1	<0.01	1.00	200%	<0.001
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1	<0.01	1.00	30%	<0.001
HFC-134A Emissions from Magnesium Production and Processing	HFCs	0.1	<0.01	1.00	4%	<0.001
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	CH_4	0.1	<0.01	1.00	56%	<0.001
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	+	<0.01	1.00	90%	<0.001
CH_4 Emissions from Mobile Combustion: Marine	CH_4	+	<0.01	1.00	73%	<0.001
CO_2 Emissions from Land Converted to Wetlands	CO_2	+	<0.01	1.00	30%	<0.001
CH_4 Emissions from Ferroalloy Production	CH_4	+	<0.01	1.00	12%	<0.001
CH_4 Emissions from Land Converted to Coastal Wetlands	CH_4	+	<0.01	1.00	30%	<0.001
CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+	<0.01	1.00	10%	<0.001
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+	<0.01	1.00	19%	<0.001
CH_4 Emissions from Peatlands Remaining Peatlands	CH_4	+	<0.01	1.00	62%	<0.001
CO_2 Emissions from Magnesium Production and Processing	CO_2	+	<0.01	1.00	3%	<0.001
N_2O Emissions from Peatlands Remaining Peatlands	N_2O	+	<0.01	1.00	61%	<0.001
CH_4 Emissions from Incineration of Waste	CH_4	+	<0.01	1.00	NE	<0.001
CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	0.0	<0.01	1.00	NE	<0.001

+ Does not exceed 0.05 MMT CO_2 Eq.
[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.
NE (Not Estimated)
NA (Not Available)

Table A-8: 1990-2015 Key Source Category Approach 1 and 2 Analysis—Trend Assessment, without LULUCF

IPCC Source Categories	Direct GHG	1990 Estimate (MMT CO_2 Eq.)	2015 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	% Cumulative Total
CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	175.3	526.1	0.05	0.003	18.4	18
CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,547.6	1,350.5	0.04	0.004	13.4	32
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,188.9	1,460.9	0.04	0.002	12.4	44
Emissions from Substitutes for Ozone Depleting Substances	Several	0.3	168.6	0.03	0.003	9.0	53

CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	155.3	65.9	0.01	0.002	5.1	58
CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	97.5	23.7	0.01	0.001	4.1	62
CH_4 Emissions from Landfills	CH_4	179.6	115.7	0.01	0.007	3.7	66
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	99.7	47.9	0.01	0.001	3.0	69
CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	408.9	467.5	0.01	<0.001	2.4	71
CH_4 Emissions from Natural Gas Systems	CH_4	196.5	160.0	0.01	0.002	2.3	74
HFC-23 Emissions from HCFC-22 Production	HFCs	46.1	5.0	0.01	0.001	2.3	76
Fugitive Emissions from Coal Mining	CH_4	96.5	60.9	0.01	0.001	2.1	78
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	187.4	159.2	0.01	<0.001	1.9	80
CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	97.4	66.8	0.01	<0.001	1.8	82
CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	142.1	175.4	<0.01	<0.001	1.5	83
CH_4 Emissions from Manure Management	CH_4	37.2	66.3	<0.01	0.001	1.5	85
N_2O Emissions from Mobile Combustion: Road	N_2O	37.7	11.3	<0.01	0.001	1.5	86
PFC Emissions from Aluminum Production	PFCs	21.5	2.0	<0.01	<0.001	1.1	87
SF_6 Emissions from Electrical Transmission and Distribution	SF_6	23.1	4.2	<0.01	0.001	1.1	88
CH_4 Emissions from Petroleum Systems	CH_4	58.3	41.5	<0.01	0.004	1.0	89
CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	63.3	47.3	<0.01	<0.001	1.0	90
CO_2 Emissions from Mobile Combustion: Marine	CO_2	44.3	31.6	<0.01	<0.001	0.8	91
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	N_2O	7.4	19.5	<0.01	0.003	0.6	92
N_2O Emissions from Adipic Acid Production	N_2O	15.2	4.3	<0.01	<0.001	0.6	92
CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	12.0	2.9	<0.01	<0.001	0.5	93
Indirect N_2O Emissions from Applied Nitrogen	N_2O	44.6	38.0	<0.01	0.002	0.4	93
CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	278.3	295.5	<0.01	<0.001	0.4	94
CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	238.0	252.8	<0.01	<0.001	0.4	94
CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	27.2	34.6	<0.01	<0.001	0.3	94
CO_2 Emissions from Petrochemical Production	CO_2	21.3	28.1	<0.01	<0.001	0.3	95
Direct N_2O Emissions from Agricultural Soil Management	N_2O	212.0	213.3	<0.01	<0.001	0.3	95
CO_2 Emissions from Mobile Combustion: Other	CO_2	73.3	81.6	<0.01	<0.001	0.3	95
CO_2 Emissions from Other Process Uses of Carbonates	CO_2	4.9	10.8	<0.01	<0.001	0.3	96
CH_4 Emissions from Rice Cultivation	CH_4	16.0	11.2	<0.01	<0.001	0.3	96
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	117.7	127.0	<0.01	<0.001	0.3	96
CO_2 Emissions from Cement Production	CO_2	33.3	39.6	<0.01	<0.001	0.3	97

SF_6 Emissions from Magnesium Production and Processing	SF_6	5.2	0.9	<0.01	<0.001	0.2	97
CO_2 Emissions from Aluminum Production	CO_2	6.8	2.8	<0.01	<0.001	0.2	97
CH_4 Emissions from Mobile Combustion: Road	CH_4	5.2	1.5	<0.01	<0.001	0.2	97
CO_2 Emissions from Natural Gas Systems	CO_2	37.7	42.4	<0.01	<0.001	0.2	97
CH_4 Emissions from Enteric Fermentation	CH_4	164.2	166.5	<0.01	<0.001	0.2	98
N_2O Emissions from Manure Management	N_2O	14.0	17.7	<0.01	<0.001	0.2	98
CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	0.0	3.2	<0.01	0.001	0.2	98
CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	3.0	0.0	<0.01	<0.001	0.2	98
CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	3.8	1.1	<0.01	<0.001	0.1	98
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.5	4.3	<0.01	<0.001	0.1	98
CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	0.6	3.4	<0.01	<0.001	0.1	99
CO_2 Emissions from Ammonia Production	CO_2	13.0	10.8	<0.01	<0.001	0.1	99
CO_2 Emissions from Urea Fertilization	CO_2	2.4	5.0	<0.01	<0.001	0.1	99
CO_2 Emissions from Incineration of Waste	CO_2	8.0	10.7	<0.01	<0.001	0.1	99
CH_4 Emissions from Composting	CH_4	0.4	2.1	<0.01	<0.001	0.1	99
Non-CO_2 Emissions from Stationary Combustion - Residential	CH_4	5.2	3.9	<0.01	0.001	0.1	99
N_2O Emissions from Composting	N_2O	0.3	1.9	<0.01	<0.001	0.1	99
N_2O Emissions from Wastewater Treatment	N_2O	3.4	5.0	<0.01	<0.001	0.1	99
CH_4 Emissions from Wastewater Treatment	CH_4	15.7	14.8	<0.01	<0.001	0.1	99
CO_2 Emissions from Lime Production	CO_2	11.7	13.3	<0.01	<0.001	0.1	99
PFC, HFC, SF_6, and NF_3 Emissions from Semiconductor Manufacture	Several	3.6	4.8	<0.01	<0.001	0.1	100
Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	7.2	6.4	<0.01	<0.001	0.1	100
CO_2 Emissions from Liming	CO_2	4.7	3.8	<0.01	<0.001	0.1	100
N_2O Emissions from Nitric Acid Production	N_2O	12.1	11.6	<0.01	<0.001	0.1	100
Non-CO_2 Emissions from Stationary Combustion - Industrial	N_2O	3.1	2.4	<0.01	<0.001	<0.1	100
N_2O Emissions from Mobile Combustion: Other	N_2O	1.2	2.0	<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
Non-CO_2 Emissions from Stationary Combustion - Industrial	CH_4	1.8	1.5	<0.01	<0.001	<0.1	100
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.7	1.5	<0.01	<0.001	<0.1	100
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.2	1.6	<0.01	<0.001	<0.1	100
CO_2 Emissions from Glass Production	CO_2	1.5	1.3	<0.01	<0.001	<0.1	100
CO_2 Emissions from Zinc Production	CO_2	0.6	0.9	<0.01	<0.001	<0.1	100
Non-CO_2 Emissions from Stationary Combustion - Residential	N_2O	1.0	0.8	<0.01	<0.001	<0.1	100
CO_2 Emissions from Ferroalloy Production	CO_2	2.2	2.0	<0.01	<0.001	<0.1	100
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.4	0.2	<0.01	<0.001	<0.1	100

N_2O Emissions from Semiconductor Manufacture	N_2O	+	0.2	<0.01	<0.001	<0.1	100
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.3	0.5	<0.01	<0.001	<0.1	100
N_2O Emissions from Incineration of Waste	N_2O	0.5	0.3	<0.01	<0.001	<0.1	100
N_2O Emissions from Product Uses	N_2O	4.2	4.2	<0.01	<0.001	<0.1	100
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	2.8	2.8	<0.01	<0.001	<0.1	100
CO_2 Emissions from Petroleum Systems	CO_2	3.6	3.6	<0.01	<0.001	<0.1	100
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	CH_4	0.3	0.4	<0.01	<0.001	<0.1	100
HFC-134A Emissions from Magnesium Production and Processing	HFCs	0.0	0.1	<0.01	<0.001	<0.1	100
Non-CO_2 Emissions from Stationary Combustion - Commercial	N_2O	0.4	0.3	<0.01	<0.001	<0.1	100
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.2	0.3	<0.01	<0.001	<0.1	100
CH_4 Emissions from Petrochemical Production	CH_4	0.2	0.2	<0.01	<0.001	<0.1	100
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.1	+	<0.01	<0.001	<0.1	100
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1	0.1	<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
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6	0.6	<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
Non-CO_2 Emissions from Stationary Combustion - Commercial	CH_4	1.0	1.1	<0.01	<0.001	<0.1	100
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1	0.1	<0.01	<0.001	<0.1	100
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	CH_4	+	0.1	<0.01	<0.001	<0.1	100
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+	+	<0.01	<0.001	<0.1	100
CH_4 Emissions from Ferroalloy Production	CH_4	+	+	<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 Magnesium Production and Processing	CO_2	+	+	<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

+ Does not exceed 0.05 MMT CO_2 Eq.
Note: LULUCF sources and sinks are not included in this analysis.

1 **Table A-9: 1990-2015 Key Source Category Approach 1 and 2 Analysis—Trend Assessment, with LULUCF**

IPCC Source Categories	Direct GHG	1990 Estimate ($MM TCO_2$ Eq.)	2015 Estimate ($MMT CO_2$ Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	Percent Contribution to Trend (%)	Cumulative Contribution to Trend (%)
CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	175.3	526.1	0.04	0.002	16.3	16
CO_2 Emissions from Mobile Combustion: Road	CO_2	1,188.9	1,460.9	0.03	0.002	11.6	28
CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,547.6	1,350.5	0.03	0.003	10.9	39
Emissions from Substitutes for Ozone Depleting Substances	Several	0.3	168.6	0.02	0.002	7.9	47
CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	155.3	65.9	0.01	0.002	4.4	51
CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	97.5	23.7	0.01	0.001	3.6	55
CO_2 Emissions from Land Converted to Cropland	CO_2	100.7	28.6	0.01	0.004	3.5	58
CH_4 Emissions from Landfills	CH_4	179.6	115.7	0.01	0.005	3.2	61
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	99.7	47.9	0.01	0.001	2.5	64
CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	408.9	467.5	0.01	<0.001	2.3	66
CO_2 Emissions from Forest Land Remaining Forest Land	CO_2	698.4	667.0	0.01	0.002	2.2	69
CO_2 Emissions from Land Converted to Grassland	CO_2	245.2	294.2	0.01	0.001	2.0	71
HFC-23 Emissions from HCFC-22 Production	HFCs	46.1	5.0	0.01	0.001	2.0	73
CH_4 Emissions from Natural Gas Systems	CH_4	196.5	160.0	0.01	0.002	1.9	74
Fugitive Emissions from Coal Mining	CH_4	96.5	60.9	<0.01	0.001	1.8	76
CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	97.4	66.8	<0.01	<0.001	1.5	78
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	187.4	159.2	<0.01	<0.001	1.5	79
CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	142.1	175.4	<0.01	<0.001	1.4	81
CH_4 Emissions from Manure Management	CH_4	37.2	66.3	<0.01	0.001	1.3	82
CO_2 Emissions from Cropland Remaining Cropland	CO_2	40.9	14.0	<0.01	0.008	1.3	83
N_2O Emissions from Mobile Combustion: Road	N_2O	37.7	11.3	<0.01	0.001	1.3	85
CO_2 Emissions from Land Converted to Settlements	CO_2	123.8	150.2	<0.01	<0.001	1.1	86
PFC Emissions from Aluminum Production	PFCs	21.5	2.0	<0.01	<0.001	0.9	87
SF_6 Emissions from Electrical Transmission and Distribution	SF_6	23.1	4.2	<0.01	0.001	0.9	88
CO_2 Emissions from Land Converted to Forest Land	CO_2	92.0	75.2	<0.01	<0.001	0.9	89
CH_4 Emissions from Petroleum Systems	CH_4	58.3	41.5	<0.01	0.003	0.9	89
CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	63.3	47.3	<0.01	<0.001	0.8	90

CO_2 Emissions from Settlements Remaining Settlements	CO_2	86.2	102.1	<0.01	0.001	0.7	91
CO_2 Emissions from Mobile Combustion: Marine	CO_2	44.3	31.6	<0.01	<0.001	0.6	91
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	N_2O	7.4	19.5	<0.01	0.003	0.6	92
N_2O Emissions from Adipic Acid Production	N_2O	15.2	4.3	<0.01	<0.001	0.5	93
CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	278.3	295.5	<0.01	<0.001	0.5	93
CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	238.0	252.8	<0.01	<0.001	0.4	94
CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	12.0	2.9	<0.01	<0.001	0.4	94
Indirect N_2O Emissions from Applied Nitrogen	N_2O	44.6	38.0	<0.01	0.002	0.4	94
CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	27.2	34.6	<0.01	<0.001	0.3	95
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	117.7	127.0	<0.01	<0.001	0.3	95
CO_2 Emissions from Mobile Combustion: Other	CO_2	73.3	81.6	<0.01	<0.001	0.3	95
CO_2 Emissions from Petrochemical Production	CO_2	21.3	28.1	<0.01	<0.001	0.3	96
CO_2 Emissions from Other Process Uses of Carbonates	CO_2	4.9	10.8	<0.01	<0.001	0.3	96
CO_2 Emissions from Cement Production	CO_2	33.3	39.6	<0.01	<0.001	0.3	96
CH_4 Emissions from Rice Cultivation	CH_4	16.0	11.2	<0.01	<0.001	0.2	96
SF_6 Emissions from Magnesium Production and Processing	SF_6	5.2	0.9	<0.01	<0.001	0.2	97
CO_2 Emissions from Aluminum Production	CO_2	6.8	2.8	<0.01	<0.001	0.2	97
CH_4 Emissions from Forest Fires	CH_4	3.2	7.3	<0.01	0.001	0.2	97
CH_4 Emissions from Mobile Combustion: Road	CH_4	5.2	1.5	<0.01	<0.001	0.2	97
CO_2 Emissions from Natural Gas Systems	CO_2	37.7	42.4	<0.01	<0.001	0.2	97
Direct N_2O Emissions from Agricultural Soil Management	N_2O	212.0	213.3	<0.01	<0.001	0.2	97
N_2O Emissions from Manure Management	N_2O	14.0	17.7	<0.01	<0.001	0.2	98
CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	0.0	3.2	<0.01	<0.001	0.2	98
CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	3.0	0.0	<0.01	<0.001	0.1	98
CO_2 Emissions from Grassland Remaining Grassland	CO_2	4.2	7.3	<0.01	0.002	0.1	98
CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.5	4.3	<0.01	<0.001	0.1	98
CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	3.8	1.1	<0.01	<0.001	0.1	98
CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	0.6	3.4	<0.01	<0.001	0.1	98
N_2O Emissions from Forest Fires	N_2O	2.1	4.8	<0.01	0.001	0.1	99
CO_2 Emissions from Urea Fertilization	CO_2	2.4	5.0	<0.01	<0.001	0.1	99

CO_2 Emissions from Incineration of Waste	CO_2	8.0	10.7	<0.01	<0.001	0.1	99
CO_2 Emissions from Ammonia Production	CO_2	13.0	10.8	<0.01	<0.001	0.1	99
CH_4 Emissions from Composting	CH_4	0.4	2.1	<0.01	<0.001	0.1	99
N_2O Emissions from Composting	N_2O	0.3	1.9	<0.01	<0.001	0.1	99
N_2O Emissions from Wastewater Treatment	N_2O	3.4	5.0	<0.01	<0.001	0.1	99
Non-CO_2 Emissions from Stationary Combustion - Residential	CH_4	5.2	3.9	<0.01	<0.001	0.1	99
CO_2 Emissions from Lime Production	CO_2	11.7	13.3	<0.01	<0.001	0.1	99
CH_4 Emissions from Enteric Fermentation	CH_4	164.2	166.5	<0.01	<0.001	0.1	99
CH_4 Emissions from Wastewater Treatment	CH_4	15.7	14.8	<0.01	<0.001	0.1	99
PFC, HFC, SF_6, and NF_3 Emissions from Semiconductor Manufacture	Several	3.6	4.8	<0.01	<0.001	0.1	99
N_2O Emissions from Settlement Soils	N_2O	1.4	2.6	<0.01	<0.001	0.1	100
CO_2 Emissions from Liming	CO_2	4.7	3.8	<0.01	<0.001	<0.1	100
Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	7.2	6.4	<0.01	<0.001	<0.1	100
N_2O Emissions from Nitric Acid Production	N_2O	12.1	11.6	<0.01	<0.001	<0.1	100
N_2O Emissions from Mobile Combustion: Other	N_2O	1.2	2.0	<0.01	<0.001	<0.1	100
Non-CO_2 Emissions from Stationary Combustion - Industrial	N_2O	3.1	2.4	<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
Non-CO_2 Emissions from Stationary Combustion - Industrial	CH_4	1.8	1.5	<0.01	<0.001	<0.1	100
N_2O Emissions from Forest Soils	N_2O	0.1	0.5	<0.01	<0.001	<0.1	100
N_2O Emissions from Grass Fires	N_2O	0.1	0.4	<0.01	<0.001	<0.1	100
CO_2 Emissions from Titanium Dioxide Production	CO_2	1.2	1.6	<0.01	<0.001	<0.1	100
N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.7	1.5	<0.01	<0.001	<0.1	100
CO_2 Emissions from Peatlands Remaining Peatlands	CO_2	1.1	0.8	<0.01	<0.001	<0.1	100
CH_4 Emissions from Grass Fires	CH_4	0.1	0.4	<0.01	<0.001	<0.1	100
CO_2 Emissions from Zinc Production	CO_2	0.6	0.9	<0.01	<0.001	<0.1	100
CO_2 Emissions from Glass Production	CO_2	1.5	1.3	<0.01	<0.001	<0.1	100
Non-CO_2 Emissions from Stationary Combustion - Residential	N_2O	1.0	0.8	<0.01	<0.001	<0.1	100
CO_2 Emissions from Ferroalloy Production	CO_2	2.2	2.0	<0.01	<0.001	<0.1	100
N_2O Emissions from Semiconductor Manufacture	N_2O	+	0.2	<0.01	<0.001	<0.1	100
CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.4	0.2	<0.01	<0.001	<0.1	100
CH_4 Emissions from Mobile Combustion: Other	CH_4	0.3	0.5	<0.01	<0.001	<0.1	100
N_2O Emissions from Incineration of Waste	N_2O	0.5	0.3	<0.01	<0.001	<0.1	100
CO_2 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CO_2	8.6	8.7	<0.01	<0.001	<0.1	100
N_2O Emissions from Product Uses	N_2O	4.2	4.2	<0.01	<0.001	<0.1	100

Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	CH_4	0.3	0.4	<0.01	<0.001	<0.1	100
CO_2 Emissions from Soda Ash Production and Consumption	CO_2	2.8	2.8	<0.01	<0.001	<0.1	100
HFC-134A Emissions from Magnesium Production and Processing	HFCs	0.0	0.1	<0.01	<0.001	<0.1	100
CO_2 Emissions from Petroleum Systems	CO_2	3.6	3.6	<0.01	<0.001	<0.1	100
Non-CO_2 Emissions from Stationary Combustion - Commercial	N_2O	0.4	0.3	<0.01	<0.001	<0.1	100
CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.2	0.3	<0.01	<0.001	<0.1	100
CH_4 Emissions from Petrochemical Production	CH_4	0.2	0.2	<0.01	<0.001	<0.1	100
CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.1	+	<0.01	<0.001	<0.1	100
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1	0.1	<0.01	<0.001	<0.1	100
Non-CO_2 Emissions from Stationary Combustion - Commercial	CH_4	1.0	1.1	<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
N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6	0.6	<0.01	<0.001	<0.1	100
N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1	0.1	<0.01	<0.001	<0.1	100
Non-CO_2 Emissions from Stationary Combustion - U.S. Territories	CH_4	+	0.1	<0.01	<0.001	<0.1	100
CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+	+	<0.01	<0.001	<0.1	100
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	N_2O	0.1	0.1	<0.01	<0.001	<0.1	100
CO_2 Emissions from Land Converted to Wetlands	CO_2	+	+	<0.01	<0.001	<0.1	100
CH_4 Emissions from Ferroalloy Production	CH_4	+	+	<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
CH_4 Emissions from Land Converted to Coastal Wetlands	CH_4	+	+	<0.01	<0.001	<0.1	100
CH_4 Emissions from Peatlands Remaining Peatlands	CH_4	+	+	<0.01	<0.001	<0.1	100
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CH_4	3.4	3.5	<0.01	<0.001	<0.1	100
CO_2 Emissions from Magnesium Production and Processing	CO_2	+	+	<0.01	<0.001	<0.1	100
CH_4 Emissions from Mobile Combustion: Marine	CH_4	+	+	<0.01	<0.001	<0.1	100
N2O Emissions from Peatlands Remaining Peatlands	N_2O	+	+	<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 MMT CO_2 Eq.

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 Negara, and K. Tanabe (eds.). Hayman, Kanagawa, Japan.

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 eight 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, sector-based emission estimates in line with a Tier 2 method in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). 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-36 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). The 2015 total adjusted energy consumption across all sectors, including U.S. Territories, and energy types was 72,449.2 trillion British thermal units (TBtu), as indicated in the last entry of column 13 in Table A-10. 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 *Monthly Energy Review* (EIA 2016).

There are also three basic differences between the consumption data presented in Table A-10 and Table A-11 through Table A-36 and those recommended in the IPCC (2006) 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 (2006) emission inventory methodology. This convention is followed because data obtained from EIA are based on HHV. Of note, however, is that EIA renewable energy statistics are often published using LHV. The difference between the two conventions relates to the treatment of the heat energy that is consumed in the process of evaporating the water contained in the fuel. The simplified convention used by the International Energy Agency for converting from HHV to LHV is to multiply the energy content by 0.95 for petroleum and coal and by 0.9 for natural gas.

Second, while EIA's energy use data for the United States includes only the 50 U.S. states and the District of Columbia, the data reported to the United Nations Framework Convention on Climate Change (UNFCCC) are to include

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

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

energy consumption within U.S. 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-36. 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 degrees Fahrenheit) for processes accounted for in the Industrial Processes and Product Use 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 and Product Use 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 degrees Fahrenheit)—were reallocated to the Industrial Processes and Product Use 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 and Product Use chapter, and are removed from the energy and non-energy consumption estimates within the Energy chapter.

- Coking coal 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 (>401 degrees Fahrenheit) 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: Adjust Sectoral Allocation of Distillate Fuel Oil and Motor Gasoline

EPA conducted a separate bottom-up analysis of transportation fuel consumption based on data from the Federal Highway Administration (FHWA). The FHWA data indicated that the amount of distillate and motor gasoline consumption allocated to the transportation sector in the EIA statistics should be adjusted. Therefore, for the estimates presented in the U.S. Inventory, the transportation sector's distillate fuel and motor gasoline consumption was adjusted to match the value obtained from the bottom-up analysis. As the total distillate and motor gasoline consumption estimate from EIA are considered to be accurate at the national level, the distillate and motor gasoline consumption totals for the residential, commercial, and industrial sectors were adjusted proportionately.

[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.

Step 5: 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 some of this C when they are used and/or burned as waste. 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-37, was subtracted from total fuel consumption.

Step 6: Subtract Consumption of International Bunker Fuels

Emissions from international transport activities, or international bunker fuel consumption, are not included in national totals and instead reported separately, as required by the IPCC (2006) and UNFCCC (2014) inventory reporting guidelines. 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-38). Emissions from international bunker fuels have been estimated separately and not included in national totals.[4]

Step 7: 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-36) by fuel-specific C content coefficients (see Table A-39 and Table A-40) 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 2006), with modifications reflecting fuel qualities specific to the United States.

Step 8: 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 million metric tons of carbon dioxide equivalents (MMT 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-41). 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.

To provide a more detailed accounting of emissions from transportation, fuel consumption data by vehicle type and transportation mode were used to allocate emissions by fuel type calculated for the transportation end-use sector. Additional information on the allocation is available in Annex 3.2.

[BEGIN BOX]

Box 1. Uses of Greenhouse Gas Reporting Program Data in Reporting Emissions from Industrial Sector Fossil Fuel Combustion

As described in the calculation methodology, total fossil fuel consumption for each year is based on aggregated end-use sector consumption published by the EIA. The availability of facility-level combustion emissions through EPA's Greenhouse Gas Reporting Program (GHGRP) has provided an opportunity to better characterize the industrial sector's energy consumption and emissions in the United States, through a disaggregation of EIA's industrial sector fuel consumption data from select industries.

For EPA's GHGRP 2010, 2011, 2012, 2013, 2014, and 2015 reporting years, facility-level fossil fuel combustion emissions reported through the GHGRP were categorized and distributed to specific industry types by utilizing facility-

[4] Refer to the International Bunker Fuels section of the Energy chapter and Annex 3.3 for a description of the methodology for distinguishing between international and domestic fuel consumption.

reported NAICS codes (as published by the U.S. Census Bureau). As noted previously in this report, the definitions and provisions for reporting fuel types in EPA's GHGRP include some differences from the Inventory's use of EIA national fuel statistics to meet the UNFCCC reporting guidelines. The IPCC has provided guidance on aligning facility-level reported fuels and fuel types published in national energy statistics, which guided this exercise.[5]

This year's effort represents an attempt to align, reconcile, and coordinate the facility-level reporting of fossil fuel combustion emissions under EPA's GHGRP with the national-level approach presented in this report. Consistent with recommendations for reporting the Inventory to the UNFCCC, progress was made on certain fuel types for specific industries and has been included in the Common Reporting Format (CRF) tables that are submitted to the UNFCCC along with this report.[6] However, a full mapping was not completed this year due to fuel category differences between national statistics published by EIA and facility-level reported GHGRP data. Efforts in reconciling fuels focused on standard, common fuel types (e.g., natural gas, distillate fuel oil) where the fuels in EIA's national statistics aligned well with facility-level GHGRP data. For these reasons, the current information presented in the CRF tables should be viewed as an initial attempt at this exercise. Additional efforts will be made for future Inventory reports to improve the mapping of fuel types, and examine ways to reconcile and coordinate any differences between facility-level data and national statistics.

Additionally, this year's analysis expanded this effort through the full time series presented in this report, by linking EPA's GHGRP facility-level reporting with the information published by EIA in its Manufacturing Energy Consumption Survey (MECS) data. The GHGRP and MECS data provided disaggregated industrial fuel consumption by NAICS codes for certain years of the 1990-2015 time series. The GHGRP data are available for 2010, 2011, 2012, 2013, 2014, and 2015. The MECS data are available for 1991, 1994, 1998, 2002, 2006, and 2010. In order to disaggregate NAICS codes for the full entire time series, the GHGRP and MECS data were used in conjunction with the annual aggregate EIA MER data to implement splicing techniques as advised in the 2006 IPCC Guidelines "Volume 1 General Guidance and Reporting, Chapter 5 Time Series Consistency" to provide the full time series[7]. The results of the industrial sector disaggregation effort are provided in the CRF tables submitted with this Inventory. It is believed that the current analysis has led to improvements in the presentation of data in the Inventory, but further work will be conducted, and future improvements will be realized in subsequent Inventory reports.

Additionally, to assist in the disaggregation of industrial fuel consumption, EIA will now synthesize energy consumption data using the same procedure as is used for the last historical (benchmark) year of the Annual Energy Outlook (AEO). This procedure reorganizes the most recent data from the MECS (conducted every four years) into the nominal data submission year using the same energy-economy integrated model used to produce the AEO projections, the National Energy Modeling System (NEMS). EIA believes this "nowcasting" technique provides an appropriate estimate of energy consumption for the CRF.

To address gaps in the time series, EIA performs a NEMS model projection, using the MECS baseline sub-sector energy consumption. The NEMS model accounts for changes in factors that influence industrial sector energy consumption, and has access to data which may be more recent than MECS, such as industrial sub-sector macro industrial output (i.e., shipments) and fuel prices. By evaluating the impact of these factors on industrial subsector energy consumption, NEMS can anticipate changes to the energy shares occurring post-MECS and can provide a way to appropriately disaggregate the energy-related emissions data into the CRF.

While the fuel consumption values for the various manufacturing sub-sectors are not directly surveyed for all years, they represent EIA's best estimate of historical consumption values for non-MECS years. Moreover, as an integral part of each AEO publication, this synthetic data series is likely to be maintained consistent with all available EIA and non-EIA data sources even as the underlying data sources evolve for both manufacturing and non-manufacturing industries alike.

Other sectors' fuel consumption (i.e., commercial, residential, transportation) will be benchmarked with the latest aggregate values from the *Monthly Energy Review*.[8] EIA will work with the EPA to back cast these values to 1990.

[END BOX]

[5] See Section 4 "Use of Facility-Level Data in Good Practice National Greenhouse Gas Inventories" of the IPCC meeting report, and specifically the section on using facility-level data in conjunction with energy data, at <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

[6] See <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html>.

[7] Available online at: <http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/1_Volume1/V1_5_Ch5_Timeseries.pdf>

[8] See <http://www.eia.gov/totalenergy/data/monthly/>.

Table A-10: 2015 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
	Total Consumption (TBtu)[a]							Adjustments (TBtu)[b]				
									Unadjusted NEU Consumption			Total Adjusted
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Bunker Fuel**	**Ind.**	**Trans.**	**Terr.**	**Consumption**
Total Coal	**NE**	**31.1**	**827.4**	**NE**	**14,138.3**	**36.9**	**15,033.6**		**131.7**			**14,901.9**
Residential Coal	NE						NE					NE
Commercial Coal		31.1					31.1					31.1
Industrial Coking Coal			121.4				121.4		121.4			
Industrial Other Coal			706.0				706.0		10.3			695.6
Transportation Coal				NE			NE					NE
Electric Power Coal					14,138.3		14,138.3					14,138.3
U.S. Territory Coal (bit)						36.9	36.9					36.9
Natural Gas	**4,769.0**	**3,309.4**	**9,131.3**	**731.7**	**9,926.5**	**60.9**	**27,928.7**		**311.8**			**27,616.9**
Total Petroleum	**981.6**	**671.8**	**8,442.1**	**25,190.0**	**276.0**	**528.9**	**36,090.5**	**1,540.7**	**4,472.0**	**148.1**	**53.6**	**29,876.0**
Asphalt & Road Oil			831.7				831.7		831.7			
Aviation Gasoline				21.1			21.1					21.1
Distillate Fuel Oil	498.7	325.7	1,056.9	6,342.9	70.4	74.9	8,369.5	113.5	5.8			8,250.2
Jet Fuel				3,204.2	NA	55.2	3,259.3	1,020.4				2,239.0
Kerosene	9.8	1.4	2.0			7.2	20.4					20.4
LPG	473.2	155.1	2,490.9	48.3		13.4	3,180.9		2,215.1			965.9
Lubricants			156.8	148.1		1.0	306.0		156.8	148.1	1.0	
Motor Gasoline		181.4	645.5	14,971.6		175.9	15,974.4					15,974.4
Residual Fuel		7.7		453.8	93.9	148.7	704.1	406.8				297.2
Other Petroleum												
AvGas Blend Components			(0.4)				(0.4)					(0.4)
Crude Oil												
MoGas Blend Components												
Misc. Products			188.9			52.6	241.5		188.9		52.6	
Naphtha (<401 deg. F)			428.1				428.1		428.1			
Other Oil (>401 deg. F)			229.0				229.0		229.0			
Pentanes Plus			160.5				160.5		80.2			80.2
Petroleum Coke		0.5	663.3		111.7		775.5		62.5			713.0
Still Gas			1,495.0				1,495.0		162.2			1,332.8
Special Naphtha			99.3				99.3		99.3			
Unfinished Oils			(17.8)				(17.8)					(17.8)
Waxes			12.4				12.4		12.4			
Geothermal					**54.3**		**54.3**					**54.3**
Total (All Fuels)	**5,750.6**	**4,012.3**	**18,400.8**	**25,921.7**	**24,395.0**	**626.6**	**79,107.1**	**1,540.7**	**4,915.5**	**148.1**	**53.6**	**72,449.2**

[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-37), and international bunker fuel consumption (see Table A-38). Note: Parentheses indicate negative values. NE (Not Estimated); NA (Not Available).

Table A-11: 2015 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] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**NE**	**31.1**	**695.6**	**NE**	**14,138.3**	**36.9**	**14,901.9**	**NE**	**2.9**	**65.9**	**NE**	**1,350.5**	**3.4**	**1,422.7**
Residential Coal	NE						NE	NE						NE
Commercial Coal		31.1					31.1		2.9					2.9
Industrial Other Coal			695.6				695.6			65.9				65.9
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					14,138.3		14,138.3					1,350.5		1,350.5
U.S. Territory Coal (bit)						36.9	36.9						3.4	3.4
Natural Gas	**4,769.0**	**3,309.4**	**8,819.5**	**731.7**	**9,926.5**	**60.9**	**27,616.9**	**252.8**	**175.4**	**467.5**	**38.8**	**526.1**	**3.2**	**1,463.8**
Total Petroleum	**981.6**	**671.8**	**3,970.1**	**23,501.2**	**276.0**	**475.3**	**29,876.0**	**66.8**	**47.3**	**295.5**	**1,694.5**	**23.7**	**34.6**	**2,162.3**
Asphalt & Road Oil														
Aviation Gasoline				21.1			21.1				1.5			1.5
Distillate Fuel Oil	498.7	325.7	1,051.1	6,229.4	70.4	74.9	8,250.2	36.9	24.1	77.7	460.7	5.2	5.5	610.2
Jet Fuel				2,183.8	NA	55.2	2,239.0				157.7		4.0	161.7
Kerosene	9.8	1.4	2.0			7.2	20.4	0.7	0.1	0.1			0.5	1.5
LPG	473.2	155.1	275.8	48.3		13.4	965.9	29.2	9.6	17.0	3.0		0.8	59.6
Lubricants														
Motor Gasoline		181.4	645.5	14,971.6		175.9	15,974.4		12.9	46.1	1,068.1		12.5	1,139.6
Residual Fuel		7.7		47.0	93.9	148.7	297.2		0.6		3.5	7.0	11.2	22.3
Other Petroleum														
AvGas Blend Components			(0.4)				(0.4)			(0.0)				(0.0)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			80.2				80.2			5.6				5.6
Petroleum Coke		0.5	600.8		111.7		713.0		0.1	61.3		11.4		72.8
Still Gas			1,332.8				1,332.8			88.9				88.9
Special Naphtha														
Unfinished Oils			(17.8)				(17.8)			(1.3)				(1.3)
Waxes														
Geothermal					**54.3**		**54.3**					**0.4**		**0.4**
Total (All Fuels)	**5,750.6**	**4,012.3**	**13,485.3**	**24,232.9**	**24,395.0**	**573.0**	**72,449.2**	**319.6**	**225.7**	**828.8**	**1,733.2**	**1,900.7**	**41.2**	**5,049.2**

NE (Not Estimated)
NA (Not Available)
[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-37), and international bunker fuel consumption (see Table A-38).
Note: Parentheses indicate negative values.

Table A-12: 2014 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] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**NE**	**40.2**	**799.0**	**NE**	**16,427.4**	**36.9**	**17,303.5**	**NE**	**3.8**	**75.6**	**NE**	**1,569.1**	**3.4**	**1,652.0**
Residential Coal	NE						NE	NE						NE
Commercial Coal		40.2					40.2		3.8					3.8
Industrial Other Coal			799.0				799.0			75.6				75.6
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					16,427.4		16,427.4					1,569.1		1,569.1
U.S. Territory Coal (bit)						36.9	36.9						3.4	3.4
Natural Gas	**5,242.5**	**3,571.9**	**8,836.8**	**759.7**	**8,361.7**	**60.6**	**26,833.2**	**277.9**	**189.3**	**468.4**	**40.3**	**443.2**	**3.2**	**1,422.2**
Total Petroleum	**989.7**	**543.6**	**3,635.6**	**23,446.8**	**295.5**	**475.3**	**29,386.5**	**67.5**	**38.3**	**271.7**	**1,690.1**	**25.3**	**34.6**	**2,127.5**
Asphalt & Road Oil														
Aviation Gasoline				21.7			21.7				1.5			1.5
Distillate Fuel Oil	514.0	343.8	1,309.3	6,051.5	82.2	74.9	8,375.7	38.0	25.4	96.8	447.5	6.1	5.5	619.4
Jet Fuel				2,057.0	NA	55.2	2,112.2				148.6		4.0	152.5
Kerosene	13.7	2.0	2.8			7.2	25.8	1.0	0.1	0.2			0.5	1.9
LPG	461.9	151.4	280.8	47.2		13.4	954.8	28.5	9.3	17.3	2.9		0.8	58.9
Lubricants														
Motor Gasoline		37.9	134.7	15,192.0		175.9	15,540.5		2.7	9.6	1,083.8		12.5	1,108.6
Residual Fuel		7.9		77.4	95.1	148.7	329.2		0.6		5.8	7.1	11.2	24.7
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			44.2				44.2			3.1				3.1
Petroleum Coke		0.5	592.1		118.2		710.8		0.1	60.5		12.1		72.6
Still Gas			1,352.4				1,352.4			90.2				90.2
Special Naphtha														
Unfinished Oils			(80.6)				(80.6)			(6.0)				(6.0)
Waxes														
Geothermal					**54.2**		**54.2**					**0.4**		**0.4**
Total (All Fuels)	**6,232.2**	**4,155.8**	**13,271.5**	**24,206.5**	**25,138.7**	**572.7**	**73,577.3**	**345.4**	**231.4**	**815.8**	**1,730.4**	**2,038.0**	**41.2**	**5,202.1**

NE (Not Estimated)
NA (Not Available)
[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-37), and international bunker fuel consumption (see Table A-38).
Note: Parentheses indicate negative values.

Table A-13: 2013 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] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**NE**	**41.4**	**800.0**	**NE**	**16,450.6**	**36.9**	**17,328.8**	**NE**	**3.9**	**75.7**	**NE**	**1,571.3**	**3.4**	**1,654.4**
Residential Coal	NE						NE	NE						NE
Commercial Coal		41.4					41.4		3.9					3.9
Industrial Other Coal			800.0				800.0			75.7				75.7
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					16,450.6		16,450.6					1,571.3		1,571.3
U.S. Territory Coal (bit)						36.9	36.9						3.4	3.4
Natural Gas	**5,022.9**	**3,379.8**	**8,525.3**	**887.3**	**8,376.3**	**56.6**	**26,248.2**	**266.2**	**179.1**	**451.9**	**47.0**	**444.0**	**3.0**	**1,391.2**
Total Petroleum	**935.9**	**540.1**	**3,823.8**	**23,108.5**	**255.2**	**510.1**	**29,173.6**	**63.4**	**38.0**	**284.6**	**1,666.0**	**22.4**	**37.1**	**2,111.6**
Asphalt & Road Oil														
Aviation Gasoline				22.4			22.4				1.5			1.5
Distillate Fuel Oil	457.2	319.6	1,169.8	5,866.3	55.4	80.4	7,948.6	33.8	23.6	86.5	433.9	4.1	5.9	587.9
Jet Fuel				2,036.9	NA	59.2	2,096.1				147.1		4.3	151.4
Kerosene	8.3	1.0	1.5			7.7	18.4	0.6	0.1	0.1			0.6	1.3
LPG	470.5	153.9	349.0	44.4		14.4	1,032.2	29.0	9.5	21.5	2.7		0.9	63.7
Lubricants														
Motor Gasoline		40.8	268.7	14,937.2		188.8	15,435.6		2.9	19.2	1,065.6		13.5	1,101.2
Residual Fuel		24.4		201.4	77.2	159.6	462.6		1.8		15.1	5.8	12.0	34.7
Other Petroleum														
AvGas Blend Components			(0.4)				(0.4)			(0.0)				(0.0)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			47.1				47.1			3.3				3.3
Petroleum Coke		0.4	600.9		122.5		723.7		0.0	61.4		12.5		73.9
Still Gas			1,370.6				1,370.6			91.4				91.4
Special Naphtha														
Unfinished Oils			16.7				16.7			1.2				1.2
Waxes														
Geothermal					**53.8**		**53.8**					**0.4**		**0.4**
Total (All Fuels)	**5,958.8**	**3,961.3**	**13,149.1**	**23,995.8**	**25,135.8**	**603.6**	**72,804.4**	**329.7**	**221.0**	**812.2**	**1,713.0**	**2,038.1**	**43.5**	**5,157.6**

NE (Not Estimated)
NA (Not Available)
[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-37), and international bunker fuel consumption (see Table A-38).
Note: Parentheses indicate negative values.

Table A-14: 2012 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] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**NE**	**43.6**	**782.3**	**NE**	**15,821.2**	**36.9**	**16,684.0**	**NE**	**4.1**	**74.1**	**NE**	**1,511.2**	**3.4**	**1,592.8**
Residential Coal	NE						NE	NE						NE
Commercial Coal		43.6					43.6		4.1					4.1
Industrial Other Coal			782.3				782.3			74.1				74.1
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					15,821.2		15,821.2					1,511.2		1,511.2
U.S. Territory Coal (bit)						36.9	36.9						3.4	3.4
Natural Gas	**4,242.1**	**2,959.5**	**8,203.0**	**779.8**	**9,286.8**	**49.2**	**25,520.3**	**224.8**	**156.9**	**434.8**	**41.3**	**492.2**	**2.6**	**1,352.6**
Total Petroleum	**846.7**	**506.0**	**3,650.4**	**22,963.0**	**214.2**	**516.1**	**28,696.4**	**57.7**	**35.7**	**274.1**	**1,655.4**	**18.3**	**37.6**	**2,078.9**
Asphalt & Road Oil														
Aviation Gasoline				25.1			25.1				1.7			1.7
Distillate Fuel Oil	437.5	322.1	1,144.7	5,780.1	52.4	81.3	7,818.1	32.4	23.8	84.7	427.5	3.9	6.0	578.2
Jet Fuel				1,985.2	NA	59.9	2,045.1				143.4		4.3	147.7
Kerosene	7.7	1.2	2.0			7.8	18.7	0.6	0.1	0.1			0.6	1.4
LPG	401.6	137.6	345.0	37.2		14.6	935.9	24.8	8.5	21.3	2.3		0.9	57.8
Lubricants														
Motor Gasoline		13.3	87.1	14,924.3		191.1	15,215.9		1.0	6.2	1,064.7		13.6	1,085.5
Residual Fuel		31.4		211.1	76.7	161.5	480.6		2.4		15.8	5.8	12.1	36.1
Other Petroleum														
AvGas Blend Components			(0.0)				(0.0)			(0.0)				(0.0)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			42.2				42.2			3.0				3.0
Petroleum Coke		0.4	649.1		85.1		734.6		0.0	66.3		8.7		75.0
Still Gas			1,320.2				1,320.2			88.1				88.1
Special Naphtha														
Unfinished Oils			60.1				60.1			4.5				4.5
Waxes														
Geothermal					**53.1**		**53.1**					**0.4**		**0.4**
Total (All Fuels)	**5,088.8**	**3,509.1**	**12,635.7**	**23,742.8**	**25,375.3**	**602.1**	**70,953.8**	**282.5**	**196.7**	**782.9**	**1,696.8**	**2,022.2**	**43.6**	**5,024.7**

NE (Not Estimated)
NA (Not Available)
[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-37), and international bunker fuel consumption (see Table A-38).
Note: Parentheses indicate negative values

Table A-15: 2011 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] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**NE**	**61.7**	**866.1**	**NE**	**18,035.2**	**36.9**	**18,999.9**	**NE**	**5.8**	**82.0**	**NE**	**1,722.7**	**3.4**	**1,813.9**
Residential Coal	NE						NE	NE						NE
Commercial Coal		61.7					61.7		5.8					5.8
Industrial Other Coal			866.1				866.1			82.0				82.0
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					18,035.2		18,035.2					1,722.7		1,722.7
U.S. Territory Coal (bit)						36.9	36.9						3.4	3.4
Natural Gas	**4,804.6**	**3,216.1**	**7,873.4**	**733.5**	**7,712.2**	**27.1**	**24,366.9**	**254.7**	**170.5**	**417.3**	**38.9**	**408.8**	**1.4**	**1,291.5**
Total Petroleum	**1,039.1**	**619.5**	**3,672.0**	**23,145.2**	**295.0**	**503.8**	**29,274.6**	**70.9**	**44.1**	**275.7**	**1,668.8**	**25.8**	**36.7**	**2,121.9**
Asphalt & Road Oil														
Aviation Gasoline				27.1			27.1				1.9			1.9
Distillate Fuel Oil	534.8	400.5	1,255.8	5,814.5	63.7	79.3	8,148.5	39.6	29.6	92.9	430.0	4.7	5.9	602.6
Jet Fuel				2,029.9	NA	58.5	2,088.4				146.6		4.2	150.8
Kerosene	18.5	3.2	3.6			7.6	32.9	1.4	0.2	0.3			0.6	2.4
LPG	485.8	140.5	235.4	34.0		14.2	909.8	30.0	8.7	14.5	2.1		0.9	56.1
Lubricants														
Motor Gasoline		21.3	123.2	14,981.8		186.6	15,313.0		1.5	8.8	1,068.8		13.3	1,092.4
Residual Fuel		53.7	46.9	258.0	93.1	157.6	609.2		4.0	3.5	19.4	7.0	11.8	45.7
Other Petroleum														
AvGas Blend Components			0.0				0.0			0.0				0.0
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			27.3				27.3			1.9				1.9
Petroleum Coke		0.2	600.3		138.3		738.8		0.0	61.3		14.1		75.4
Still Gas			1,323.4				1,323.4			88.3				88.3
Special Naphtha														
Unfinished Oils			56.1				56.1			4.2				4.2
Waxes														
Geothermal					**52.3**		**52.3**					**0.4**		**0.4**
Total (All Fuels)	**5,843.6**	**3,897.3**	**12,411.5**	**23,878.7**	**26,094.7**	**567.8**	**72,693.6**	**325.5**	**220.4**	**775.0**	**1,707.6**	**2,157.7**	**41.5**	**5,227.7**

NE (Not Estimated)
NA (Not Available)
[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-37), and international bunker fuel consumption (see Table A-38).

Table A-16: 2010 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] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**NE**	**69.7**	**951.6**	**NE**	**19,133.5**	**36.9**	**20,191.6**	**NE**	**6.6**	**90.1**	**NE**	**1,827.6**	**3.4**	**1,927.7**
Residential Coal	NE						NE	NE						NE
Commercial Coal		69.7					69.7		6.6					6.6
Industrial Other Coal			951.6				951.6			90.1				90.1
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					19,133.5		19,133.5					1,827.6		1,827.6
U.S. Territory Coal (bit)						36.9	36.9						3.4	3.4
Natural Gas	**4,878.1**	**3,164.7**	**7,683.2**	**719.0**	**7,527.6**	**27.8**	**24,000.4**	**258.6**	**167.7**	**407.2**	**38.1**	**399.0**	**1.5**	**1,272.1**
Total Petroleum	**1,116.2**	**643.5**	**3,699.2**	**23,447.1**	**370.3**	**501.6**	**29,777.9**	**76.0**	**45.8**	**278.2**	**1,690.2**	**31.4**	**36.5**	**2,158.2**
Asphalt & Road Oil														
Aviation Gasoline				27.0			27.0				1.9			1.9
Distillate Fuel Oil	557.0	388.0	1,134.4	5,706.1	79.7	78.9	7,944.0	41.2	28.7	83.9	422.0	5.9	5.8	587.5
Jet Fuel				2,097.5	NA	58.2	2,155.6				151.5		4.2	155.7
Kerosene	29.1	4.8	7.3			7.5	48.8	2.1	0.4	0.5			0.6	3.6
LPG	530.1	140.1	219.7	29.5		14.2	933.6	32.7	8.6	13.6	1.8		0.9	57.6
Lubricants														
Motor Gasoline		48.5	243.1	15,314.8		186.1	15,792.5		3.5	17.3	1,092.5		13.3	1,126.6
Residual Fuel		61.7	32.2	272.2	154.1	156.8	676.9		4.6	2.4	20.4	11.6	11.8	50.8
Other Petroleum														
AvGas Blend Components			(0.2)				(0.2)			(0.0)				(0.0)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			77.8				77.8			5.4				5.4
Petroleum Coke		0.3	633.0		136.6		770.0		0.0	64.6		13.9		78.6
Still Gas			1,324.0				1,324.0			88.3				88.3
Special Naphtha														
Unfinished Oils			28.0				28.0			2.1				2.1
Waxes														
Geothermal					**51.9**		**51.9**					**0.4**		**0.4**
Total (All Fuels)	**5,994.3**	**3,877.8**	**12,334.0**	**24,166.0**	**27,083.3**	**566.2**	**74,021.7**	**334.6**	**220.1**	**775.5**	**1,728.3**	**2,258.4**	**41.4**	**5,358.3**

NE (Not Estimated)
NA (Not Available)
[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-37), and international bunker fuel consumption (see Table A-38).
Note: Parentheses indicate negative values.

Table A-17: 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] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**NE**	**73.4**	**877.3**	**NE**	**18,225.3**	**36.9**	**19,212.8**	**NE**	**6.9**	**83.0**	**NE**	**1,740.9**	**3.4**	**1,834.2**
Residential Coal	NE						NE	NE						NE
Commercial Coal		73.4					73.4		6.9					6.9
Industrial Other Coal			877.3				877.3			83.0				83.0
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					18,225.3		18,225.3					1,740.9		1,740.9
U.S. Territory Coal (bit)						36.9	36.9						3.4	3.4
Natural Gas	**4,883.1**	**3,186.6**	**7,125.1**	**714.9**	**7,022.4**	**27.4**	**22,959.4**	**258.8**	**168.9**	**377.6**	**37.9**	**372.2**	**1.5**	**1,216.9**
Total Petroleum	**1,138.2**	**668.6**	**3,550.0**	**23,303.6**	**382.4**	**531.0**	**29,573.7**	**77.5**	**47.6**	**267.0**	**1,679.1**	**32.2**	**38.6**	**2,142.0**
Asphalt & Road Oil														
Aviation Gasoline				26.6			26.6				1.8			1.8
Distillate Fuel Oil	563.4	382.4	1,018.1	5,488.2	69.6	83.4	7,605.1	41.7	28.3	75.3	405.9	5.1	6.2	562.4
Jet Fuel				2,134.2	NA	61.5	2,195.7				154.1		4.4	158.6
Kerosene	27.7	4.2	4.4			8.0	44.3	2.0	0.3	0.3			0.6	3.2
LPG	547.1	138.9	201.7	28.0		15.0	930.7	33.8	8.6	12.4	1.7		0.9	57.4
Lubricants														
Motor Gasoline		71.6	328.2	15,440.8		197.5	16,038.2		5.1	23.4	1,101.5		14.1	1,144.1
Residual Fuel		71.3	67.3	185.7	181.0	165.7	670.9		5.4	5.1	13.9	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			63.8				63.8			4.5				4.5
Petroleum Coke		0.2	624.0		131.8		756.1		0.0	63.7		13.5		77.2
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					**51.2**		**51.2**					**0.4**		**0.4**
Total (All Fuels)	**6,021.3**	**3,928.5**	**11,552.3**	**24,018.5**	**25,681.3**	**595.2**	**71,797.2**	**336.3**	**223.5**	**727.7**	**1,717.0**	**2,145.7**	**43.5**	**5,193.5**

NE (Not Estimated)
NA (Not Available)
[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-37), and international bunker fuel consumption (see Table A-38).
Note: Parentheses indicate negative values.

Table A-18: 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] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**NE**	**80.8**	**1,081.5**	**NE**	**20,513.0**	**36.9**	**21,712.0**	**NE**	**7.6**	**102.4**	**NE**	**1,959.4**	**3.4**	**2,072.8**
Residential Coal	NE						NE	NE						NE
Commercial Coal		80.8					80.8		7.6					7.6
Industrial Other Coal			1,081.5				1,081.5			102.4				102.4
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					20,513.0		20,513.0					1,959.4		1,959.4
U.S. Territory Coal (bit)						36.9	36.9						3.4	3.4
Natural Gas	**5,010.1**	**3,228.4**	**7,571.4**	**692.1**	**6,828.9**	**29.3**	**23,360.2**	**265.5**	**171.1**	**401.3**	**36.7**	**361.9**	**1.6**	**1,238.1**
Total Petroleum	**1,201.5**	**635.0**	**3,994.0**	**24,342.5**	**459.3**	**489.9**	**31,122.2**	**82.1**	**44.9**	**299.2**	**1,755.1**	**38.4**	**35.8**	**2,255.5**
Asphalt & Road Oil														
Aviation Gasoline				28.3			28.3				2.0			2.0
Distillate Fuel Oil	627.5	321.3	1,103.1	6,058.8	72.5	110.3	8,293.5	46.4	23.8	81.6	448.1	5.4	8.2	613.4
Jet Fuel				2,396.1	NA	35.0	2,431.1				173.0		2.5	175.6
Kerosene	21.3	4.4	3.8			5.9	35.4	1.6	0.3	0.3			0.4	2.6
LPG	552.7	158.0	226.7	40.1		15.7	993.3	34.1	9.7	14.0	2.5		1.0	61.3
Lubricants														
Motor Gasoline		80.0	437.3	15,547.9		133.7	16,198.9		5.7	31.2	1,109.2		9.5	1,155.6
Residual Fuel		71.0	131.5	271.3	240.4	189.3	903.5		5.3	9.9	20.4	18.1	14.2	67.8
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			76.5				76.5			5.4				5.4
Petroleum Coke		0.3	645.7		146.4		792.3		0.0	65.9		14.9		80.9
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					**50.6**		**50.6**					**0.4**		**0.4**
Total (All Fuels)	**6,211.6**	**3,944.2**	**12,646.8**	**25,034.6**	**27,851.8**	**556.0**	**76,245.1**	**347.6**	**223.6**	**802.8**	**1,791.8**	**2,360.1**	**40.8**	**5,566.7**

NE (Not Estimated)
NA (Not Available)
[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-37), and international bunker fuel consumption (see Table A-38).
Note: Parentheses indicate negative values.

Table A-19: 2007 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] (MMT 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**	**1,130.8**	**NE**	**20,807.7**	**36.9**	**22,053.2**	**0.7**	**6.7**	**107.0**	**NE**	**1,987.3**	**3.4**	**2,105.1**
Residential Coal	7.8						7.8	0.7						0.7
Commercial Coal		70.0					70.0		6.7					6.7
Industrial Other Coal			1,130.8				1,130.8			107.0				107.0
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					20,807.7		20,807.7					1,987.3		1,987.3
U.S. Territory Coal (bit)						36.9	36.9						3.4	3.4
Natural Gas	**4,835.4**	**3,085.1**	**7,521.3**	**663.5**	**7,005.2**	**26.7**	**23,137.2**	**256.3**	**163.5**	**398.6**	**35.2**	**371.3**	**1.4**	**1,226.3**
Total Petroleum	**1,219.9**	**679.7**	**4,584.5**	**25,577.1**	**647.8**	**549.8**	**33,258.8**	**84.3**	**48.6**	**342.2**	**1,850.9**	**52.9**	**40.3**	**2,419.2**
Asphalt & Road Oil														
Aviation Gasoline				31.6			31.6				2.2			2.2
Distillate Fuel Oil	692.4	366.1	1,177.0	6,393.6	88.7	136.5	8,854.2	51.2	27.1	87.0	472.9	6.6	10.1	654.8
Jet Fuel				2,485.0	NA	55.5	2,540.4				179.5		4.0	183.5
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	379.1	21.9		11.6	1,017.7	29.8	7.5	23.4	1.4		0.7	62.8
Lubricants														
Motor Gasoline		107.3	536.9	16,258.9		155.1	17,058.1		7.7	38.5	1,166.0		11.1	1,223.4
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			89.7				89.7			6.3				6.3
Petroleum Coke		0.4	708.4		162.6		871.3		0.0	72.3		16.6		89.0
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)	**6,063.2**	**3,834.8**	**13,236.6**	**26,240.5**	**28,510.7**	**613.3**	**78,499.1**	**341.3**	**218.8**	**847.9**	**1,886.1**	**2,411.9**	**45.1**	**5,751.0**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.

Table A-20: 2006 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] (MMT 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**	**1,188.8**	**NE**	**20,461.9**	**36.9**	**21,758.7**	**0.6**	**6.2**	**112.6**	**NE**	**1,953.7**	**3.4**	**2,076.6**
Residential Coal	6.4						6.4	0.6						0.6
Commercial Coal		64.8					64.8		6.2					6.2
Industrial Other Coal			1,188.8				1,188.8			112.6				112.6
Transportation Coal				NE			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**	**7,323.2**	**625.0**	**6,375.1**	**26.14**	**21,727.0**	**237.3**	**153.8**	**388.2**	**33.1**	**338.0**	**1.4**	**1,151.8**
Total Petroleum	**1,202.3**	**677.6**	**4,709.0**	**25,651.7**	**637.0**	**619.9**	**33,497.4**	**83.4**	**48.5**	**351.7**	**1,849.5**	**53.2**	**45.4**	**2,431.8**
Asphalt & Road Oil														
Aviation Gasoline				33.4			33.4				2.3			2.3
Distillate Fuel Oil	690.4	389.0	1,194.7	6,334.2	73.4	90.2	8,771.8	51.1	28.8	88.4	468.5	5.4	6.7	648.7
Jet Fuel				2,523.8	NA	76.1	2,599.9				182.3		5.5	187.8
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	369.7	27.5		6.6	972.5	27.5	7.6	22.8	1.7		0.4	60.0
Lubricants														
Motor Gasoline		74.7	577.2	16,426.4		187.9	17,266.1		5.3	41.2	1,171.8		13.4	1,231.7
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			70.0				70.0			4.9				4.9
Petroleum Coke		0.3	724.3		203.0		927.6		0.0	74.0		20.7		94.7
Still Gas			1,496.2				1,496.2			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)	**5,684.6**	**3,644.0**	**13,221.0**	**26,276.6**	**27,523.7**	**682.9**	**77,032.8**	**321.3**	**208.6**	**852.6**	**1,882.6**	**2,345.3**	**50.2**	**5,660.6**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.

Table A-21: 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] (MMT 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			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**	**7,329.7**	**623.9**	**6,014.5**	**24.3**	**22,012.0**	**262.2**	**162.9**	**388.5**	**33.1**	**318.8**	**1.3**	**1,166.7**
Total Petroleum	**1,368.3**	**715.6**	**4,327.7**	**25,799.2**	**1,222.1**	**622.7**	**34,055.5**	**94.9**	**51.3**	**324.2**	**1,854.0**	**97.9**	**45.6**	**2,467.8**
Asphalt & Road Oil														
Aviation Gasoline				35.4			35.4				2.4			2.4
Distillate Fuel Oil	771.6	404.2	1,127.5	6,186.2	114.5	121.3	8,725.4	57.1	29.9	83.4	457.5	8.5	9.0	645.3
Jet Fuel				2,621.7	NA	66.0	2,687.7				189.3		4.8	194.1
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	349.6	28.2		0.8	1,022.8	31.7	8.1	21.6	1.7		0.0	63.1
Lubricants														
Motor Gasoline		42.3	328.9	16,671.3		193.6	17,236.1		3.0	23.4	1,183.7		13.7	1,223.8
Residual Fuel		115.8	237.4	256.4	876.5	235.2	1,721.3		8.7	17.8	19.3	65.8	17.7	129.3
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			98.1				98.1			6.9				6.9
Petroleum Coke		0.3	706.6		231.1		938.0		0.0	72.1		23.6		95.8
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)	**6,323.1**	**3,885.8**	**12,876.6**	**26,423.1**	**28,024.0**	**679.7**	**78,212.2**	**357.8**	**223.5**	**828.0**	**1,887.0**	**2,400.9**	**49.9**	**5,747.1**

NE – Not Estimated

NA – Not Available

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).

[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.

Table A-22: 2004 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] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**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			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**	**7,913.5**	**602.0**	**5,594.9**	**24.6**	**22,316.9**	**264.1**	**169.7**	**419.6**	**31.9**	**296.7**	**1.3**	**1,183.4**
Total Petroleum	**1,467.8**	**764.3**	**4,197.3**	**25,533.5**	**1,201.0**	**653.1**	**33,817.0**	**102.2**	**54.7**	**314.4**	**1,835.2**	**95.8**	**47.9**	**2,450.3**
Asphalt & Road Oil														
Aviation Gasoline				31.2			31.2				2.2			2.2
Distillate Fuel Oil	871.3	443.6	1,130.6	5,910.4	111.2	134.4	8,601.5	64.4	32.8	83.6	437.1	8.2	9.9	636.1
Jet Fuel				2,584.8	NA	68.8	2,653.6				186.7		5.0	191.6
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	372.7	19.1		0.8	1,056.3	31.6	9.4	23.0	1.2		0.0	65.2
Lubricants														
Motor Gasoline		25.5	212.4	16,801.6		198.1	17,237.5		1.8	15.1	1,194.1		14.1	1,225.1
Residual Fuel		122.5	204.7	186.4	879.0	245.0	1,637.6		9.2	15.4	14.0	66.0	18.4	123.0
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			111.2				111.2			7.8				7.8
Petroleum Coke		0.3	719.1		210.8		930.1		0.0	73.4		21.5		95.0
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)	**6,460.1**	**4,068.2**	**13,372.8**	**26,135.5**	**27,151.5**	**709.7**	**77,897.7**	**367.4**	**234.2**	**852.3**	**1,867.1**	**2,335.9**	**52.1**	**5,709.2**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-23: 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] (MMT 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				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**	**7,845.1**	**627.4**	**5,246.2**	**26.9**	**22,216.0**	**275.9**	**172.7**	**415.4**	**33.2**	**277.8**	**1.4**	**1,176.4**
Total Petroleum	**1,468.3**	**764.6**	**3,959.1**	**24,919.1**	**1,204.8**	**621.7**	**32,937.5**	**101.9**	**54.7**	**297.2**	**1,789.0**	**95.0**	**45.3**	**2,383.2**
Asphalt & Road Oil														
Aviation Gasoline				30.2			30.2				2.1			2.1
Distillate Fuel Oil	853.5	454.2	1,058.2	5,704.9	160.8	120.5	8,352.1	63.1	33.6	78.3	421.9	11.9	8.9	617.7
Jet Fuel				2,482.5	NA	76.1	2,558.5				179.3		5.5	184.8
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	326.8	17.9		10.5	1,056.6	33.7	9.7	20.2	1.1		0.7	65.3
Lubricants														
Motor Gasoline		23.5	126.9	16,584.5		209.9	16,944.8		1.7	9.0	1,177.2		14.9	1,202.8
Residual Fuel		111.1	176.4	99.1	869.4	193.9	1,450.0		8.3	13.2	7.4	65.3	14.6	108.9
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			110.4				110.4			7.7				7.7
Petroleum Coke		0.3	701.9		174.7		876.8		0.0	71.7		17.8		89.5
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)	**6,689.9**	**4,107.5**	**13,052.9**	**25,546.6**	**26,685.0**	**682.4**	**76,764.4**	**378.9**	**235.2**	**829.6**	**1,822.3**	**2,304.2**	**49.9**	**5,620.0**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-24: 2002 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] (MMT 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**	**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				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	**4,995.0**	**3,212.5**	**8,086.3**	**698.9**	**5,766.8**	**22.8**	**22,782.3**	**264.7**	**170.3**	**428.6**	**37.0**	**305.7**	**1.2**	**1,207.5**
Total Petroleum	**1,360.9**	**647.4**	**3,794.7**	**24,961.9**	**961.2**	**556.9**	**32,283.0**	**94.1**	**46.2**	**284.6**	**1,793.6**	**76.8**	**40.6**	**2,335.9**
Asphalt & Road Oil														
Aviation Gasoline				33.7			33.7				2.3			2.3
Distillate Fuel Oil	763.8	394.5	1,051.2	5,590.0	127.3	92.8	8,019.6	56.5	29.2	77.7	413.4	9.4	6.9	593.1
Jet Fuel				2,565.5	NA	61.8	2,627.3				185.3		4.5	189.7
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	393.3	14.3		11.2	1,096.7	33.2	8.7	24.3	0.9		0.7	67.8
Lubricants														
Motor Gasoline		16.2	110.8	16,530.5		189.5	16,847.0		1.1	7.9	1,174.6		13.5	1,197.1
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			111.9				111.9			7.8				7.8
Petroleum Coke		0.2	696.3		175.2		871.7		0.0	71.1		17.9		89.0
Still Gas			1,399.4				1,399.4			93.4				93.4
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)	**6,368.1**	**3,949.7**	**13,124.6**	**25,660.9**	**26,560.2**	**590.5**	**76,254.1**	**360.0**	**225.0**	**829.8**	**1,830.6**	**2,272.7**	**42.8**	**5,560.9**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-25: 2001 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] (MMT 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				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**	**7,949.0**	**658.0**	**5,458.1**	**22.9**	**22,074.3**	**259.1**	**164.2**	**421.3**	**34.9**	**289.3**	**1.2**	**1,170.0**
Total Petroleum	**1,464.9**	**720.4**	**3,919.6**	**24,453.7**	**1,276.4**	**632.4**	**32,467.4**	**101.9**	**51.6**	**293.8**	**1,754.6**	**98.4**	**46.2**	**2,346.5**
Asphalt & Road Oil														
Aviation Gasoline				34.9			34.9				2.4			2.4
Distillate Fuel Oil	844.1	472.4	1,184.5	5,411.3	170.3	109.4	8,192.1	62.4	34.9	87.6	400.2	12.6	8.1	605.9
Jet Fuel				2,626.3	NA	98.9	2,725.2				189.7		7.1	196.8
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	372.1	13.7		7.0	1,061.2	32.5	8.8	23.0	0.8		0.4	65.6
Lubricants														
Motor Gasoline		3.8	30.3	16,208.0		187.8	16,429.9		0.3	2.1	1,149.4		13.3	1,165.2
Residual Fuel		69.9	146.7	159.5	1,002.8	228.4	1,607.2		5.2	11.0	12.0	75.3	17.2	120.7
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			131.6				131.6			9.2				9.2
Petroleum Coke		0.2	683.3		103.2		786.7		0.0	69.8		10.5		80.3
Still Gas			1,417.3				1,417.3			94.6				94.6
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)	**6,365.9**	**3,914.5**	**13,227.1**	**25,111.8**	**26,395.0**	**659.0**	**75,673.3**	**362.2**	**225.0**	**843.0**	**1,789.4**	**2,257.9**	**47.8**	**5,525.2**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-26: 2000 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu)[a]							Emissions[b] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**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				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**	**3,251.5**	**8,656.0**	**672.0**	**5,293.4**	**12.7**	**22,990.2**	**270.7**	**172.5**	**459.1**	**35.6**	**280.8**	**0.7**	**1,219.4**
Total Petroleum	**1,429.5**	**695.0**	**3,577.9**	**24,659.5**	**1,144.1**	**471.8**	**31,977.9**	**99.0**	**49.7**	**267.7**	**1,769.8**	**88.4**	**34.2**	**2,308.8**
Asphalt & Road Oil														
Aviation Gasoline				36.3			36.3				2.5			2.5
Distillate Fuel Oil	780.0	423.3	1,006.4	5,436.7	174.7	71.3	7,892.3	57.7	31.3	74.4	402.1	12.9	5.3	583.7
Jet Fuel				2,700.3	NA	74.1	2,774.3				195.0		5.3	200.4
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	468.7	11.9		8.0	1,193.9	34.4	9.3	29.0	0.7		0.5	74.0
Lubricants														
Motor Gasoline				16,030.9		185.2	16,216.1				1,136.2		13.1	1,149.3
Residual Fuel		91.6	184.1	443.5	870.8	130.9	1,720.8		6.9	13.8	33.3	65.4	9.8	129.2
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			171.6				171.6			12.0				12.0
Petroleum Coke		0.2	697.6		98.6		796.4		0.0	71.2		10.1		81.3
Still Gas			1,431.2				1,431.2			95.5				95.5
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)	**6,545.4**	**4,038.5**	**13,582.7**	**25,331.5**	**26,705.8**	**494.7**	**76,698.6**	**370.8**	**230.9**	**854.1**	**1,805.5**	**2,296.9**	**35.9**	**5,594.0**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-27: 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] (MMT 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				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**	**8,424.6**	**675.3**	**4,902.1**		**21,952.0**	**256.3**	**165.1**	**446.6**	**35.8**	**259.9**		**1,163.8**
Total Petroleum	**1,344.0**	**614.9**	**3,580.6**	**24,062.3**	**1,211.2**	**461.1**	**31,274.1**	**92.9**	**43.8**	**269.4**	**1,725.3**	**93.8**	**33.5**	**2,258.9**
Asphalt & Road Oil														
Aviation Gasoline				39.2			39.2				2.7			2.7
Distillate Fuel Oil	706.9	374.4	986.1	5,245.8	140.0	79.4	7,532.5	52.3	27.7	72.9	388.0	10.4	5.9	557.1
Jet Fuel				2,664.8	NA	59.5	2,724.4				192.5		4.3	196.8
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				15,922.5		164.1	16,086.6				1,128.0		11.6	1,139.7
Residual Fuel		73.3	150.9	175.7	958.7	146.0	1,504.6		5.5	11.3	13.2	72.0	11.0	113.0
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			182.5				182.5			12.8				12.8
Petroleum Coke		0.1	719.8		112.5		832.4		0.0	73.5		11.5		85.0
Still Gas			1,414.1				1,414.1			94.3				94.3
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)	**6,192.9**	**3,832.5**	**13,378.0**	**24,737.6**	**25,443.4**	**471.3**	**74,055.7**	**350.6**	**218.8**	**845.9**	**1,761.1**	**2,190.5**	**34.5**	**5,401.3**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-28: 1998 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu)[a]							Emissions[b] (MMT CO_2 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				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**	**8,826.0**	**666.1**	**4,674.9**		**21,896.1**	**246.0**	**163.3**	**467.4**	**35.3**	**247.6**		**1,159.5**
Total Petroleum	**1,209.0**	**610.1**	**3,473.3**	**23,285.5**	**1,306.1**	**445.5**	**30,329.5**	**84.1**	**43.7**	**262.6**	**1,671.4**	**101.3**	**32.5**	**2,195.6**
Asphalt & Road Oil														
Aviation Gasoline				35.5			35.5				2.5			2.5
Distillate Fuel Oil	676.8	376.0	1,030.5	4,949.9	135.6	71.9	7,240.7	50.1	27.8	76.2	366.1	10.0	5.3	535.5
Jet Fuel				2,608.0	NA	59.9	2,667.8				188.4		4.3	192.7
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				15,595.6		160.4	15,756.0				1,107.5		11.4	1,118.9
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			147.0				147.0			10.3				10.3
Petroleum Coke		0.1	707.7		123.6		831.4		0.0	72.3		12.6		84.9
Still Gas			1,431.0				1,431.0			95.5				95.5
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)	**5,866.6**	**3,786.5**	**13,770.1**	**23,951.6**	**25,247.1**	**456.1**	**73,078.0**	**331.2**	**215.9**	**869.1**	**1,706.6**	**2,177.4**	**33.4**	**5,333.7**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-29: 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] (MMT 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**	**1,457.6**	**NE**	**18,904.5**	**10.4**	**20,518.0**	**1.5**	**12.3**	**137.6**	**NE**	**1,797.0**	**1.0**	**1,949.5**
Residential Coal	16.0						16.0	1.5						1.5
Commercial Coal		129.4					129.4		12.3					12.3
Industrial Other Coal			1,457.6				1,457.6			137.6				137.6
Transportation Coal				NE			NE				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**	**9,032.5**	**780.3**	**4,125.5**		**22,316.6**	**270.1**	**174.2**	**479.0**	**41.4**	**218.8**		**1,183.4**
Total Petroleum	**1,335.0**	**655.9**	**3,898.2**	**22,698.3**	**926.7**	**445.4**	**29,959.4**	**93.1**	**47.1**	**290.2**	**1,628.8**	**72.2**	**32.4**	**2,163.9**
Asphalt & Road Oil														
Aviation Gasoline				39.7			39.7				2.7			2.7
Distillate Fuel Oil	787.3	399.6	1,059.3	4,797.9	110.5	81.6	7,236.3	58.2	29.6	78.3	354.8	8.2	6.0	535.2
Jet Fuel				2,553.8	NA	62.1	2,615.9				184.4		4.5	188.9
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				15,156.2		160.1	15,316.2				1,075.6		11.4	1,087.0
Residual Fuel		111.2	240.1	136.5	714.6	131.1	1,333.5		8.4	18.0	10.3	53.7	9.8	100.1
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			164.5				164.5			11.5				11.5
Petroleum Coke		0.1	639.9		101.6		741.6		0.0	65.3		10.4		75.7
Still Gas			1,435.0				1,435.0			95.7				95.7
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)	**6,443.9**	**4,070.6**	**14,388.4**	**23,478.6**	**24,007.0**	**455.8**	**72,844.3**	**364.7**	**233.6**	**906.8**	**1,670.1**	**2,088.4**	**33.4**	**5,297.1**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-30: 1996 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu)[a]							Emissions[b] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**16.6**	**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				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**	**9,020.3**	**736.9**	**3,862.4**		**22,200.4**	**283.9**	**171.1**	**478.3**	**39.1**	**204.8**		**1,177.2**
Total Petroleum	**1,398.0**	**719.1**	**3,914.4**	**22,506.2**	**817.3**	**434.7**	**29,789.7**	**97.6**	**51.8**	**291.7**	**1,615.2**	**63.4**	**31.6**	**2,151.3**
Asphalt & Road Oil														
Aviation Gasoline				37.4			37.4				2.6			2.6
Distillate Fuel Oil	840.5	438.3	1,050.9	4,594.9	109.3	76.5	7,110.4	62.2	32.4	77.7	339.8	8.1	5.7	525.9
Jet Fuel				2,556.0	NA	78.5	2,634.5				184.6		5.7	190.3
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				14,987.5		151.4	15,138.9				1,063.6		10.7	1,074.4
Residual Fuel		137.2	284.7	314.9	628.4	118.0	1,483.1		10.3	21.4	23.6	47.2	8.9	111.4
Other Petroleum														
AvGas Blend Components			7.0				7.0			0.5				0.5
Crude Oil			13.7				13.7			1.0				1.0
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			177.5				177.5			12.4				12.4
Petroleum Coke		0.1	638.6		79.6		718.3		0.0	65.2		8.1		73.3
Still Gas			1,434.9				1,434.9			95.7				95.7
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)	**6,769.0**	**4,067.0**	**14,389.7**	**23,243.1**	**23,157.6**	**445.0**	**72,071.4**	**383.1**	**234.5**	**907.4**	**1,654.3**	**2,021.0**	**32.6**	**5,232.8**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-31: 1995 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu)[a]							Emissions[b] (MMT 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			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**	**8,722.5**	**724.0**	**4,302.0**		**21,798.6**	**262.7**	**164.2**	**462.5**	**38.4**	**228.1**		**1,155.9**
Total Petroleum	**1,262.3**	**695.0**	**3,542.8**	**21,939.9**	**754.5**	**461.9**	**28,656.3**	**88.5**	**50.2**	**263.6**	**1,571.5**	**58.7**	**33.6**	**2,066.0**
Asphalt & Road Oil														
Aviation Gasoline				39.6			39.6				2.7			2.7
Distillate Fuel Oil	793.2	419.8	969.7	4,379.4	108.0	89.5	6,759.5	58.7	31.0	71.7	323.9	8.0	6.6	499.9
Jet Fuel				2,428.8	NA	75.7	2,504.5				172.2		5.4	177.6
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		2.7	30.1	14,687.1		146.8	14,866.6		0.2	2.1	1,042.4		10.4	1,055.2
Residual Fuel		141.5	286.2	387.3	566.0	140.7	1,521.6		10.6	21.5	29.1	42.5	10.6	114.3
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			169.0				169.0			11.8				11.8
Petroleum Coke		0.1	600.7		80.6		681.4		0.0	61.3		8.2		69.6
Still Gas			1,369.5				1,369.5			91.4				91.4
Special Naphtha														
Unfinished Oils			(320.9)				(320.9)			(23.8)				(23.8)
Waxes														
Geothermal					**45.6**		**45.6**					**0.3**		**0.3**
Total Coal	**6,233.9**	**3,907.8**	**13,792.3**	**22,663.8**	**22,568.4**	**472.1**	**69,638.3**	**352.8**	**225.6**	**870.5**	**1,609.9**	**1,947.9**	**34.5**	**5,041.2**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-32: 1994 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu)[a]							Emissions[b] (MMT 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				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**	**8,290.3**	**708.5**	**3,977.3**	**-**	**20,897.9**	**262.9**	**157.0**	**439.4**	**37.6**	**210.8**		**1,107.6**
Total Petroleum	**1,306.7**	**746.7**	**3,699.5**	**21,494.2**	**1,058.7**	**506.3**	**28,812.1**	**91.9**	**54.1**	**274.7**	**1,539.4**	**81.2**	**36.9**	**2,078.3**
Asphalt & Road Oil														
Aviation Gasoline				38.1			38.1				2.6			2.6
Distillate Fuel Oil	858.1	447.9	977.4	4,183.3	120.0	118.8	6,705.4	63.5	33.1	72.3	309.4	8.9	8.8	495.9
Jet Fuel				2,473.8	NA	65.8	2,539.5				175.5		4.7	180.2
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				14,407.0		147.4	14,554.4				1,022.9		10.5	1,033.4
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			169.4				169.4			11.9				11.9
Petroleum Coke		0.1	594.9		69.7		664.7		0.0	60.7		7.1		67.9
Still Gas			1,404.0				1,404.0			93.7				93.7
Special Naphtha														
Unfinished Oils			(279.2)				(279.2)			(20.7)				(20.7)
Waxes														
Geothermal					**53.0**		**53.0**					**0.4**		**0.4**
Total Coal	**6,287.4**	**3,826.8**	**13,584.7**	**22,202.8**	**22,349.9**	**516.3**	**68,767.8**	**356.8**	**222.4**	**864.8**	**1,577.0**	**1,931.2**	**37.8**	**4,990.0**

NE (Not Estimated)

NA (Not Available)

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).

[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.

Table A-33: 1993 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu)[a]							Emissions[b] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**25.7**	**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			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**	**8,272.5**	**644.7**	**3,537.5**		**20,441.3**	**268.4**	**155.0**	**438.6**	**34.2**	**187.5**		**1,083.7**
Total Petroleum	**1,348.5**	**743.4**	**3,588.7**	**20,866.3**	**1,123.8**	**459.4**	**28,129.9**	**94.9**	**53.8**	**267.4**	**1,498.2**	**86.4**	**33.6**	**2,034.3**
Asphalt & Road Oil														
Aviation Gasoline				38.4			38.4				2.7			2.7
Distillate Fuel Oil	883.3	447.2	989.9	3,889.4	86.5	104.9	6,401.1	65.3	33.1	73.2	287.6	6.4	7.8	473.4
Jet Fuel				2,368.4	NA	62.1	2,430.5				168.2		4.4	172.6
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				14,182.3		127.8	14,310.1				1,010.9		9.1	1,020.0
Residual Fuel		172.7	382.9	367.5	958.6	155.9	2,037.7		13.0	28.8	27.6	72.0	11.7	153.0
Other Petroleum														
AvGas Blend Components			0.2				0.2			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			166.1				166.1			11.6				11.6
Petroleum Coke		0.2	614.6		78.6		693.4		0.0	62.8		8.0		70.8
Still Gas			1,384.6				1,384.6			92.4				92.4
Special Naphtha														
Unfinished Oils			(396.0)				(396.0)			(29.3)				(29.3)
Waxes														
Geothermal					**57.3**		**57.3**					**0.4**		**0.4**
Total Coal	**6,437.5**	**3,783.9**	**13,446.1**	**21,511.0**	**21,914.5**	**469.0**	**67,562.0**	**365.8**	**220.1**	**855.7**	**1,532.4**	**1,906.9**	**34.4**	**4,915.3**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-34: 1992 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu)[a]							Emissions[b] (MMT 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**	**1,554.6**	**NE**	**16,465.6**	**8.8**	**18,171.1**	**2.5**	**11.3**	**147.4**	**NE**	**1,569.6**	**0.8**	**1,731.6**
Residential Coal	25.6						25.6	2.5						2.5
Commercial Coal		116.6					116.6		11.3					11.3
Industrial Other Coal			1,554.6				1,554.6			147.4				147.4
Transportation Coal				NE			NE				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**	**8,125.3**	**608.1**	**3,511.5**		**19,920.7**	**254.5**	**152.1**	**430.5**	**32.2**	**186.0**		**1,055.4**
Total Petroleum	**1,365.8**	**788.9**	**3,759.2**	**20,361.3**	**990.7**	**444.9**	**27,710.8**	**96.5**	**57.3**	**279.5**	**1,464.6**	**75.5**	**32.5**	**2,005.9**
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	6,272.6	68.9	35.6	76.1	271.1	5.4	6.8	463.9
Jet Fuel				2,343.8	NA	61.3	2,405.1				166.6		4.4	171.0
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				13,891.2		122.1	14,013.3				992.8		8.7	1,001.5
Residual Fuel		189.1	323.9	400.1	872.2	154.6	1,939.8		14.2	24.3	30.0	65.5	11.6	145.7
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			161.3				161.3			11.3				11.3
Petroleum Coke		0.1	627.2		45.0		672.2		0.0	64.0		4.6		68.6
Still Gas			1,418.4				1,418.4			94.6				94.6
Special Naphtha														
Unfinished Oils			(354.8)				(354.8)			(26.3)				(26.3)
Waxes														
Geothermal					**55.1**		**55.1**					**0.4**		**0.4**
Total Coal	**6,196.0**	**3,776.7**	**13,439.1**	**20,969.4**	**21,022.9**	**453.7**	**65,857.7**	**353.5**	**220.6**	**857.4**	**1,496.9**	**1,831.5**	**33.3**	**4,793.2**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-35: 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
	Adjusted Consumption (TBtu)[a]							Emissions[b] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**25.4**	**115.5**	**1,602.7**	**NE**	**16,249.7**	**7.7**	**18,001.0**	**2.4**	**11.1**	**152.1**	**NE**	**1,548.2**	**0.7**	**1,714.6**
Residential Coal	25.4						25.4	2.4						2.4
Commercial Coal		115.5					115.5		11.1					11.1
Industrial Other Coal			1,602.7				1,602.7			152.1				152.1
Transportation Coal				NE			NE				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**	**7,827.8**	**620.3**	**3,377.4**		**19,288.1**	**247.3**	**148.1**	**414.7**	**32.9**	**178.9**		**1,021.8**
Total Petroleum	**1,381.5**	**881.8**	**3,430.9**	**19,715.8**	**1,198.3**	**425.4**	**27,033.6**	**97.5**	**64.0**	**255.7**	**1,414.7**	**90.7**	**30.9**	**1,953.5**
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				2,373.6	NA	78.2	2,451.8				168.8		5.6	174.4
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		31.8	72.3	13,605.3		124.7	13,834.1		2.3	5.2	969.7		8.9	986.0
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			39.0				39.0			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			147.0				147.0			10.3				10.3
Petroleum Coke			587.6		29.3		616.9			60.0		3.0		63.0
Still Gas			1,385.9				1,385.9			92.5				92.5
Special Naphtha														
Unfinished Oils			(450.2)				(450.2)			(33.3)				(33.3)
Waxes														
Geothermal					**54.5**		**54.5**					**0.4**		**0.4**
Total Coal	**6,074.0**	**3,792.7**	**12,861.4**	**20,336.1**	**20,879.8**	**433.2**	**64,377.2**	**347.2**	**223.3**	**822.5**	**1,447.6**	**1,818.2**	**31.6**	**4,690.3**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-36: 1990 Energy Consumption Data and CO_2 Emissions from Fossil Fuel Combustion by Fuel Type

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu)[a]							Emissions[b] (MMT CO_2 Eq.) from Energy Use						
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**
Total Coal	**31.1**	**124.5**	**1,640.5**	**NE**	**16,261.0**	**7.0**	**18,064.0**	**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			1,640.5				1,640.5			155.3				**155.3**
Transportation Coal				NE			NE				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**	**7,716.4**	**679.9**	**3,308.5**		**18,877.9**	**238.0**	**142.1**	**408.9**	**36.0**	**175.3**		**1,000.3**
Total Petroleum	**1,375.2**	**869.4**	**3,743.8**	**20,323.1**	**1,289.4**	**374.8**	**27,975.7**	**97.4**	**63.3**	**278.3**	**1,457.7**	**97.5**	**27.2**	**2,021.5**
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				2,590.1	NA	61.0	2,651.1				184.2		4.3	188.6
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				13,810.1		101.0	13,911.1				983.5		7.2	990.7
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			125.2				125.2			8.8				8.8
Petroleum Coke			591.2		30.4		621.5			60.4		3.1		63.5
Still Gas			1,436.5				1,436.5			95.8				95.8
Special Naphtha														
Unfinished Oils			(369.0)				(369.0)			(27.3)				(27.3)
Waxes														
Geothermal					**52.7**		**52.7**					**0.4**		**0.4**
Total Coal	**5,897.2**	**3,676.0**	**13,100.6**	**21,003.0**	**20,911.6**	**381.9**	**64,970.3**	**338.3**	**217.4**	**842.5**	**1,493.8**	**1,820.8**	**27.9**	**4,740.7**

NE (Not Estimated)
NA (Not Available)
[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-37), and international bunker fuel consumption (see Table A-38).
[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.
Note: Parentheses indicate negative values.

Table A-37: Unadjusted Non-Energy Fuel Consumption (TBtu)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Industry	**4,544.0**	**5,089.7**	**5,576.5**	**5,263.7**	**5,425.7**	**5,342.9**	**5,847.2**	**5,483.3**	**5,470.0**	**5,225.2**	**4,769.7**	**4,510.2**	**4,753.0**	**4,665.0**	**4,611.3**	**4,823.4**	**4,725.1**	**4,915.5**
Industrial Coking Coal	0.0	37.8	53.5	24.8	40.3	51.9	167.8	80.4	62.9	2.3	29.2	6.4	64.8	60.8	132.5	119.3	48.2	121.4
Industrial Other Coal	8.2	11.3	12.4	11.3	12.0	11.9	11.9	11.9	11.9	11.9	11.9	11.9	10.3	10.3	10.3	10.3	10.3	10.3
Natural Gas to Chemical Plants, Other Uses	305.9	371.0	401.7	391.8	380.7	345.3	306.6	270.4	233.4	233.6	233.6	233.6	311.8	311.8	311.8	311.8	311.8	311.8
Asphalt & Road Oil	1,170.2	1,178.2	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	877.8	859.5	826.7	783.3	792.6	831.7
LPG	1,201.4	1,586.9	1,759.3	1,642.3	1,766.3	1,701.6	1,768.5	1,659.5	1,734.6	1,726.7	1,596.6	1,748.0	1,901.6	1,943.4	1,990.5	2,149.0	2,148.7	2,215.1
Lubricants	186.3	177.8	189.9	174.0	171.9	159.0	161.0	160.2	156.1	161.2	149.6	134.5	149.5	141.8	130.5	138.1	144.0	156.8
Pentanes Plus	125.2	169.0	171.6	131.6	111.9	110.4	111.2	98.1	70.1	89.7	76.5	63.8	77.7	27.3	42.2	47.1	44.2	80.2
Naphtha (<401 deg. F)	347.8	373.0	613.5	493.7	582.6	613.0	749.4	698.7	628.9	562.5	477.2	471.9	490.6	487.3	453.9	517.8	442.6	428.1
Other Oil (>401 deg. F)	753.9	801.0	722.2	662.5	632.1	699.4	779.5	708.0	790.6	744.1	647.8	424.8	452.5	388.5	287.2	223.9	247.2	229.0
Still Gas	36.7	47.9	17.0	49.3	61.7	59.0	62.9	67.7	57.2	44.2	47.3	133.9	147.8	163.6	160.6	166.7	164.6	162.2
Petroleum Coke	123.1	120.6	98.5	174.3	145.8	122.8	217.7	186.9	213.6	201.2	224.5	180.7	61.0	62.4	67.6	62.4	61.4	62.5
Special Naphtha	107.1	70.8	97.4	78.5	102.4	80.5	51.0	62.5	70.1	78.0	84.9	46.2	26.1	22.6	14.7	100.0	106.1	99.3
Other (Wax/Misc.)																		
Distillate Fuel Oil	7.0	6.8	11.7	11.7	11.7	11.7	11.7	11.7	17.5	17.5	17.5	17.5	5.8	5.8	5.8	5.8	5.8	5.8
Waxes	33.3	40.6	33.1	36.3	32.2	31.1	30.8	31.4	26.2	21.9	19.1	12.2	17.1	15.1	15.3	16.5	14.8	12.4
Miscellaneous Products	137.8	97.1	119.2	124.9	134.2	126.0	113.4	112.8	136.0	133.5	142.0	151.8	158.7	164.7	161.6	171.2	182.7	188.9
Transportation	**176.0**	**167.9**	**179.4**	**164.3**	**162.4**	**150.1**	**152.1**	**151.3**	**147.4**	**152.2**	**141.3**	**127.1**	**141.2**	**133.9**	**123.2**	**130.4**	**136.0**	**148.1**
Lubricants	176.0	167.9	179.4	164.3	162.4	150.1	152.1	151.3	147.4	152.2	141.3	127.1	141.2	133.9	123.2	130.4	136.0	148.1
U.S. Territories	**86.7**	**90.8**	**152.2**	**80.3**	**140.2**	**123.5**	**110.8**	**121.9**	**133.4**	**108.4**	**132.1**	**59.6**	**56.4**	**56.7**	**58.1**	**57.4**	**53.6**	**53.6**
Lubricants	0.7	2.0	3.1	0.0	3.0	4.9	5.1	4.6	6.2	5.9	2.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Other Petroleum (Misc. Prod.)	86.0	88.8	149.1	80.3	137.2	118.6	105.7	117.3	127.2	102.5	129.4	58.5	55.4	55.7	57.1	56.4	52.6	52.6
Total	**4,806.7**	**5,348.5**	**5,908.0**	**5,508.4**	**5,728.3**	**5,616.5**	**6,110.1**	**5,756.6**	**5,750.8**	**5,485.9**	**5,043.0**	**4,696.8**	**4,950.6**	**4,855.7**	**4,792.7**	**5,011.2**	**4,914.7**	**5,117.2**

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 and Product Use Chapter.

Table A-38: International Bunker Fuel Consumption (TBtu)

Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Marine Residual Fuel Oil	715.7	523.2	444.1	426.0	448.9	471.8	553.1	581.0	599.4	607.5	654.6	604.8	619.8	518.4	459.5	379.8	369.2	406.8
Marine Distillate Fuel Oil & Other	158.0	125.7	85.9	72.4	82.6	103.9	143.6	126.9	119.3	111.3	122.2	111.0	128.2	107.4	91.7	75.4	82.0	113.5
Aviation Jet Fuel	539.4	703.4	880.1	799.7	774.8	783.0	797.7	853.1	855.6	872.7	796.8	749.1	865.4	919.9	916.3	931.6	985.1	1,020.4
Total	**1,413.1**	**1,352.3**	**1,410.0**	**1,298.1**	**1,306.3**	**1,358.7**	**1,494.4**	**1,561.0**	**1,574.2**	**1,591.5**	**1,573.6**	**1,464.9**	**1,613.4**	**1,545.7**	**1,467.4**	**1,386.9**	**1,436.3**	**1,540.7**

Note: Further information on the calculation of international bunker fuel consumption of aviation jet fuel is provided in Annex 3.3: Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption.

Table A-39: Key Assumptions for Estimating CO_2 Emissions

Fuel Type	C Content Coefficient (MMT C/QBtu)
Coal	
Residential Coal	[c]
Commercial Coal	[c]
Industrial Coking Coal	[c]
Industrial Other Coal	[c]
Electric Power Coal	[c]
U.S. Territory Coal (bit)	25.14
Pipeline Natural Gas	
Flare Gas[a]	14.92
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	[c]
Kerosene	19.96
LPG (energy use)	[c]
LPG (non-energy use)	[c]
Lubricants	20.20
Motor Gasoline	[c]
Residual Fuel Oil No. 5	19.89
Residual Fuel Oil No. 6[b]	20.48
Other Petroleum	
AvGas Blend Components	18.87
Crude Oil	[c]
MoGas Blend Components	[c]
Misc. Products	[c]
Misc. Products (Territories)	20.00
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	[c]
Waxes	19.80
Geothermal	**2.05**

[c] These coefficients vary annually due to fluctuations in fuel quality (see Table A-40).

[a] Flare gas is not used in the CO_2 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 CO_2 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).

Table A-40: Annually Variable C Content Coefficients by Year (MMT C/QBtu)

Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Residential Coal	26.20	26.13	26.01	26.00	25.98	26.04	25.91	26.09	26.29	25.94	25.71[a]	25.71[a]	25.71[a]	25.71[a]	25.71[a]	25.71[a]	25.71[a]	25.71[a]
Commercial Coal	26.00	26.13	26.01	26.00	25.98	26.04	25.91	26.09	26.29	25.94	25.71	25.71	25.71	25.71	25.71	25.71	25.71	25.71
Industrial Coking Coal	31.00	31.00	31.00	31.00	31.00	31.00	31.00	31.00	31.00	31.00	31.00	31.00	31.00	31.00	31.00	31.00	31.00	31.00
Industrial Other Coal	25.82	25.80	25.74	25.66	25.57	25.55	25.56	25.80	25.84	25.82	25.82	25.82	25.82	25.82	25.82	25.82	25.82	25.82
Electric Power Coal	25.96	25.93	26.00	26.00	26.05	26.09	26.10	26.09	26.04	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05
Pipeline Natural Gas	14.45	14.46	14.47	14.46	14.46	14.44	14.46	14.46	14.46	14.46	14.46	14.46	14.46	14.46	14.46	14.46	14.46	14.46
LPG (energy use)	16.86	16.82	16.89	16.87	16.85	16.86	16.84	16.84	16.83	16.82	16.83	16.83	16.83	16.83	16.83	16.83	16.83	16.83
LPG (non-energy use)	17.06	17.09	17.09	17.10	17.09	17.09	17.07	17.06	17.06	17.05	17.06	17.06	17.06	17.06	17.06	17.06	17.06	17.06
Motor Gasoline	19.42	19.36	19.33	19.34	19.38	19.36	19.38	19.36	19.45	19.56	19.46	19.46	19.46	19.46	19.46	19.46	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	19.70	19.70
MoGas Blend Components	19.42	19.36	19.33	19.34	19.38	19.36	19.38	19.36	19.45	19.56	19.46	19.46	19.46	19.46	19.46	19.46	19.46	19.46
Misc. Products	20.15	20.21	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31
Unfinished Oils	20.15	20.21	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31
Crude Oil	20.15	20.21	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31

[a] 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-41: Electricity Consumption by End-Use Sector (Billion Kilowatt-Hours)

End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Residential	924	1,043	1,192	1,202	1,265	1,276	1,292	1,359	1,352	1,392	1,381	1,365	1,446	1,423	1,375	1,395	1,407	1,400
Commercial	838	953	1,159	1,191	1,205	1,199	1,230	1,275	1,300	1,336	1,336	1,307	1,330	1,328	1,327	1,337	1,352	1,358
Industrial	1,070	1,163	1,235	1,159	1,156	1,181	1,186	1,169	1,158	1,154	1,142	1,044	1,103	1,124	1,123	1,129	1,136	1,097
Transportation	5	5	5	6	6	7	7	8	7	8	8	8	8	8	7	8	8	8
Total	**2,837**	**3,164**	**3,592**	**3,557**	**3,632**	**3,662**	**3,716**	**3,811**	**3,817**	**3,890**	**3,866**	**3,724**	**3,887**	**3,883**	**3,832**	**3,868**	**3,903**	**3,863**

Note: Does not include the U.S. Territories.

Source: EIA (2016).

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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 (CO_2) 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-42.

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., million metric tons C per quadrillion Btu or MMT C/QBtu), those fuels that are typically described in volumetric units (i.e., 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-quarter 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-42: Carbon Content Coefficients Used in this Report (MMT Carbon/QBtu)

Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Coal																		
Residential Coal[a]	26.20	26.13	26.01	26.00	25.98	26.04	25.91	26.09	26.29	25.94	25.71[b]	25.71[b]	25.71[b]	25.71[b]	25.71[b]	25.71[b]	25.71[b]	25.71[b]
Commercial Coal[a]	26.20	26.13	26.01	26.00	25.98	26.04	25.91	26.09	26.29	25.94	25.71	25.71	25.71	25.71	25.71	25.71	25.71	25.71
Industrial Coking Coal[a]	25.53	25.57	25.63	25.63	25.65	25.63	25.63	25.60	25.60	25.61	25.61	25.61	25.61	25.61	25.61	25.61	25.61	25.61
Industrial Other Coal[a]	25.82	25.80	25.74	25.66	25.57	25.55	25.56	25.80	25.84	25.82	25.82	25.82	25.82	25.82	25.82	25.82	25.82	25.82
Utility Coal[a,c]	25.96	25.93	26.00	26.00	26.05	26.09	26.10	26.09	26.04	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05
Pipeline Natural Gas[d]	**14.45**	**14.46**	**14.47**	**14.46**	**14.46**	**14.44**	**14.46**	**14.46**	**14.46**	**14.46**	**14.46**	**14.46**	**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**	**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	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	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	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	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	20.47	20.47
Jet Fuel[a]	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	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	19.96	19.96
LPG (energy use)[d]	16.86	16.82	16.89	16.87	16.85	16.86	16.84	16.84	16.83	16.82	16.83	16.83	16.83	16.83	16.83	16.83	16.83	16.83
LPG (non-energy use)[d]	17.06	17.09	17.09	17.10	17.09	17.09	17.07	17.06	17.06	17.05	17.06	17.06	17.06	17.06	17.06	17.06	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	20.20	20.20
Motor Gasoline[d]	19.42	19.36	19.33	19.34	19.38	19.36	19.38	19.36	19.45	19.56	19.46	19.46	19.46	19.46	19.46	19.46	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	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	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	18.87	18.87
Mo. Gas Blend Comp[c]	19.42	19.36	19.33	19.34	19.38	19.36	19.38	19.36	19.45	19.56	19.46	19.46	19.46	19.46	19.46	19.46	19.46	19.46
Crude Oil[d]	20.15	20.21	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31
Misc. Products[d]	20.15	20.21	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31

Misc. Products (Terr.)	20.15	20.21	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31	20.31	20.31	20.31	20.31	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	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	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	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	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	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	19.74	19.74
Unfinished Oils[d]	20.15	20.21	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28	20.31	20.31	20.31	20.31	20.31	20.31	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	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	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**	**2.05**	**2.05**

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

[b] 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. .

[c] 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.

[d] C 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 (2006) 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-43.[9]

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

Carbon 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 MMT C/QBtu.

Step 2: Determine Weighted Average Carbon Content by State

Carbon 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[10] 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.[11] 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.

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

where,

C_{sector} = The C content by consuming 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.

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

[10] U.S. Energy Information Administration (EIA). *Coal Distribution – Annual* (2001-2009b); and *Coal Industry Annual* (1990-2001).

[11] 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-42 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.

Table A-43: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank (MMT C/QBtu) (1990-2015)

Consuming Sector	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Electric Power	25.96	25.93	26.00	26.00	26.05	26.09	26.10	26.09	26.04	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05
Industrial Coking	25.53	25.57	25.63	25.63	25.65	25.63	25.63	25.60	25.60	25.61	25.61	25.61	25.61	25.61	25.61	25.61	25.61	25.61
Other Industrial	25.82	25.80	25.74	25.66	25.57	25.55	25.56	25.80	25.84	25.82	25.82	25.82	25.82	25.82	25.82	25.82	25.82	25.82
Residential/ Commercial	26.20	26.13	26.01	26.00	25.98	26.04	25.91	26.09	26.29	25.94	25.71	25.71	25.71	25.71	25.71	25.71	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	28.28	28.28
Bituminous	25.38	25.42	25.45	25.46	25.46	25.45	25.45	25.45	25.45	25.45	25.44	25.44	25.44	25.44	25.44	25.44	25.44	25.44
Sub-bituminous	26.50	26.50	26.49	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50	26.50
Lignite	26.58	26.59	26.61	26.62	26.63	26.62	26.62	26.62	26.62	26.64	26.65	26.65	26.65	26.65	26.65	26.65	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 (2010).

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.

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

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* (EIA 2001 through 2009a) is the source for state coal production by rank from 2001 through 2008. In prior years, the EIA reported this data in its *Coal Industry Annual* (EIA 1990 through 2001). Data for coal consumption by state of origin and consuming sector for 2001 through 2008 was obtained from the EIA's *Coal Distribution – Annual* (EIA 2001 through 2009b). For 1990 through 2000, end-use data was obtained from the *Coal Industry Annual* (EIA 1990 through 2001).

Uncertainty – TO BE UPDATED FOR FINAL INVENTORY REPORT

Carbon 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,[12] 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-44).

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.

[12] 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 C emission factors as well as county-level factors. This study's rank-based national average factors have a maximum deviation from the factors developed in this Inventory report 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-44: 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**

Note: "-" 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 (CH_4), which is 75 percent C by weight and contains 14.2 MMT 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 CH_4 (which has only one), their presence increases the overall C content of natural gas. NGLs have a commercial value greater than that of CH_4, 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[13] contributes to the gasoline/naphtha "octane pool," used primarily to make motor gasoline.

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 CH_4, 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 CH_4, 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 1,037 Btu per cubic foot, and has varied by less than 2 percent (1,022 to 1,037 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

[13] 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.

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-45.

Table A-45: 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-46.

Table A-46: Carbon Content of Pipeline-Quality Natural Gas by CO_2 and Heat Content (MMT 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 (C) 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[14] for each of the sub-samples ranged from 0.79 for samples with less than 1.5 percent CO_2 and under 1,050 Btu/cf to 0.91 for samples containing less than 1.0 percent CO_2 only. However, the sub-sample with less than 1.5 percent 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:

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

This equation was used to estimate the annual predicted carbon content of natural gas from 1990 to 2010 based on the EIA's national average pipeline-quality gas heat content for each year. The table of average C contents for each year is shown below in Table A-47.

Table A-47: Carbon Content Coefficients for Natural Gas (MMT Carbon/QBtu)

Fuel Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Natural Gas	14.45	14.46	14.47	14.46	14.46	14.46	14.46	14.46	14.46	14.46	14.46	14.46	14.46	14.46

Source: EPA (2010).

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

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. The sample dataset did not include any samples with more than 1,130 Btu per cubic foot.

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 C content for the sample sub-set representing flare gas is shown below in Table A-48.

Table A-48: Carbon Content of Flare Gas (MMT C/QBtu)

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

Source: EPA (2010).

Data Sources

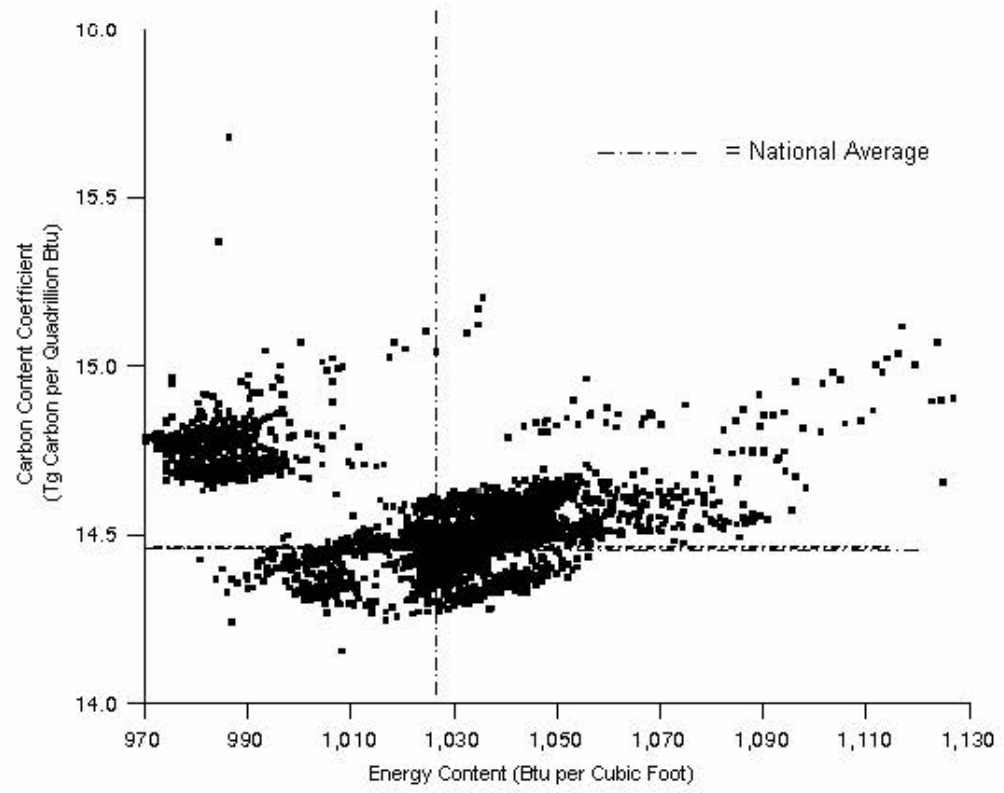
Natural gas samples were obtained from the Gas Technology Institute (1992). Average heat content data for natural gas consumed in the United States was taken from EIA (2009a).

Uncertainty – TO BE UPDATED FOR FINAL INVENTORY REPORT

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



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.

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 CH_4. 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 CO_2 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 MMT C/QBtu (see Table A-47). Additionally, a regression analysis using the full sample produced a predicted C content of 14.49 MMT C/QBtu based on a heat content of 1,029 Btu/cf (the average heat content in the United States 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 C content of 14.47 MMT 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
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[15] (dense products such as asphalt and road oil) and 247 degrees (ethane). 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 C. 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 C anodes.

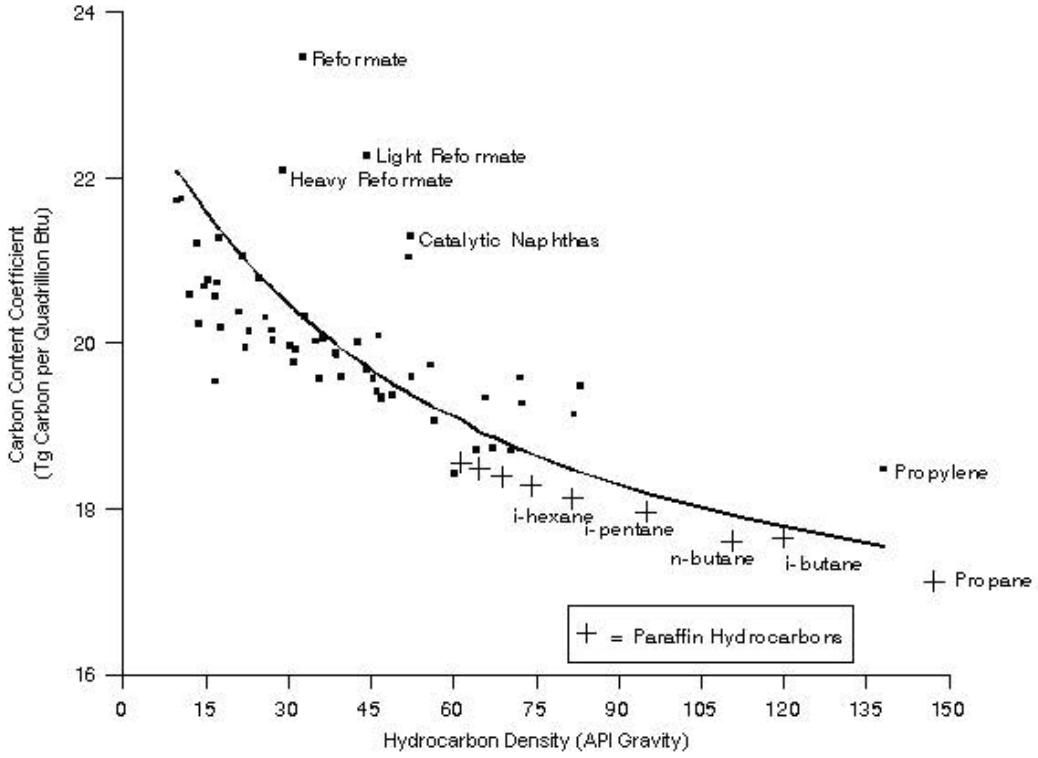
Petroleum Chemistry

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 denser, 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.

[15] 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.

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.

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.

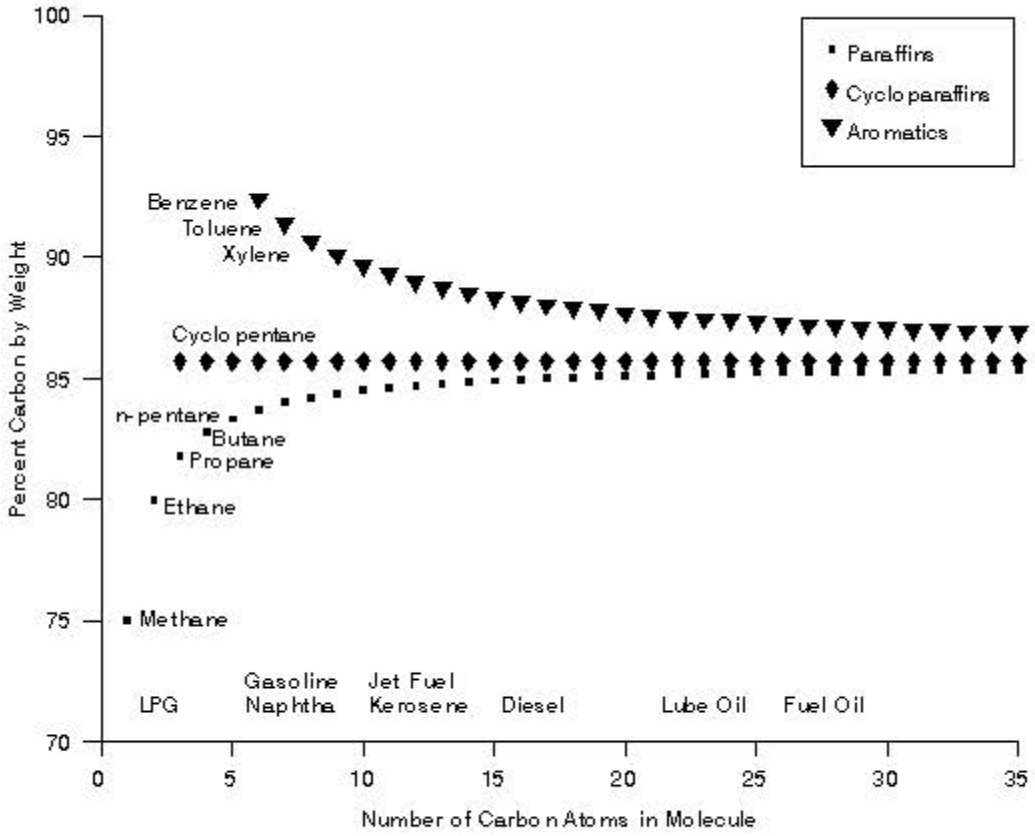
Olefins. Olefins are a very reactive and unstable form of paraffin: a straight chain with two carbon atoms double bonded together (thus are unsaturated) compared to the carbon atoms in a paraffin (which are saturated with hydrogen). They are never found in crude oil but are created in moderate quantities 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



Source: J.M. Hunt, *Petroleum Geochemistry and Geology* (San Francisco, CA, W.H. Freeman and Company, 1979), pp. 31-37.

If nothing is known 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 twenty separate petroleum products and product categories. The C contents, heat contents, and density for each product are provided below in Table A-49. A description of the methods and data sources for estimating the key parameters for each individual petroleum product appears below.

Table A-49: Carbon Content Coefficients and Underlying Data for Petroleum Products

Fuel	2008 Carbon Content (MMT 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)[a]	18.55	5.248	62.4	84.11
Other Oils (>400 deg. F)[a]	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-52.
[a] 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.
Note: "-" Indicates 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.[16] "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 through 2015 time period: regular, mid-grade and premium conventional gasoline (all years) and regular, mid-grade and premium reformulated gasoline (November 1994 to 2015). Leaded and oxygenated gasoline are not separately included in the data used for this report.[17]

[16] 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.

[17] 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.

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-50 reflects changes in the density of gasoline over time and across grades and formulations of gasoline through 2015.

Table A-50: Motor Gasoline Density, 1990 – 2015 (Degrees API)

Fuel Grade	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Conventional - Winter Grade																		
Low Octane	62.0	59.8	61.6	61.7	61.6	61.8	62.4	62.6	62.7	63.1	63.0	63.0	63.0	63.0	63.0	63.0	63.0	63.0
High Octane	59.0	58.0	59.7	59.1	59.0	59.9	60.7	60.9	60.0	60.3	60.9	60.9	60.9	60.9	60.9	60.9	60.9	60.9
Conventional - Summer Grade																		
Low Octane	58.2	56.1	56.8	57.2	56.5	56.8	57.4	57.9	57.8	57.5	58.6	58.6	58.6	58.6	58.6	58.6	58.6	58.6
High Octane	55.5	55.1	55.8	55.5	55.7	56.0	57.0	57.0	57.4	56.9	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0
Reformulated - Winter Grade																		
Low Octane	NA	61.9	62.7	62.6	61.9	62.1	62.7	62.8	62.3	62.1	62.4	62.4	62.4	62.4	62.4	62.4	62.4	62.4
High Octane	NA	59.9	61.1	61.0	61.8	61.9	61.8	61.8	61.7	62.1	62.5	62.5	62.5	62.5	62.5	62.5	62.5	62.5
Reformulated - Summer Grade																		
Low Octane	NA	58.5	58.4	58.8	58.2	59.1	58.1	58.4	58.7	58.5	59.1	59.1	59.1	59.1	59.1	59.1	59.1	59.1
High Octane	NA	56.7	58.3	58.2	58.0	58.7	58.9	58.1	59.0	59.3	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8

Notes: NA – Not Applicable, fuel type was not analyzed.
Source: National Institute of Petroleum and Energy Research (1990 through 2015).

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-51.

Table A-51: 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.[18] Ethanol, also called ethyl alcohol, is an anhydrous alcohol with molecular formula C_2H_5OH. Ethanol has a lower C 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

[18] 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.

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 percent hydrocarbons) and 90 percent gasoline, known as E10, is widely used in the United States 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.[19] 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,[20] 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,[21] the density of the constituent, share of the constituent[22] 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 the National Institute for Petroleum and Energy Research (NIPER) and the density of each constituent. The ether additives listed in Table A-51 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 C 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.

Data Sources

Data for the density of motor gasoline were derived from NIPER (1990 through 2015). Data on the characteristics of reformulated gasoline, including C share, were also taken from NIPER (1990 through 2015).

Standard heat contents for motor gasoline of 5.253 MMBtu per barrel conventional gasoline and 5.150 MMBtu per barrel reformulated gasoline[23] were adopted from EIA (2009a).

Uncertainty

The uncertainty underlying the C content coefficients for motor gasoline has three underlying sources: (1) the uncertainty in the averages published by NIPER, (2) 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 (3) 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 2015. 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

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

[20] "Ethanol Market Penetration." Alternative Fuels and Advanced Vehicles Data Center, U.S. DOE. Available at <http://www.afdc.energy.gov/afdc/ethanol/market.html>. Retrieved 2-19-2010.

[21] 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.

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

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

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 through 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 -63.0/+74.5 percent of the mean across the Winter 2007 through 2008 and -51.3/+49.6 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 -6.5/+6.4 percent for the same set of winter samples and -8.8/+15.7 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 C factors.

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 2015.

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 2015, 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 through 1995, 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 2015.

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 C content factors for 1996 onward.

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 No. 1 and No. 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 No. 1 and No. 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 No. 1 and No. 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 degrees 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, 15 ppm 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 United States, 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 No. 1, No. 2 and No. 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 No. 5 and No. 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 No. 5 and No. 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-52 summarizes the physical characteristic of LPG.

Table A-52: Physical Characteristics of Liquefied Petroleum Gases

Compound	Chemical Formula	Density (Barrels Per Metric Ton)	Carbon Content (Percent)	Energy Content (MMBtu/Barrel)	Carbon Content Coefficient (MMT 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-53.

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 Education. The energy content of each LPG is from the EPA (2009b). LPG consumption was based on data obtained from API (1990 through 2015) and EIA (2009b). Non-fuel use of LPG was obtained from API (1990 through 2015).

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-53: Consumption and Carbon Content Coefficients of Liquefied Petroleum Gases, 1990-2015

	1990	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Energy Consumption (QBtu)													
Fuel Use	**0.88**	**1.31**	**1.21**	**1.19**	**1.20**	**1.13**	**1.13**	**1.16**	**1.16**	**1.16**	**1.16**	**1.16**	**1.16**
Ethane	0.04	0.10	0.06	0.06	0.07	0.06	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Propane	0.77	1.07	1.08	1.07	1.09	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
Butane	0.06	0.07	0.05	0.05	0.05	0.05	0.03	0.05	0.05	0.05	0.05	0.05	0.05
Isobutane	0.01	0.06	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Non-Fuel Use	**1.35**	**1.90**	**1.70**	**1.74**	**1.78**	**1.67**	**1.80**	**1.96**	**1.96**	**1.96**	**1.96**	**1.96**	**1.96**
Ethane	0.71	1.04	0.91	0.98	1.03	0.95	1.12	1.22	1.22	1.22	1.22	1.22	1.22
Propane	0.51	0.65	0.63	0.63	0.64	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Butane	0.11	0.11	0.12	0.12	0.11	0.12	0.08	0.12	0.12	0.12	0.12	0.12	0.12

Isobutane	0.02		0.09		0.03	0.02	0.01	0.00	0.01	0.03	0.03	0.03	0.03	0.03	0.03
Carbon Content (MMT C/QBtu)															
Fuel Use	16.86		16.89		16.84	16.83	16.82	16.83	16.83	16.83	16.83	16.83	16.83	16.83	16.83
Non-Fuel Use	17.06		17.09		17.06	17.06	17.05	17.06	17.06	17.06	17.06	17.06	17.06	17.06	17.06

Sources: Fuel use of LPG based on data from EIA (2009b) and API (1990 through 2008). Non-fuel use of LPG from API (1990 through 2008). Volumes converted using the energy contents provided in Table A-52. 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 MMT 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 by-products, 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 (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-54 below shows the composition of those samples.

Table A-54: Composition, Energy Content, and Carbon Content Coefficient for Four Samples of Still Gas

Sample	Hydrogen (%)	Methane (%)	Ethane (%)	Propane (%)	Btu Per Cubic Foot	Carbon Content (MMT 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-54.

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 MMT C/QBtu.

Data Sources

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 MMT 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 MMT C/QBtu to 21.48 MMT 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 MMT 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 MMT C/QBtu used for distillate fuel No. 2 is also adopted for this portion of the petrochemical feedstocks category.

Data Sources

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.

Uncertainty

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 C 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 degrees 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 to 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.

Methodology

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 MMT C/QBtu.

Data Sources

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

Uncertainty

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 to 550 degrees Fahrenheit, whereas No. 1 oils typically boil over a range from 350 to 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 MMT 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: (1) Stoddard solvent, used in dry cleaning; (2) high flash point solvent, used as an industrial paint because of its slow evaporative characteristics; (3) odorless solvent, most often used for residential paints; and (4) 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 MMT 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-55, below.

Table A-55: Characteristics of Non-hexane Special Naphthas

Special Naphtha	Aromatic Content (Percent)	Density (Degrees API)	Carbon Share (Percent Mass)	Carbon Content (MMT 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 MMT 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 MMT 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.

Methodology

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.[24] 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 2015 crude oil quality data (30.21 degrees API and 1.47 percent sulfur) produces an estimated C content of 84.79 percent. Applying the

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

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 MMT C/QBtu.

Data Sources

Carbon 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).

Uncertainty

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

Original 1994 Analysis

A set of 5,426 coal samples from the EIA coal analysis file were used to develop C content estimates. The results from that sample set appear below in Table A-56. 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-56: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank, 1990 – 2000 (MMT 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
Bituminous	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37
Sub-bituminous	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 by 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).

2002 Update

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 (USGS) 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 through 2007 Inventory and are provided in Table A-58.

Table A-57: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank, 1990 – 2000 (MMT 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).

2007 Update

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-58 contains the annual coefficients that resulted from the 2007 analysis.

Table A-58: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank, 1990-2007 (MMT 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 MMT 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 MMT C/QBtu. The average C contents from the 1994 calculations are presented in Table A-59 below for comparison.

Table A-59: Carbon Content of Pipeline-Quality Natural Gas by Energy Content (MMT 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 C 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-60 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 (U.S. 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-49 above. Each of the C coefficients applied in the previous Inventory is provided below for comparison (Table A-60).

Table A-60: Carbon Content Coefficients and Underlying Data for Petroleum Products

Fuel	2007 Carbon Content (MMT 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)[a]	16.99	(See b)	(See b)	(See b)
LPG (energy use)	17.18	(See b)	(See b)	(See b)
LPG (non-energy use)	16.76	(See b)	(See b)	(See b)
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[c]	67.1[c]	84.11[c]
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	18.24	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-52.
[b] Heat, density, and percent carbon values are provided separately for ethane, propane and isobutene.
[c] 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.
Note: "-" Indicates no sample data available.
Sources: EIA (1994); EIA (2008a); SAIC (2007).

Additional revisions to the Inventory's C 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 MMT C/QBtu to 19.33 MMT 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.

1990 through 2008 Inventory Update

The coefficient was revised again for the 1990 through 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 United States. 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 MMT C/QBtu to 16.99 MMT 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-60).

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-61, below, compares the values applied for each of the compounds under the two sets of coefficient calculations. The C 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-61: Physical Characteristics of Liquefied Petroleum Gases

		1990-2007	Updated	1990-2007	Updated	1990-2007	Updated
Compound	Chemical Formula	Density (bbl / MT)	Density (bbl / MT)	Energy Content (MMBtu/bbl)	Energy Content (MMBtu/bbl)	C Content Coefficient (MMT C/QBtu)	C Content Coefficient (MMT 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 through 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-50), in the list and proportion of constituents that form the blend and in the blended C share based on those constituents.

Table A-62: Carbon Content Coefficients for Petroleum Products, 1990-2007 (MMT 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.

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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-63. 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, liquefied petroleum gases (LPG), pentanes plus, naphthas, other oils, still gas, special naphtha), asphalt and road oil, lubricants, waxes, and miscellaneous products. The storage factors[25] 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 non-energy use (NEU) products.

Table A-63: 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]	65%
Natural Gas to Chemical Plants[b]	65%
Asphalt & Road Oil	100%
LPG[b]	65%
Lubricants	9%
Pentanes Plus[b]	65%
Naphtha (<401 deg. F)[b]	65%
Other Oil (>401 deg. F)[b]	65%
Still Gas[b]	65%
Petroleum Coke[c]	30%
Special Naphtha[b]	65%
Distillate Fuel Oil	50%
Waxes	58%
Miscellaneous Products	0%
Transportation	
Lubricants	9%
U.S. Territories	
Lubricants	9%
Other Petroleum (Misc. Prod.)	10%

[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 and Product Use chapter.
[b] The storage factor listed is the value for 2015 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 and Product Use 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.

[25] 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.[26]

After adjustments for (1) use in industrial processes and (2) net exports, these eight fuel categories constituted approximately 219.4 MMT CO_2 Eq., or 65 percent, of the 337.7 MMT CO_2 Eq. of non-energy fuel consumption in 2015. For 2015, the storage factor for the eight fuel categories was 66 percent. In other words, of the net consumption, 66 percent was destined for long-term storage in products—including products subsequently combusted for waste disposal—while the remaining 34 percent was emitted to the atmosphere directly as CO_2 (e.g., through combustion of industrial by-products) 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 2015.

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 EIA

[26] Naphthas are compounds distilled from petroleum containing 4 to 12 carbon atoms per molecule and having a boiling point less than 401 degrees Fahrenheit. "Other oils" are distillates containing 12 to 25 carbon atoms per molecule and having a boiling point greater than 401 degrees Fahrenheit.

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[27] and cover a complete time series from 1990 to 2015. 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-64. As shown in the table, the United States has been a net exporter of chemical intermediates and products throughout the 1990 to 2015 period.

Table A-64: Net Exports of Petrochemical Feedstocks, 1990 – 2015 (MMT CO_2 Eq.)

	1990	2005	2011	2012	2013	2014	2015
Net Exports	12.0	6.5	8.0	10.1	8.4	3.7	5.4

After adjusting for imports and exports, the C budget is adjusted for the quantity of C that is used in the Industrial Processes and Product Use 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-64) 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). Carbon 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.[28]

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

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

[28] 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.

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. 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-65. Summing the C stored and dividing it by total C outputs yields the overall storage factor, as shown in the following equation for 2015:

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

$$143.7 \text{ MMT } CO_2 \text{ Eq.} / (143.7 + 59.5 + 16.1) \text{ MMT } CO_2 \text{ Eq.} = 66\%$$

Table A-65: C Stored and Emitted by Products from Feedstocks in 2015 (MMT CO_2 Eq.)

Product/Waste Type	C Stored (MMT CO_2 Eq.)	C Emitted (MMT CO_2 Eq.)
Industrial Releases	**0.1**	**6.1**
TRI Releases	0.1	1.0
Industrial VOCs	NA	4.1
Non-combustion CO	NA	0.6
Hazardous Waste Incin.	NA	0.4
Energy Recovery	**NA**	**40.6**
Products	**143.6**	**12.9**
Plastics	121.9	NA
Synthetic Rubber	13.7	NA
Antifreeze and deicers	NA	1.0
Abraded tire rubber	NA	0.3
Food additives	NA	1.1
Silicones	0.5	NA
Synthetic Fiber	7.3	NA
Pesticides	0.2	0.2
Soaps, shampoos, detergents	NA	4.8
Solvent VOCs	NA	5.5
Total	**143.7**	**59.5**

NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

The C unaccounted for is the difference between the C accounted for (discussed below) and the total C in the Total US Petrochemical consumption, which are the potential carbon emissions from all energy consumption in Non-Energy Use.

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 (TRI), industrial emissions of volatile organic compounds (VOCs), CO emissions (other than those related to fuel combustion), and emissions from hazardous waste incineration.

TRI Releases

Fossil-derived C is found in many toxic substances released by industrial facilities. The 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."[29] The C released in each disposal location is provided in Table A-66.

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 2015 time series were not readily available. Since this category is small (less than 1 MMT C emitted and stored), the 1998 value was applied for the entire time series.

Table A-66: 1998 TRI Releases by Disposal Location (kt CO_2 Eq.)

Disposal Location	Carbon Stored (kt CO_2 Eq.)	Carbon Emitted (kt CO_2 Eq.)
Air Emissions	NA	924.0
Surface Water Discharges	NA	6.7
Underground Injection	89.4	NA
RCRA Subtitle C Landfill Disposal	1.4	NA
Other On-Site Land Releases	NA	15.9
Off-site Releases	6.4	36.0
Total	**97.2**	**982.6**

NA (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 (EPA 2016) and disaggregated based on EPA (2003), which has been published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. The 1990 through 2015 Trends data include information on NMVOC emissions by end-use category; some of these fall into the heading of "industrial releases" in Table A-65 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 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

[29] Only the top nine 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 nine chemicals (i.e., 8 percent attributed to RCRA Landfills and 92 percent in the "Other" category).

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-67 for 1990 through 2015. Industrial NMVOC emissions in 2015 were 4.1 MMT CO_2 Eq. and solvent evaporation emissions in 2015 were 5.5 MMT CO_2 Eq.

Table A-67: Industrial and Solvent NMVOC Emissions

	1990	1995	2000	2005	2011	2012	2013	2014	2015
Industrial NMVOCs[a]									
NMVOCs ('000 Short Tons)	1,279	1,358	802	825	1,289	1,342	1,396	1,449	1,449
Carbon Content (%)	85%	85%	85%	85%	85%	85%	85%	85%	85%
Carbon Emitted (MMT CO_2 Eq.)	3.6	3.8	2.3	2.3	3.6	3.8	3.9	4.1	4.1
Solvent Evaporation[b]									
Solvents ('000 Short Tons)	5,750	6,183	4,832	4,245	2,811	2,855	2,898	2,942	2,942
Carbon Content (%)	56%	56%	56%	56%	56%	56%	56%	56%	56%
Carbon Emitted (MMT CO_2 Eq.)	10.8	11.6	9.0	7.9	5.3	5.3	5.4	5.5	5.5

[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 data (EPA 2016), and disaggregated based on EPA (2003). 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 and Product Use 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 by-products of non-fuel use of feedstocks, and are thus included in the calculation of the petrochemical feedstocks storage factor. Table A-68 lists the CO emissions that remain after taking into account the exclusions listed above.

Table A-68: Non-Combustion Carbon Monoxide Emissions

	1990	1995	2000	2005	2011	2012	2013	2014	2015
CO Emissions ('000 Short Tons)	489	481	623	461	349	376	403	431	431
Carbon Emitted (MMT CO_2 Eq.)	0.7	0.7	0.9	0.7	0.5	0.5	0.6	0.6	0.6

Note: 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).[30] 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,

[30] [42 U.S.C. §6924, SDWA §3004]

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 Resource Conservation and Recovery Act (RCRA) Information system (EPA 2013a), formerly reported in its Biennial Reporting System (BRS) database (EPA 2000a, 2009, 2015a). 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 RCRA Information/BRS database for reporting years 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, 2011, 2013, and 2014 (EPA 2000a, 2009, 2013a, 2015a). 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-69). 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 2015 were 0.4 MMT CO_2 Eq. Table A-70 lists the CO_2 emissions from hazardous waste incineration.

Table A-69: 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-70: CO_2 Emitted from Hazardous Waste Incineration (MMT CO_2 Eq.)

	1990	1995	2000	2005	2011	2012	2013	2014	2015
C Emissions	1.1	1.7	1.0	0.6	0.4	0.4	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, 2006, and 2010 (EIA 1994, 1997, 2001, 2005, 2010, 2013b). 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 unreacted raw material feedstocks or generate by-products 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 by-products 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; liquor or black liquor; woodchips and bark; 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., by-products of the iron and steel production process) is addressed in the Iron and Steel production section in the Industrial Processes and Product Use 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 subtract 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. Liquor or black liquor and woodchips and bark are assumed to be biogenic fuels, in accordance with IPCC (2006), and therefore are not included in the Inventory. 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-71). 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 MMT CO_2. Petrochemical feedstocks combusted for energy recovery corresponded to 42.7 MMT CO_2 Eq. in 1991, 34.6 MMT CO_2 Eq. in 1994, 57.7 MMT CO_2 Eq. in 1998, 68.6 MMT CO_2 Eq. in 2002, 73.5 MMT CO_2 Eq. in 2006, and 40.6 MMT CO_2 Eq. in 2010. Values for petrochemical feedstocks burned for energy recovery for years between 1991 and 1994, between 1994 and 1998, between 1998 and 2002, between 2002 and 2006, and between 2007 and 2010 have been estimated by linear interpolation. The value for 1990 is assumed to be the same as the value for 1991, and the value for 2011, 2012, 2013, 2014, and 2015 are assumed to be the same as the value for 2010 (Table A-72).

Table A-71: Summary of 2010 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	6	1,349	153	54
Chemicals	325	376	7	0	266	110
Plastics and Rubber Products	326	0	0	0	0	0
Nonmetallic Mineral Products	327	1	7	0	0	0
Primary Metals	331	0	0	0	12	29
Fabricated Metal Products	332	0	0	0	0	0
Machinery	333	0	0	0	0	1
Computer and Electronic Products	334	0	0	0	0	0
Electrical Equip., Appliances, Components	335	0	0	0	0	0
Transportation Equipment	336	2	0	0	0	3
Furniture and Related Products	337	0	0	0	0	0
Miscellaneous	339	0	0	0	0	0
Total (Trillion Btu)		**379**	**20**	**1,349**	**432**	**195**
Average C Content (MMT/QBtu)		18.14	20.62	17.51	0	19.37
Fraction Oxidized		1	1	1	0	1
Total C (MMT)		**6.88**	**0.41**	**23.62**	**0.00**	**3.79**
Total C (MMT) (ex. still gas from refining)		**6.88**	**0.41**	**NA**	**NA**	**3.79**

NA (Not Applicable)
[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-72: Carbon Emitted from Fuels Burned for Energy Recovery (MMT CO_2 Eq.)

	1990	1995	2000	2005	2011	2012	2013	2014	2015
C Emissions	42.7	40.4	63.1	72.3	40.6	40.6	40.6	40.6	40.6

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 through 2014 were taken directly or derived from the American Chemistry Council (ACC 2007 through 2015 supplemented by Vallianos 2011, 2012, 2013, 2014, 2015). Data for 2015 is assumed equal to that of 2014. In 2009, the American Chemistry Council consolidated the resin categories for which it reports plastics production. Production numbers in the original categories were provided via personal correspondence for 2009, 2011, 2012, 2013, and 2014 (Vallianos 2011, 2012, 2013, 2014, 2015). Production numbers for 2015 have been proxied to 2014 value. Production figures for the consolidated resin categories in 2010 were linearly interpolated from 2009 and 2011 data. Production was organized by resin type (see Table A-73) 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-74 and Table A-75. 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-73: 2015 Plastic Resin Production (MMT dry weight) and C Stored (MMT CO_2 Eq.)

Resin Type	2015 Production[a] (MMT dry weight)	Carbon Stored (MMT CO_2 Eq.)
Epoxy	0.3	0.7
Urea	0.5	0.6
Melamine	0.5	0.5
Phenolic	1.6	4.5
Low-Density Polyethylene (LDPE)	3.0	9.4
Linear Low-Density Polyethylene (LLDPE)	5.8	18.3
High Density Polyethylene (HDPE)	7.4	23.1
Polypropylene (PP)	6.5	20.3
Acrylonitrile-butadiene-styrene (ABS)	0.4	1.4
Other Styrenics[b]	0.5	1.7
Polystyrene (PS)	2.3	7.7
Nylon	0.5	1.2
Polyvinyl chloride (PVC)[c]	6.3	8.9
Thermoplastic Polyester	3.5	7.9
All Other (including Polyester (unsaturated))	6.1	15.4
Total	**45.1**	**121.9**

[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 Styrene-acrylonitrile (SAN).
[c] Includes copolymers.
Note: Totals may not sum due to independent rounding.

Table A-74: 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[a]
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-75)
Polyvinyl Chloride (PVC)	38%	Polyvinyl chloride
Thermoplastic Polyester	63%	Polyethylene terephthalate
All Other	69%	Weighted average of other resin production

[a] Does not include alcoholic hydrogens.

Table A-75: 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 *2015 U.S. Scrap Tire Management Summary* (RMA 2016), while the tire composition information is from the "Scrap Tires, Facts and Figures" section of the organization's website (RMA 2009). 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, 2008, 2009a, 2011a, 2013b; 2014) 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 pounds per scrap tire, while the abraded rubber from scrap commercial tires was assumed to be 10 pounds per scrap tire. Data on abraded rubber weight were obtained by calculating the average weight difference between new and scrap tires (RMA 2016). Import and export data were obtained from the published by the U.S. International Trade Commission (U.S. International Trade Commission 2016).

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-76). 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-76: 2002 Rubber Consumption (kt) and C Content (%)

Elastomer Type	2002 Consumption (kt)[a]	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	**NA**	**90%**
Total	**2,215**	**NA**

NA (Not Applicable)
[a] Includes consumption in Canada.
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, 2011, 2012, 2013). The most recent data available were for 2012, so it was assumed that the 2013, 2014, and 2015 consumption was equal to that of 2012. These data are organized by year and fiber type. For each fiber, a C content was assigned based on molecular formula (see Table A-77). 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-77: 2015 Fiber Production (MMT), C Content (%), and C Stored (MMT CO_2 Eq.)

Fiber Type	Production (MMT)	C Content	C Stored (MMT CO_2 Eq.)
Polyester	1.2	63%	2.8
Nylon	0.6	64%	1.3
Olefin	1.0	86%	3.2
Acrylic	+	68%	0.1
Total	**2.8**	**NA**	**7.3**

+ Less than 0.05 MMT
NA (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, 2000/2001, 2006/2007 Pesticides Industry Sales and Usage Market Estimates* (EPA 1998, 1999, 2002, 2004, 2011b) reports. The most recent data available were for 2007, so it was assumed that the 2008 through 2015 consumption was equal to that of 2007. 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 2007 total pesticide active ingredient consumption was not specified by chemical type in the *Sales and Usage* report (EPA 2011b). 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-78: Active Ingredient Consumption in Pesticides (Million lbs.) and C Emitted and Stored (MMT CO_2 Eq.) in 2007

Pesticide Use[a]	Active Ingredient (Million lbs.)	C Emitted (MMT CO_2 Eq.)	C Stored (MMT CO_2 Eq.)
Agricultural Uses	473.5	0.1	0.1
Non-Agricultural Uses	76.8	+	+
Home & Garden	30.3	+	+
Industry/Gov't/Commercial	46.5	+	+
Other	337.7	0.1	0.1
Total	**888.0**	**0.2**	**0.2**

+ Less than 0.05 MMT CO_2 Eq.
[a] 2007 estimates (EPA 2011b).
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, 2007, 2012 Economic Census (U.S. Bureau of the Census 1994, 1999, 2004, 2009, 2014). Production 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, 2002 and 2007, and 2007 and 2012; production for 2013 through 2015 was assumed to equal the 2012 value. Cleanser production values were adjusted by import and export data to develop U.S. 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[31] 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 MMT 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 2015, value of shipments was adjusted to 1997 dollars using the producer price index for soap and other detergent manufacturing (Bureau of Labor Statistics 2015). The ratio of value of shipments to carbon content was then applied to arrive at total carbon content of cleansers. Estimates are shown in Table A-79.

Table A-79: C Emitted from Utilization of Soaps, Shampoos, and Detergents (MMT CO_2 Eq.)

	1990	1995	2000	2005	2011	2012	2013	2014	2015
C Emissions	3.6	4.2	4.5	6.7	5.4	4.7	4.7	4.8	4.8

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).

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

Annual production data for each glycol compound used as antifreeze and deicers were obtained from the *Guide to the Business of Chemistry* (ACC 2016) and the EPA Chemical Data Access Tool (CDAT) (EPA 2014). 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[32] and from similar data published in the Chemical Market Reporter, which became ICIS Chemical Business in 2005.[33] 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. ICIS last reported total demand for propylene glycol and diethylene glycol in 2006, and triethylene glycol demand in 2007. EPA reported total U.S. production of propylene glycol, diethylene glycol, and triethylene glycol in 2012 in the CDAT (EPA 2014). Total demand for these compounds for 2012 was calculated from the 2012 production data using import and export data. Demand for propylene glycol and diethylene glycol was interpolated for years between 2006 and 2012, and demand for triethylene glycol was interpolated for years between 2007 and 2012, using the calculated 2012 total demand values for each compound and the most recently reported total demand data from ICIS. Values for 2013, 2014, and 2015 for these compounds were assumed to be the same as the 2012 values. Production data for ethylene glycol was provided by the 2016 *Guide to the Business of Chemistry* (ACC 2016).

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-80.

Table A-80: C Emitted from Utilization of Antifreeze and Deicers (MMT CO_2 Eq.)

	1990	1995	2000	2005	2011	2012	2013	2014	2015
C Emissions	1.2	1.4	1.5	1.2	0.7	0.9	0.8	0.9	1.0

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 2016). Historical values for adipic acid were adjusted according to the most recent data in the 2016 *Guide to the Business of Chemistry*. 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[34] and from similar data published in the Chemical Market Reporter, which became ICIS Chemical Business in 2005.[35] 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.

ICIS last reported total demand for glycerin and benzoic acid in 2007, and demand for propionic acid in 2008. Total demand for acetic acid and maleic anhydride were last reported by ICIS in 2005, and dipropylene glycol demand in 2004. ICIS last reported cresylic acid demand in 1999. EPA reported total U.S. production of these compounds in 2012 in the CDAT (EPA 2014). Total demand for these compounds for 2012 was calculated from the 2012 production data using import and export data. Demand for each of these compounds was interpolated for years between the most recently reported total demand data from ICIS and 2012, using the calculated 2012 total demand values for each compound. Values for 2013, 2014, and 2015 for these compounds were assumed to be the same as the 2012 values.

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-81.

[32] See <http://www.the-innovation-group.com/ChemProfiles>.

[33] See <http://www.icis.com/home/default.aspx>.

[34] See <http://www.the-innovation-group.com/ChemProfiles>.

[35] See <http://www.icis.com/home/default.aspx>.

Table A-81: C Emitted from Utilization of Food Additives (MMT CO_2 Eq.)

	1990	1995	2000	2005	2011	2012	2013	2014	2015
C Emissions	0.6	0.7	0.7	0.8	1.0	1.1	1.1	1.1	1.1

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 2015b). 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.[36] ICIS last reported production of methyl chloride in 2007. EPA reported total U.S. production of methyl chloride in 2012 in the CDAT (EPA 2014). Total consumption of methyl chloride for 2012 was calculated from the 2012 production data using import and export data. Production of methyl chloride was interpolated for years between 2007 and 2012, using the calculated 2012 total production value for methyl chloride and the most recently reported total production data from ICIS. The production values for 2013, 2014 and 2015 were assumed to be the same as the 2012 value.

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-82.

Table A-82: C Stored in Silicone Products (MMT CO_2 Eq.)

	1990	1995	2000	2005	2011	2012	2013	2014	2015
C Storage	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5

Uncertainty – TO BE UPDATED FOR FINAL INVENTORY REPORT

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 2014. 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 exports. An additional 10 percent (for a total of ±45 percent) was applied to the production of other oils (>401 degrees. Fahrenheit) 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 with a mean of 65 percent, a standard deviation of 5.8 percent, and the 95 percent confidence interval of 52 percent and 72 percent. This compares to the calculated Inventory estimate of 65 percent. The analysis produced a C emission distribution with a mean of 75.1 MMT CO_2 Eq., standard deviation of 21.3 MMT CO_2 Eq., and 95 percent confidence limits of 49.6 and 125.3 MMT CO_2 Eq. This compares with a calculated Inventory estimate of 75.1 MMT 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.

[36] Ibid.

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 BoC for the major categories of petrochemical feedstocks (EIA 2001; NPRA 2001; and U.S. Bureau of the Census 2015). 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, 2006, and 2010 (EIA 1994, 1997, 2001, 2005, 2010,

2013b). 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 zero 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, 2001, and 2007; the majority of the time series data were interpolated or held constant at the latest (2007) 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.[37] 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 99.56 percent of the C in asphalt cement was retained (i.e., stored), and less than 0.44 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.

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 – TO BE UPDATED FOR FINAL INVENTORY REPORT

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 2014. 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

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

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 percent and 100 percent, with the mean value of 99 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 0.26 MMT CO_2 Eq., standard deviation of 0.12 and 95 percent confidence limits of 0.11 MMT CO_2 Eq. and 0.57 MMT CO_2 Eq. This compares to an Inventory calculated estimate of 0.26 MMT 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 (2015b), the C content from U.S. production of lubricants in 2015 was approximately 6.2 MMT 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 2015 were about 5.6 MMT C, or 20.6 MMT 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.[38] 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-83 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

[38] 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.

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-83: 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 [a]	64%	0.6%
Dumped on the ground or in storm sewers	6%	NA
Landfilled	2%	1.8%
Re-refined into lube oil base stock and other products	8%	0.2%
Weighted Average	**NA**	**2.9%**

NA (Not Applicable)
[a] For example, in boilers or space heaters.

Greases

Table A-84 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.

Table A-84: 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	90%	77.0%
Dumped on the ground or in storm sewers	10%	4.8%
Weighted Average	**NA**	**81.8%**

NA (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* (U.S. Bureau of the Census 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 – TO BE UPDATED FOR FINAL INVENTORY REPORT

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 2014. 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 18.9 MMT CO_2 Eq., standard deviation of 1.5 and 95 percent confidence limits of 15.5 MMT CO_2 Eq. and 21.9 MMT CO_2 Eq. This compares to an inventory calculated estimate of 18.9 MMT 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-85 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-85: 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-86 categorizes wax end uses identified by the NPRA, and lists the estimated C storage factor of each end use.

Table A-86: 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

Notes: Totals may not sum due to independent rounding. Estimates of percent stored are based on professional judgment, ICF International.
Source mass percentages: NPRA (2002).

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 – TO BE UPDATED FOR FINAL INVENTORY REPORT

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 2014. 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 70 percent, around the mean value of 58 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 MMT CO_2 Eq. and 0.7 MMT CO_2 Eq., with a mean value of 0.4 MMT CO_2 Eq. This compares with a calculated Inventory estimate of 0.5 MMT 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 by-products (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 by-products could potentially be used as feedstocks for manufacture of durable goods, but such by-products are more likely to be used in emissive uses. Lube refining by-products 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 (2009), the C content of miscellaneous petroleum products in 2015 was approximately 20.2 MMT 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 percent being stored long-term. EIA (2014) defines "miscellaneous products" as "all finished products not classified elsewhere (e.g., petrolatum, lube refining by-products (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. 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 – TO BE UPDATED FOR FINAL INVENTORY REPORT

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 2014. 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 percent) 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 MMT 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 4 percent and 24 percent, with a mean of 4 percent. This compares to the Inventory calculation of weighted average (across the various fuels) storage factor of about 4 percent. The analysis produced an emission distribution, with the 95 percent confidence limit of 14.2 MMT CO_2 Eq. and 21.7 MMT CO_2 Eq., and a mean of 19.6 MMT CO_2 Eq. This compares with the Inventory estimate of 19.6 MMT 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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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 emission factors and methods from the Intergovernmental Panel on Climate Change (IPCC). 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-87 through Table A-92.

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 from industrial, commercial, residential, and U.S. Territories, estimates were based upon consumption of coal, gas, oil, and wood. Energy consumption and wood consumption data for the United States were obtained from the Energy Information Administration's (EIA) *Monthly Energy Review, December 2016* and Published Supplemental Tables on Petroleum Product detail (EIA 2016). Because the United States does not include U.S. Territories in its national energy statistics, fuel consumption data for U.S. Territories were collected from EIA's International Energy Statistics database (EIA 2014) and Jacobs (2010).[39] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[40] Construction and agricultural fuel use was obtained from EPA (2016c) and FHWA (1996 through 2016). The energy consumption data by sector were then adjusted from higher to lower heating values by multiplying by 0.90 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 (IEA). Table A-87 provides annual energy consumption data for the years 1990 through 2015.

In this Inventory, the emission estimation methodology for the electric power sector used a Tier 2 methodology as fuel consumption by technology-type for the electricity generation sector was obtained from the Acid Rain Program Dataset (EPA 2016a). This combustion technology-and fuel-use data was available by facility from 1996 to 2015. Since there was a difference between the EPA (2016a) and EIA (2016) total energy consumption estimates, the remainder between total energy consumption using EPA (2016a) and EIA (2016) was apportioned to each combustion technology type and fuel combination using a ratio of energy consumption by technology type from 1996 to 2015.

Energy consumption estimates were not available from 1990 to 1995 in the EPA (2016a) dataset, and as a result, consumption was calculated using total electric power consumption from EIA (2016a) and the ratio of combustion technology and fuel types from EPA 2016a. The consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type to the total EIA consumption for each year from 1990 to 1995.

Step 2: Determine the Amount of CH_4 and N_2O Emitted

Activity data for industrial, commercial, residential, and U.S. Territories and fuel type for each of these sectors were then multiplied by default Tier 1 emission factors to obtain emission estimates. Emission factors for the residential, commercial, and industrial 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-88 provides emission factors used for each sector and fuel type. For the electric power sector, emissions were estimated by multiplying fossil fuel and wood consumption by technology- and fuel-specific

[39] U.S. Territories data also include combustion from mobile activities because data to allocate U.S. 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.

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

Tier 2 IPCC emission factors shown in Table A-89. Emission factors were used from the *2006 IPCC Guidelines* as the factors presented in these IPCC guidelines were taken directly from U.S. Environmental Protection Agency (EPA) publications on emissions rates for combustion sources.

Estimates of NO_x, CO, and NMVOC Emissions

Emissions estimates for NO_x, CO, and NMVOCs were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2016b), and disaggregated based on EPA (2003).

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 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.

The basic calculation procedure for most source categories presented in EPA (2003) and EPA (2016b) 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 2006).

Table A-87: Fuel Consumption by Stationary Combustion for Calculating CH_4 and N_2O Emissions (TBtu)

Fuel/End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Coal	**19,610**	**20,888**	**23,080**	**22,391**	**22,343**	**22,576**	**22,636**	**22,949**	**22,458**	**22,710**	**22,225**	**19,670**	**20,697**	**18,989**	**16,715**	**17,399**	**17,359**	**15,103**
Residential	31	17	11	12	12	12	11	8	6	8	0	0	0	0	0	0	0	0
Commercial	124	117	92	97	90	82	103	97	65	70	81	73	70	62	44	41	40	31
Industrial	1,640	1,527	1,349	1,358	1,244	1,249	1,262	1,219	1,189	1,131	1,081	877	952	866	782	800	799	696
Electric Power	17,807	19,217	21,618	20,920	20,987	21,199	21,228	21,591	21,161	21,465	21,026	18,682	19,639	18,024	15,852	16,521	16,483	14,339
U.S. Territories	7	10	10	4	11	34	32	33	37	37	37	37	37	37	37	37	37	37
Petroleum	**6,166**	**5,659**	**6,148**	**6,632**	**6,010**	**6,394**	**6,561**	**6,486**	**6,201**	**6,064**	**5,241**	**4,670**	**4,728**	**4,417**	**4,065**	**4,204**	**4,027**	**4,553**
Residential	1,375	1,262	1,429	1,465	1,361	1,468	1,468	1,368	1,202	1,220	1,202	1,138	1,116	1,039	847	936	990	982
Commercial	869	695	695	720	647	765	764	716	678	680	635	669	643	619	506	540	544	672
Industrial	2,750	2,380	2,283	2,535	2,371	2,496	2,669	2,776	3,111	2,996	2,427	1,949	2,054	1,988	1,924	2,038	1,866	2,255
Electric Power	797	860	1,269	1,279	1,074	1,043	1,007	1,004	590	618	488	383	412	266	273	180	153	169
U.S. Territories	375	462	472	632	557	622	653	623	620	550	490	531	502	504	516	510	475	475
Natural Gas	**17,266**	**19,337**	**20,919**	**20,224**	**20,908**	**20,894**	**21,152**	**20,938**	**20,626**	**22,019**	**22,286**	**21,952**	**22,912**	**23,115**	**24,137**	**24,949**	**25,745**	**26,463**
Residential	4,491	4,954	5,105	4,889	4,995	5,209	4,981	4,946	4,476	4,835	5,010	4,883	4,878	4,805	4,242	5,023	5,242	4,769
Commercial	2,682	3,096	3,252	3,097	3,212	3,261	3,201	3,073	2,902	3,085	3,228	3,187	3,165	3,216	2,960	3,380	3,572	3,309
Industrial	7,716	8,723	8,656	7,949	8,086	7,845	7,914	7,330	7,323	7,521	7,571	7,125	7,683	7,873	8,203	8,525	8,837	8,820
Electric Power	2,376	2,564	3,894	4,266	4,591	4,551	5,032	5,565	5,899	6,550	6,447	6,730	7,159	7,194	8,683	7,964	8,033	9,505
U.S. Territories	0	0	13	23	23	27	25	24	26	27	29	27	28	27	49	57	61	61
Wood	**2,216**	**2,370**	**2,262**	**2,006**	**1,995**	**2,002**	**2,121**	**2,137**	**2,099**	**2,089**	**2,059**	**1,931**	**1,981**	**2,010**	**2,010**	**2,170**	**2,230**	**2,043**
Residential	580	520	420	370	380	400	410	430	380	420	470	500	440	450	420	580	580	432
Commercial	66	72	71	67	69	71	70	70	65	70	73	73	72	69	61	70	73	73
Industrial	1,442	1,652	1,636	1,443	1,396	1,363	1,476	1,452	1,472	1,413	1,339	1,178	1,273	1,309	1,339	1,312	1,325	1,295
Electric Power	129	125	134	126	150	167	165	185	182	186	177	180	196	182	190	207	251	244
U.S. Territories	NE	NE	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-88: CH_4 and N_2O Emission Factors by Fuel Type and Sector (g/GJ)[a]

Fuel/End-Use Sector	CH_4	N_2O
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	4	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)

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

Table A-89: CH_4 and N_2O Emission Factors by Technology Type and Fuel Type for the Electric Power Sector (g/GJ)[a]

Technology	Configuration	CH_4	N_2O
Liquid Fuels			
Residual Fuel Oil/Shale Oil Boilers	Normal Firing	0.8	0.3
	Tangential Firing	0.8	0.3
Gas/Diesel Oil Boilers	Normal Firing	0.9	0.4
	Tangential Firing	0.9	0.4
Large Diesel Oil Engines >600 hp (447kW)		4	NA
Solid Fuels			
Pulverized Bituminous Combination Boilers	Dry Bottom, wall fired	0.7	0.5
	Dry Bottom, tangentially fired	0.7	1.4
	Wet bottom	0.9	1.4
Bituminous Spreader Stoker Boilers	With and without re-injection	1	0.7
Bituminous Fluidized Bed Combustor	Circulating Bed	1	61
	Bubbling Bed	1	61
Bituminous Cyclone Furnace		0.2	0.6
Lignite Atmospheric Fluidized Bed		NA	71
Natural Gas			
Boilers		1	1
Gas-Fired Gas Turbines >3MW		1	1
Large Dual-Fuel Engines		258	NA
Combined Cycle		4	3
Peat			
Peat Fluidized Bed Combustion	Circulating Bed	3	7
	Bubbling Bed	3	3
Biomass			
Wood/Wood Waste Boilers		11	7
Wood Recovery Boilers		1	1

NA (Not Applicable)

[a] Ibid.

Table A-90: NO_x Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Electric Power	**6,045**	**5,792**	**4,829**	**4,454**	**4,265**	**3,930**	**3,595**	**3,434**	**3,249**	**3,064**	**2,847**	**2,552**	**2,226**	**1,893**	**1,779**	**1,666**	**1,552**	**1,321**
Coal	5,119	5,061	4,130	3,802	3,634	3,349	3,063	2,926	2,768	2,611	2,426	2,175	1,896	1,613	1,516	1,419	1,323	1,126
Fuel Oil	200	87	147	149	142	131	120	114	108	102	95	85	74	63	59	55	52	44
Natural gas	513	510	376	325	310	286	262	250	236	223	207	186	162	138	129	121	113	96
Wood	NA	NA	36	37	36	33	30	29	27	26	24	21	19	16	15	14	13	11
Other Fuels[a]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Internal Combustion	213	134	140	140	143	132	121	115	109	103	95	86	75	63	60	56	52	44
Industrial	**2,559**	**2,650**	**2,278**	**2,296**	**1,699**	**1,641**	**1,580**	**1,515**	**1,400**	**1,285**	**1,165**	**1,126**	**1,087**	**1,048**	**1,028**	**1,009**	**990**	**990**
Coal	530	541	484	518	384	371	357	342	316	290	263	254	245	237	232	228	223	223
Fuel Oil	240	224	166	153	114	110	106	101	94	86	78	75	73	70	69	67	66	66
Natural gas	877	999	710	711	526	508	489	469	433	398	361	348	336	324	318	312	306	306
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	119	111	109	116	86	83	80	76	70	65	59	57	55	53	52	51	50	50
Internal Combustion	792	774	809	798	591	570	549	527	486	446	405	391	378	364	357	351	344	344
Commercial	**671**	**607**	**507**	**428**	**438**	**408**	**378**	**490**	**471**	**452**	**433**	**445**	**456**	**548**	**534**	**519**	**443**	**443**
Coal	36	35	21	21	19	19	19	19	18	17	15	15	15	15	14	14	14	14
Fuel Oil	88	94	52	52	50	49	49	49	46	43	39	39	38	37	37	36	36	36
Natural gas	181	210	161	165	157	156	156	155	145	135	124	122	120	118	116	115	113	113
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	366	269	273	189	212	183	154	267	263	258	254	269	284	378	366	353	280	280
Residential	**749**	**813**	**439**	**446**	**422**	**422**	**420**	**418**	**390**	**363**	**335**	**329**	**324**	**318**	**314**	**310**	**306**	**306**
Coal[b]	NA	NA	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	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	42	44	21	22	21	21	21	20	19	18	16	16	16	16	15	15	15	15
Other Fuels[a]	707	769	417	424	402	401	400	398	371	345	318	313	308	302	298	295	291	291
Total	**10,023**	**9,862**	**8,053**	**7,623**	**6,825**	**6,401**	**5,973**	**5,858**	**5,511**	**5,163**	**4,780**	**4,452**	**4,092**	**3,807**	**3,655**	**3,504**	**3,291**	**3,061**

NA (Not Applicable)

[a] Other Fuels include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2016b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the Other Fuels category (EPA 2016b).

Note: Totals may not sum due to independent rounding.

Table A-91: CO Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Electric Power	**329**	**337**	**439**	**439**	**594**	**591**	**586**	**582**	**609**	**637**	**660**	**676**	**693**	**710**	**690**	**669**	**649**	**649**
Coal	213	227	221	220	298	296	294	292	305	319	330	339	347	356	346	335	325	325
Fuel Oil	18	9	27	28	38	37	37	37	38	40	42	43	44	45	44	42	41	41
Natural gas	46	49	96	92	125	124	123	122	128	134	138	142	145	149	145	140	136	136
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	31	32	44	43	43	43	45	47	48	50	51	52	51	49	48	48
Internal Combustion	52	52	63	67	91	90	90	89	93	97	101	103	106	108	105	102	99	99
Industrial	**797**	**958**	**1,106**	**1,137**	**1,150**	**1,116**	**1,081**	**1,045**	**968**	**892**	**815**	**834**	**853**	**872**	**871**	**869**	**868**	**868**
Coal	95	88	118	125	127	123	119	115	107	98	90	92	94	96	96	96	96	96

Fuel Oil	67	64	48	45	46	44	43	42	39	35	32	33	34	35	35	35	35	35
Natural gas	205	313	355	366	370	359	348	336	312	287	262	268	274	281	280	280	279	279
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	253	270	300	321	325	316	306	295	274	252	230	236	241	247	246	246	245	245
Internal Combustion	177	222	285	279	282	274	266	257	238	219	200	205	209	214	214	213	213	213
Commercial	**205**	**211**	**151**	**154**	**177**	**173**	**169**	**166**	**156**	**146**	**137**	**138**	**140**	**142**	**135**	**129**	**122**	**122**
Coal	13	14	14	13	15	15	15	14	14	13	12	12	12	12	12	11	11	11
Fuel Oil	16	17	17	17	20	19	19	19	18	16	15	16	16	16	15	14	14	14
Natural gas	40	49	83	84	97	95	93	91	86	80	75	76	77	78	74	71	67	67
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	136	132	36	38	44	43	42	41	39	37	34	35	35	35	34	32	30	30
Residential	**3,668**	**3,877**	**2,644**	**2,648**	**3,044**	**2,982**	**2,919**	**2,856**	**2,690**	**2,524**	**2,357**	**2,387**	**2,416**	**2,446**	**2,331**	**2,217**	**2,103**	**2,103**
Coal[b]	NA	NA	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	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	3,430	3,629	2,416	2,424	2,787	2,730	2,673	2,615	2,463	2,310	2,158	2,185	2,212	2,239	2,134	2,030	1,925	1,925
Other Fuels[a]	238	248	228	224	257	252	247	241	227	213	199	202	204	207	197	187	178	178
Total	**5,000**	**5,383**	**4,340**	**4,377**	**4,965**	**4,862**	**4,756**	**4,648**	**4,423**	**4,198**	**3,969**	**4,036**	**4,103**	**4,170**	**4,027**	**3,884**	**3,741**	**3,741**

NA (Not Applicable)

[a] Other Fuels include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2016b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the Other Fuels category (EPA 2016b).

Note: Totals may not sum due to independent rounding.

Table A-92: NMVOC Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Electric Power	**43**	**40**	**56**	**55**	**45**	**45**	**44**	**44**	**42**	**41**	**40**	**39**	**38**	**37**	**36**	**35**	**34**	**34**
Coal	24	26	27	26	21	21	21	21	20	20	19	18	18	18	17	17	16	16
Fuel Oil	5	2	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3
Natural Gas	2	2	12	12	10	10	10	10	9	9	9	9	8	8	8	8	8	8
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Internal Combustion	11	9	11	10	9	9	8	8	8	8	8	7	7	7	7	7	6	6
Industrial	**165**	**187**	**157**	**159**	**138**	**132**	**126**	**120**	**113**	**105**	**97**	**99**	**100**	**101**	**101**	**100**	**100**	**100**
Coal	7	5	9	10	9	9	8	8	7	7	6	6	7	7	7	7	7	7
Fuel Oil	11	11	9	9	7	7	7	6	6	6	5	5	5	5	5	5	5	5
Natural Gas	52	66	53	54	47	45	43	41	38	36	33	33	34	34	34	34	34	34
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	46	45	27	29	25	24	23	22	21	19	18	18	18	19	19	19	18	18
Internal Combustion	49	60	58	57	49	47	45	43	40	37	35	35	36	36	36	36	36	36
Commercial	**18**	**21**	**28**	**29**	**61**	**54**	**48**	**33**	**34**	**35**	**36**	**38**	**40**	**42**	**40**	**39**	**35**	**35**
Coal	1	1	1	1	1	1	1	1	1	+	+	+	+	+	+	+	+	+
Fuel Oil	3	3	4	4	6	5	3	2	2	2	2	2	2	2	2	2	1	1
Natural Gas	7	10	14	14	23	18	14	9	8	7	6	7	7	7	7	6	6	6
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	8	8	9	10	31	30	30	22	24	26	28	29	31	32	31	30	27	27
Residential	**686**	**725**	**837**	**836**	**1,341**	**1,067**	**793**	**518**	**465**	**411**	**358**	**378**	**399**	**419**	**392**	**365**	**338**	**338**
Coal[b]	NA	NA	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	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	651	688	809	809	1,297	1,032	767	502	450	398	346	366	386	406	380	353	327	327	
Other Fuels[a]	35	37	27	27	43	35	26	17	15	13	12	12	13	14	13	12	11	11	
Total	**912**	**973**	**1,077**	**1,080**	**1,585**	**1,298**	**1,011**	**716**	**654**	**593**	**531**	**553**	**576**	**599**	**569**	**539**	**507**	**507**	

NA (Not Applicable)
+ Does not exceed 0.5 kt.
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2016b).
[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2016b).
Note: Totals may not sum due to independent rounding.

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3.2. Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related GHG Emissions

Estimating CO_2 Emissions by Transportation Mode

Transportation-related CO_2 emissions, as presented in the CO_2 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 (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 2016a and EIA 2016b) and apportioned to individual modes (considered a "top down" approach). Carbon dioxide emissions from commercial jet fuel use are obtained directly from the Federal Aviation Administration (FAA 2017), while CO_2 emissions from other aircraft jet fuel consumption is determined using 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 consumption in the transportation sector, based on the availability of reliable data sources. A "bottom up" diesel calculation was first implemented in the 1990 through 2005 Inventory, and a bottom-up gasoline calculation was introduced in the 1990 through 2006 Inventory for the calculation of emissions from on-road vehicles. Estimated motor gasoline and diesel consumption data for on-road vehicles by vehicle type come from FHWA's *Highway Statistics*, Table VM-1 (FHWA 1996 through 2016),[41] and are based on federal and state fuel tax records.[42] These fuel consumption estimates were then combined with estimates of fuel shares by vehicle type from DOE's Transportation Energy Data Book Annex Tables A.1 through A.6 (DOE 1993 through 2016) 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 on-road vehicle categories matched the fuel consumption estimates in *Highway Statistics'* Table MF-27 (FHWA 1996 through 2016). This resulted in a final "bottom up" 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.

A primary challenge to switching from a top-down approach to a bottom-up approach for the transportation sector relates to potential incompatibilities with national energy statistics. From a multi-sector national standpoint, EIA develops the most accurate estimate of total motor gasoline and diesel fuel supplied and consumed in the United States. EIA then allocates this total fuel consumption to each major end-use sector (residential, commercial, industrial and transportation) using data from the *Fuel Oil and Kerosene Sales* (FOKS) report for distillate fuel oil and FHWA for motor gasoline. However, the "bottom-up" approach used for the on-road and non-road fuel consumption estimate, as described above, is considered to be the most representative of the transportation sector's share of the EIA total consumption. Therefore, for years in which there was a disparity between EIA's fuel allocation estimate for the transportation sector and the "bottom-up" estimate, adjustments were made to other end-use sector fuel allocations (residential, commercial and industrial) in order for the consumption of all sectors combined to equal the "top-down" EIA value.[43]

In the case of motor gasoline, estimates of fuel use by recreational boats come from the NONROAD component of EPA's MOVES2014a model (EPA 2016d), and these estimates, along with those from other sectors (e.g., commercial sector, industrial sector), were adjusted for years in which the bottom-up on-road motor gasoline consumption estimate

[41] In 2011 FHWA changed its methods for estimating vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 2010 Inventory and apply to the 2007-15 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. For example, the category "Passenger Cars" has been replaced by "Light-duty Vehicles-Short Wheelbase" and "Other 2 axle-4 Tire Vehicles" has been replaced by "Light-duty Vehicles, Long Wheelbase." This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this emission inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

[42] In 2016, FHWA changed its methods for estimating the share of motor gasoline used in on-highway and off-highway applications. This resulted in an increase in the estimated off-highway motor gasoline consumption and subsequent decrease in the on-highway motor gasoline consumption for 2015.

[43] Adjustments made to other end-use sector fuel allocations for 2015 were greater than prior inventory years due to the change FHWA made in its methods for estimating the share of motor gasoline used in on-highway and off-highway applications.

exceeded the EIA estimate for total gasoline consumption of all sectors. 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 proportionately.

Estimates of diesel fuel consumption from rail were taken from the Association of American Railroads (AAR 2008 through 2016) for Class I railroads, the American Public Transportation Association (APTA 2007 through 2016 and APTA 2006) and Gaffney (2007) for commuter rail, the Upper Great Plains Transportation Institute (Benson 2002 through 2004) and Whorton (2006 through 2013) for Class II and III railroads, and DOE's *Transportation Energy Data Book* (DOE 1993 through 2016) for passenger rail. Estimates of diesel from ships and boats were taken from EIA's *Fuel Oil and Kerosene Sales* (1991 through 2016).

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: FAA (2017) for domestic and international commercial aircraft, and DESC (2016) for domestic and international military aircraft. General aviation jet fuel consumption is calculated as the difference between total jet fuel consumption as reported by EIA and the total consumption from commercial and military jet fuel consumption. Commercial jet fuel CO_2 estimates are obtained directly from the Federal Aviation Administration (FAA 2017), while CO_2 emissions from domestic military and general aviation jet fuel consumption is determined using a top down approach. Domestic commercial jet fuel CO_2 from FAA is subtracted from total domestic jet fuel CO_2 emissions, and this remaining value is apportioned among domestic military and domestic general aviation based on their relative proportion of energy consumption. Estimates for biofuels, including ethanol and biodiesel, were discussed separately in Chapter 3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels under the methodology for Estimating CO_2 from Fossil Combustion, and in Chapter 3.10 Wood Biomass and Ethanol Consumption, and were not apportioned to specific transportation sources. Consumption estimates for biofuels were calculated based on data from the Energy Information Administration (EIA 2016).

Table A-93 displays estimated fuel consumption by fuel and vehicle type. Table A-94 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. The motor gasoline and diesel fuel consumption volumes published by EIA and FHWA include ethanol blended with gasoline and biodiesel blended with diesel. Biofuels blended with conventional fuels were subtracted from these consumption totals in order to be consistent with IPCC methodological guidance and UNFCCC reporting obligations, for which 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 fuel volumes were removed from motor gasoline consumption estimates for years 1990 through 2015 and biodiesel fuel volumes were removed from diesel fuel consumption volumes for years 2001 through 2015, as there was negligible use of biodiesel as a diesel blending competent prior to 2001. The subtraction or removal of biofuels blended into motor gasoline and diesel were conducted following the methodology outlined in Step 2 ("Remove Biofuels from Petroleum") of the EIA's *Monthly Energy Review* (MER) Section 12 notes.

In order to remove the volume of biodiesel blended into diesel fuel, the refinery and blender net volume inputs of renewable diesel fuel sourced from EIA Petroleum Supply Annual (EIA 2016) *Table 18 - Refinery Net Input of Crude Oil and Petroleum Products* and *Table 20 - Blender Net Inputs of Petroleum Products* were subtracted from the transportation sector's total diesel fuel consumption volume (for both the "top-down" EIA and "bottom-up" FHWA estimates). To remove the fuel ethanol blended into motor gasoline, ethanol energy consumption data sourced from MER *Table 10.2b - Renewable Energy Consumption: Industrial and Transportation Sectors* (EIA 2016) were subtracted from the total EIA and FHWA transportation motor gasoline energy consumption estimates.

Total ethanol and biodiesel consumption estimates are shown separately in Table A-95.[44]

[44] Note that the refinery and blender net volume inputs of renewable diesel fuel sourced from EIA's Petroleum Supply Annual (PSA) differs from the biodiesel volume presented in Table A-95. The PSA data is representative of the amount of biodiesel that refineries and blenders added to diesel fuel to make low level biodiesel blends. This is the appropriate value to subtract from total diesel fuel volume, as it represents the amount of biofuel blended into diesel to create low-level biodiesel blends. The biodiesel consumption value presented in Table A-93 is representative of the total biodiesel consumed and includes biodiesel components in all types of fuel formulations, from low level (<5%) to high level (6-20%, 100%) blends of biodiesel. This value is sourced from MER Table 10.4 and is calculated as biodiesel production plus biodiesel net imports minus biodiesel stock exchange.

Table A-93: Fuel Consumption by Fuel and Vehicle Type (million gallons unless otherwise specified)

Fuel/Vehicle Type	1990	1995	2000	2005	2006	2007[a]	2008	2009	2010	2011	2012	2013	2014	2015
Motor Gasoline[b,c]	**110,417**	**117,429**	**128,174**	**133,294**	**131,337**	**130,768**	**125,050**	**124,189**	**123,175**	**120,497**	**120,035**	**120,138**	**122,188**	**120,415**
Passenger Cars	69,763	67,496	72,320	73,856	70,791	88,607	84,714	83,918	83,230	82,621	82,464	82,463	82,692	81,485
Light-Duty Trucks	34,698	44,074	50,398	53,733	54,798	34,933	33,074	33,473	33,262	31,612	31,270	31,305	33,085	32,602
Motorcycles	194	199	208	182	210	472	487	468	411	401	459	437	427	421
Buses	39	41	43	41	41	79	81	84	82	80	92	95	102	100
Medium- and Heavy-Duty Trucks	4,350	4,044	4,065	3,922	3,961	5,164	5,220	4,798	4,773	4,383	4,358	4,455	4,506	4,440
Recreational Boats[d]	1,374	1,575	1,140	1,560	1,536	1,514	1,474	1,448	1,417	1,401	1,391	1,382	1,376	1,367
Distillate Fuel Oil (Diesel Fuel) [b,c]	**25,631**	**31,604**	**39,241**	**44,658**	**45,844**	**46,427**	**44,026**	**39,873**	**41,477**	**42,280**	**42,045**	**42,672**	**44,026**	**45,320**
Passenger Cars	771	765	356	414	403	403	363	354	367	399	401	399	408	417
Light-Duty Trucks	1,119	1,452	1,961	2,518	2,611	1,327	1,184	1,180	1,227	1,277	1,271	1,265	1,364	1,395
Buses	781	851	997	1,030	1,034	1,520	1,436	1,335	1,326	1,419	1,515	1,525	1,658	1,695
Medium- and Heavy-Duty Trucks	18,574	23,240	30,179	35,159	36,089	37,517	35,726	32,364	33,683	33,859	33,877	34,426	35,518	36,324
Recreational Boats	190	228	270	311	319	327	335	343	351	357	364	368	376	384
Ships and and Non-Recreational Boats	735	1,204	1,372	780	724	794	767	768	726	993	733	741	606	1,184
Rail[e]	3,461	3,863	4,106	4,446	4,664	4,538	4,215	3,529	3,798	3,975	3,884	3,948	4,096	3,922
Jet Fuel[f]	**19,186**	**17,991**	**20,002**	**19,420**	**18,695**	**18,407**	**17,749**	**15,809**	**15,537**	**15,036**	**14,705**	**15,088**	**15,237**	**16,176**
Commercial Aircraft	11,569	12,136	14,672	13,976	14,426	14,708	13,400	12,588	11,931	12,067	11,932	12,031	12,131	12,534
General Aviation Aircraft	4,034	3,361	3,163	3,583	2,590	2,043	2,682	1,787	2,322	1,895	1,659	2,033	1,676	2,257
Military Aircraft	3,583	2,495	2,167	1,860	1,679	1,656	1,667	1,434	1,283	1,074	1,114	1,024	1,430	1,384
Aviation Gasoline[f]	**374**	**329**	**302**	**294**	**278**	**263**	**235**	**221**	**225**	**225**	**209**	**186**	**181**	**176**
General Aviation Aircraft	374	329	302	294	278	263	235	221	225	225	209	186	181	176
Residual Fuel Oil[f, g]	**2,006**	**2,587**	**2,963**	**1,713**	**2,046**	**2,579**	**1,812**	**1,241**	**1,818**	**1,723**	**1,410**	**1,345**	**517**	**314**
Ships and Boats	2,006	2,587	2,963	1,713	2,046	2,579	1,812	1,241	1,818	1,723	1,410	1,345	517	314
Natural Gas[f] (trillion cubic feet)	**0.7**	**0.7**	**0.7**	**0.6**	**0.6**	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**	**0.8**	**0.9**	**0.7**	**0.7**
Passenger Cars	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Buses	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Pipelines	0.7	0.7	0.7	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.8	0.7	0.7
LPG[f]	**265**	**265**	**266**	**266**	**267**	**268**	**267**	**270**	**270**	**272**	**272**	**270**	**272**	**272**
Passenger Cars	1	2	3	3	4	2	1	1	1	5	6	3	4	2
Light-Duty Trucks	52	68	64	49	68	64	52	27	30	58	80	49	68	64
Medium- and Heavy-Duty Trucks	194	162	157	159	153	160	188	211	204	177	158	159	153	160
Buses	19	34	44	56	46	45	32	33	36	32	29	56	46	45
Electricity[f, h]	**4,751**	**4,975**	**5,382**	**7,506**	**7,358**	**8,173**	**7,653**	**7,768**	**7,712**	**7,672**	**7,320**	**7,625**	**7,758**	**7,637**
Rail	4,751	4,975	5,382	7,506	7,358	8,173	7,653	7,768	7,712	7,672	7,320	7,625	7,758	7,637

+ Does not exceed 0.05

[a] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007 to 2015 time period. These methodological changes include how on-road vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This resulted in large changes in fuel consumption data by vehicle class between 2006 and 2007.

[b] Figures do not include ethanol blended in motor gasoline or biodiesel blended into distillate fuel oil. Net carbon fluxes associated with ethanol are accounted for in the Land Use, Land-Use Change and Forestry chapter. This table is calculated with the heat content for gasoline without ethanol (from Table A.2 in the EIA Annual Energy Review) rather than the annually variable quantity-weighted heat content for gasoline with ethanol, which varies by year.

[c] Gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-21, MF-27, and VM-1 (FHWA 1996 through 2016). In 2016, FHWA changed its methods for estimating the share of motor gasoline used in on-highway and off-highway applications. This resulted in an increase in the estimated off-highway motor gasoline consumption and subsequent decrease in the on-highway motor gasoline consumption for 2015. Data from Table VM-1 is used to estimate the share of consumption between each on-road vehicle class. Since VM-1 data for 2015 has not been published yet, fuel consumption shares from 2014 are used as a proxy for Public Review. These fuel consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is used as a proxy.

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

[e] Class II and Class II diesel consumption data for 2015 is not available yet, therefore 2013 data is used as a proxy.

[f] Estimated based on EIA transportation sector energy estimates by fuel type, with bottom-up activity data used for apportionment to modes. Transportation sector natural gas and LPG consumption are based on data from EIA (2016). In prior Inventory years, data from DOE TEDB was used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium and heavy duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2016) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in this year's Inventory and apply to the 1990-2015 time period.

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

[h] Million kilowatt-hours

Table A-94: Energy Consumption by Fuel and Vehicle Type (Tbtu)

Fuel/Vehicle Type	1990	1995	2000	2005	2006	2007[a]	2008	2009	2010	2011	2012	2013	2014	2015
Motor Gasoline[b, c]	**13,810**	**14,687**	**16,031**	**16,671**	**16,426**	**16,259**	**15,548**	**15,441**	**15,315**	**14,982**	**14,924**	**14,937**	**15,192**	**14,972**
Passenger Cars	8,725	8,442	9,045	9,237	8,854	11,017	10,533	10,434	10,348	10,272	10,253	10,253	10,281	10,131
Light-Duty Trucks	4,340	5,512	6,303	6,720	6,854	4,343	4,112	4,162	4,136	3,930	3,888	3,892	4,114	4,054
Motorcycles	24	25	26	23	26	59	61	58	51	50	57	54	53	52
Buses	5	5	5	5	5	10	10	10	10	10	11	12	13	12
Medium- and Heavy-Duty Trucks	544	506	508	491	495	642	649	597	593	545	542	554	560	552
Recreational Boats[d]	172	197	143	195	192	188	183	180	176	174	173	172	171	170
Distillate Fuel Oil (Diesel Fuel)[c]	**3,555**	**4,379**	**5,437**	**6,186**	**6,334**	**6,394**	**6,059**	**5,488**	**5,706**	**5,814**	**5,780**	**5,866**	**6,052**	**6,229**
Passenger Cars	107	106	49	57	56	55	50	49	51	55	55	55	56	57
Light-Duty Trucks	155	201	272	349	361	183	163	162	169	176	175	174	187	192
Buses	108	118	138	143	143	209	198	184	182	195	208	210	228	233
Medium- and Heavy-Duty Trucks	2,576	3,220	4,181	4,870	4,986	5,167	4,917	4,455	4,634	4,656	4,657	4,733	4,882	4,993
Recreational Boats	26	32	37	43	44	45	46	47	48	49	50	51	52	53
Ships and Non-Recreational Boats	102	167	190	108	100	109	106	106	100	137	101	102	83	163
Rail[e]	480	535	569	616	644	625	580	486	523	547	534	543	563	539
Jet Fuel[f]	**2,590**	**2,429**	**2,700**	**2,622**	**2,524**	**2,485**	**2,396**	**2,134**	**2,097**	**2,030**	**1,985**	**2,037**	**2,057**	**2,184**
Commercial Aircraft	1,562	1,638	1,981	1,887	1,948	1,986	1,809	1,699	1,611	1,629	1,611	1,624	1,638	1,692
General Aviation Aircraft	545	454	427	484	350	276	362	241	314	256	224	274	226	305
Military Aircraft	484	337	293	251	227	224	225	194	173	145	150	138	193	187
Aviation Gasoline[f]	**45**	**40**	**36**	**35**	**33**	**32**	**28**	**27**	**27**	**27**	**25**	**22**	**22**	**21**
General Aviation Aircraft	45	40	36	35	33	32	28	27	27	27	25	22	22	21
Residual Fuel Oil[f, g]	**300**	**387**	**443**	**256**	**306**	**386**	**271**	**186**	**272**	**258**	**211**	**201**	**77**	**47**
Ships and Boats	300	387	443	256	306	386	271	186	272	258	211	201	77	47
Natural Gas[f]	**680**	**724**	**672**	**624**	**625**	**663**	**692**	**715**	**719**	**734**	**780**	**887**	**760**	**732**
Passenger Cars	+	+	0	0	0	0	0	0	0	0	0	0	0	**0**
Light-Duty Trucks	+	+	0	1	1	1	0	0	0	0	0	0	0	0
Medium- and Heavy-Duty Trucks	+	+	0	0	0	0	0	0	0	0	0	0	0	1
Buses	+	+	3	12	13	14	14	15	15	15	15	15	15	14
Pipelines	680	724	668	611	611	649	677	699	703	718	765	872	744	716
LPG[f]	**23**	**18**	**12**	**28**	**27**	**22**	**40**	**28**	**29**	**34**	**37**	**44**	**47**	**48**
Passenger Cars	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Light-Duty Trucks	3	3	3	4	6	5	4	6	5	4	2	3	5	7
Medium- and Heavy-Duty Trucks	18	18	18	17	14	13	14	13	14	16	18	17	15	13
Buses	1	1	1	2	3	4	5	4	4	3	3	3	3	2
Electricity[f]	**3**	**3**	**3**	**5**	**5**	**5**	**5**	**4**	**4**	**4**	**4**	**4**	**4**	**4**

Rail	3	3	3	5	5	5	5	4	4	4	4	4	4	4	4
Total	**21,006**	**22,667**	**25,335**	**26,428**	**26,281**	**26,246**	**25,039**	**24,023**	**24,171**	**23,883**	**23,747**	**24,000**	**24,211**	**24,237**

+ Does not exceed 0.05 tBtu

[a] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007 to 2015 time period. These methodological changes include how on-road vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This resulted in large changes in fuel consumption data by vehicle class between 2006 and 2007.

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

[c] Gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-21, MF-27, and VM-1 (FHWA 1996 through 2016). In 2016, FHWA changed its methods for estimating the share of motor gasoline used in on-highway and off-highway applications. This method change resulted in an increase in the estimated off-highway motor gasoline consumption and subsequent decrease in the on-highway motor gasoline consumption for 2015. Data from Table VM-1 is used to estimate the share of consumption between each on-road vehicle class. Since VM-1 data for 2015 has not been published yet, fuel consumption shares from 2014 are used as a proxy for Public Review. These fuel consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is used as a proxy.

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

[e] Class II and Class II diesel consumption data for 2014 and 2015 is not available yet, therefore 2013 data is used as a proxy.

[f] Estimated based on EIA transportation sector energy estimates, with bottom-up data used for apportionment to modes. Transportation sector natural gas and LPG consumption are based on data from EIA (2016). In prior Inventory years, data from DOE TEDB was used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium and heavy duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2016) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in this year's Inventory and apply to the 1990-2015 time period.

[g] Fluctuations in reported fuel consumption may reflect data collection problems. Residual fuel oil for ships and boats data is based on EIA's December 2016 Monthly Energy Review data.

Table A-95: Transportation Sector Biofuel Consumption by Fuel Type (million gallons)

Fuel Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Ethanol	712	1,326	1,590	3,860	5,207	6,563	9,263	10,537	12,282	12,329	12,324	12,646	12,900	13,385
Biodiesel	NA	NA	NA	91	261	354	304	322	260	886	899	1,429	1,417	1,494

NA (Not Available)

Note: According to the MER, there was no biodiesel consumption prior to 2001.

Estimates of CH_4 and N_2O 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_2O were derived using a methodology similar to that outlined in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

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,[45] buses, and motorcycles) were obtained from the Federal Highway Administration's (FHWA) *Highway Statistics* (FHWA 1996 through 2016).[46] 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 2016) was allocated to fuel types (gasoline, diesel, other) using historical estimates of fuel shares reported in the Appendix to the *Transportation Energy Data Book, Tables A.5 and A.6* (DOE 1993 through 2016). 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. Fuel shares were first adjusted proportionately such that gasoline and diesel shares for each vehicle/fuel type category equaled 100 percent of national VMT. 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 total VMT estimates to develop the final VMT estimates by vehicle/fuel type category.[47] The resulting national VMT estimates for gasoline and diesel on-road vehicles are presented in Table A-96 and Table A-97, 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 30 model years shown for 2015 in Table A-98. 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 MOVES2014a model for years 2009 forward (EPA 2016d).[48] Age-specific vehicle mileage accumulations were also obtained from EPA's MOVES2014a model (EPA 2016d).[49]

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-104 through Table A-107. 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

[45] Medium- and heavy-duty trucks correspond to FHWA's reporting categories of single-unit trucks and combination trucks. Single-unit trucks are defined as single frame trucks that have 2-axles and at least 6 tires or a gross vehicle weight rating (GVWR) exceeding 10,000 lbs.

[46] In 2011 FHWA changed its methods for estimated vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 2010 Inventory and apply to the 2007-14 time period. This resulted in large changes in VMT data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. For example, the category "Passenger Cars" has been replaced by "Light-duty Vehicles-Short Wheelbase" and "Other 2 axle-4 Tire Vehicles" has been replaced by "Light-duty Vehicles, Long Wheelbase." This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this emission inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

[47] 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.

[48] Age distributions were held constant for the period 1990 to 1998, and reflect a 25-year vehicle age span. EPA (2015b) provides a variable age distribution and 31-year vehicle age span beginning in year 1999.

[49] The updated vehicle distribution and mileage accumulation rates by vintage obtained from the MOVES 2014a model resulted in a decrease in emissions due to more miles driven by newer light-duty gasoline vehicles.

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 1998b).[50] EPA Tier 2 regulations affect vehicles produced starting in 2004 and are responsible for a noticeable decrease in N_2O emissions compared EPA Tier 1 emissions technology (EPA 1999b).

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 2015 were determined using confidential engine family sales data submitted to EPA (EPA 2016f). Vehicle classes and emission standard tiers to which each engine family was certified were taken from annual certification test results and data (EPA 2016e). 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_2O Emission Factors by Vehicle, Fuel, and Control Technology Type

Emission factors for gasoline and diesel on-road vehicles utilizing Tier 2 and Low Emission Vehicle (LEV) technologies were developed by ICF (2006b); all other gasoline and diesel on-road vehicle emissions factors were developed by ICF (2004). These factors were based on EPA, CARB and Environment Canada laboratory test results of different vehicle and control technology types. The EPA, CARB and Environment Canada tests were designed following the Federal Test Procedure (FTP), which covers three separate driving segments, since vehicles emit varying amounts of GHGs depending on the driving segment. These driving segments are: (1) a transient driving cycle that includes cold start and running emissions, (2) a cycle that represents running emissions only, and (3) a transient driving cycle that includes hot start and running emissions. For each test run, a bag was affixed to the tailpipe of the vehicle and the exhaust was collected; the content of this bag was 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_2O Emitted by Vehicle, Fuel, and Control Technology Type

Emissions of CH_4 and N_2O 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 "Methodology for Highway Vehicle Alternative Fuel GHG Projections Estimates" (Browning, 2016). Alternative Fuels include Compressed Natural Gas (CNG), Liquid Natural Gas (LNG), Liquefied Petroleum Gas (LPG), Ethanol, Methanol, Biodiesel, Hydrogen and Electricity. 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.[51] Except for electric vehicles and plug-in hybrid vehicles, the alternative fuel vehicle VMT were calculated using the Energy Information Administration (EIA) Alternative Fuel Vehicle Data. The EIA data provides vehicle counts and fuel use for fleet vehicles used by electricity providers, federal agencies, natural gas providers, propane providers, state agencies and transit agencies for calendar years 2003 through 2013. For 1992 to 2002, EIA Data Tables were used to estimate fuel consumption and vehicle counts by vehicle type. These tables give total vehicle fuel use and vehicle counts by fuel and calendar year for the United States over the period 1992 through 2010. Breakdowns by vehicle type for 1992 through 2002 (both fuel consumed and vehicle counts) were assumed to be at the same ratio as for 2003 where data existed. For 1990, 1991 and 2015, fuel consumed by alternative fuel and vehicle type were extrapolated based on a regression analysis using the best curve fit based upon R^2 using the nearest 5 years of data.

For the current Inventory, counts of electric vehicles (EVs) and plug-in hybrid-electric vehicles (PHEVs) were taken from data compiled by the Electric Drive Transportation Association from 2011 to 2015 (EDTA 2016). EVs were divided into cars and trucks using confidential engine family sales data submitted to EPA (EPA 2016f). Fuel use per vehicle

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

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

for personal EVs and PHEVs were assumed to be the same as those for the public fleet vehicles surveyed by EIA and provided in their data tables.

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 the Argonne National Laboratory's GREET2015 model (ANL 2015). 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 (2016). VMT estimates for AFVs by vehicle category (passenger car, light-duty truck, medium-duty and heavy-duty vehicles) are shown in Table A-98, while more detailed estimates of VMT by control technology are shown in Table A-99.

Step 2: Determine CH_4 and N_2O Emission Factors by Vehicle and Alternative Fuel Type

Methane and N_2O 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_2O 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-109.

Step 3: Determine the Amount of CH_4 and N_2O Emitted by Vehicle and Fuel Type

Emissions of CH_4 and N_2O 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

Methane and N_2O 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-103. Consumption data for ships and boats (i.e., vessel bunkering) were obtained from DHS (2008) and EIA (1991 through 2016) for distillate fuel, and DHS (2008) and EIA (2016) for residual fuel; marine transport fuel consumption data for U.S. Territories (EIA 2015) were added to domestic consumption, and this total was reduced by the amount of fuel used for international bunkers.[52] Gasoline consumption by recreational boats was obtained from the NONROAD component of EPA's MOVES2014a model (EPA 2016d). Annual diesel consumption for Class I rail was obtained from the Association of American Railroads (AAR 2008 through 2016), diesel consumption from commuter rail was obtained from APTA (2007 through 2016) and Gaffney (2007), and consumption by Class II and III rail was provided by Benson (2002 through 2004) and Whorton (2006 through 2013).[53] Diesel consumption by commuter and intercity rail was obtained from DOE (1993 through 2016). Data on the consumption of jet fuel and aviation gasoline in aircraft were obtained from EIA (2016) and FAA (2017), 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 (DESC 2016 and FAA 2017). Pipeline fuel consumption was obtained from EIA (2007 through 2016) (note: pipelines are a transportation source but are stationary, not mobile sources). Data on fuel consumption by all non-transportation mobile sources were obtained

[52] See International Bunker Fuels section of the Energy chapter.

[53] Diesel consumption from Class II and Class III railroad were unavailable for 2014. Values are proxied from 2013, which is the last year the data was available.

from the NONROAD component of EPA's MOVES2014a model (EPA 2016d) and from FHWA (1996 through 2016) for gasoline consumption for trucks used off-road.[54,55]

Emissions of CH_4 and N_2O from non-road mobile sources were calculated by multiplying U.S. default emission factors in the *2006 IPCC Guidelines* by activity data for each source type (see Table A-110).

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 2016g), 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-111 through Table A-113 provides complete emission estimates for 1990 through 2015.

Table A-96: Vehicle Miles Traveled for Gasoline On-Road Vehicles (billion miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles[b]	Motorcycles
1990	1,391.4	554.8	25.8	9.6
1991	1,341.9	627.8	25.4	9.2
1992	1,355.1	683.4	25.1	9.6
1993	1,356.8	721.0	24.9	9.9
1994	1,387.7	739.2	25.3	10.2
1995	1,421.0	763.0	25.1	9.8
1996	1,455.1	788.6	24.4	9.9
1997	1,489.0	821.6	24.0	10.1
1998	1,537.1	837.7	24.1	10.3
1999	1,559.6	868.3	24.3	10.6
2000	1,592.2	887.6	24.2	10.5
2001	1,620.1	905.9	23.9	9.6
2002	1,650.0	926.8	23.9	9.6
2003	1,663.6	944.1	24.2	9.6
2004	1,691.2	985.5	24.6	10.1
2005	1,699.7	998.8	24.8	10.5
2006	1,681.9	1,038.6	24.8	12.0
2007	2,093.7	562.8	34.2	21.4
2008	2,014.4	580.9	35.0	20.8
2009	2,005.4	592.4	32.5	20.8
2010	2,015.3	597.4	32.3	18.5
2011[a]	2,035.6	579.6	30.2	18.5
2012	2,051.6	576.8	30.5	21.4
2013	2,062.0	578.7	31.2	20.4
2014	2,058.2	612.4	31.7	20.0
2015	2,129.2	633.8	32.8	20.7

Source: Derived from FHWA (1996 through 2015), Browning (2016).

[a] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007 to 2015 time period. These methodological changes include how on-road vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This resulted in large changes in VMT data by vehicle class between 2006 and 2007.

[b] Heavy-Duty Vehicles includes Medium-Duty Trucks, Heavy-Duty Trucks, and Buses.

Note: In 2015, EIA changed its methods for estimating AFV fuel consumption. These methodological changes included how vehicle counts are estimated, moving from estimates based on modeling to one that is based on survey data. EIA now publishes data about fuel use and number of vehicles for only four types of AFV fleets: federal government, state government, transit agencies, and fuel providers. These changes were first incorporated in the 2014 Inventory and apply to the 1990-2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes.

Note: Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2016). Table VM-1 data for 2015 has not been published yet, therefore 2015 data is estimated for Public Review using the 3.5 percent increase in Traffic Volume Trends from 2014 to 2015. These mileage consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is used as a proxy.

[54] "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.

[55] In 2016, FHWA changed its methods for estimating the share of motor gasoline used in on-highway and off-highway applications. This resulted in an increase in the estimated off-highway motor gasoline consumption and subsequent decrease in the on-highway motor gasoline consumption for 2015.

Table A-97: Vehicle Miles Traveled for Diesel On-Road Vehicles (billion miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles[a]
1990	16.9	19.7	125.7
1991	16.3	21.6	129.4
1992	16.5	23.4	133.6
1993	17.9	24.7	140.6
1994	18.3	25.3	150.8
1995	17.3	26.9	159.0
1996	14.7	27.8	164.6
1997	13.5	29.0	173.8
1998	12.4	30.5	178.8
1999	9.4	32.6	185.6
2000	8.0	35.2	188.4
2001	8.1	37.0	191.5
2002	8.3	38.9	196.7
2003	8.4	39.7	199.6
2004	8.5	41.4	202.1
2005	8.5	41.9	203.4
2006	8.4	43.4	202.3
2007	10.5	23.3	281.8
2008	10.1	24.1	288.1
2009	10.0	24.6	267.6
2010	10.1	24.8	265.8
2011[b]	10.1	23.3	245.6
2012	10.1	23.1	247.9
2013	10.1	22.6	250.5
2014	10.0	24.0	254.9
2015	10.3	24.8	263.8

Source: Derived from FHWA (1996 through 2016), Browning (2016).

[a] Heavy-Duty Vehicles includes Medium-Duty Trucks, Heavy-Duty Trucks, and Buses.

[b] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007 to 2015 time period. These methodological changes include how on-road vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This resulted in large changes in VMT data by vehicle class between 2006 and 2007.

Note: In 2015, EIA changed its methods for estimating AFV fuel consumption. These methodological changes included how vehicle counts are estimated, moving from estimates based on modeling to one that is based on survey data. EIA now publishes data about fuel use and number of vehicles for only four types of AFV fleets: federal government, state government, transit agencies, and fuel providers. These changes were first incorporated in the 2014 Inventory and apply to the 1990 to 2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes.

Note: Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2016). Table VM-1 data for 2015 has not been published yet, therefore 2015 data is estimated for Public Review using the 3.5 percent increase in FHWA Traffic Volume Trends from 2014 to 2015. These mileage consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is used as a proxy.

Table A-98: Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (billion miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles[a]
1990	0.0	0.1	0.5
1991	0.0	0.1	0.5
1992	0.0	0.1	0.4
1993	0.0	0.1	0.6
1994	0.1	0.1	0.5
1995	0.1	0.1	0.5
1996	0.1	0.1	0.5
1997	0.1	0.1	0.5
1998	0.1	0.1	0.5
1999	0.1	0.1	0.5
2000	0.1	0.2	0.6
2001	0.1	0.2	0.7
2002	0.1	0.3	0.8
2003	0.2	0.3	0.9
2004	0.2	0.3	1.0
2005	0.2	0.3	1.3
2006	0.2	0.5	2.2
2007	0.3	0.6	2.7
2008	0.3	0.5	2.4
2009	0.3	0.5	2.5
2010	0.3	0.5	2.2
2011	0.6	1.2	5.6
2012	1.1	1.3	5.6
2013	2.3	2.0	8.5
2014	3.9	2.1	8.5
2015	5.1	2.2	8.9

Source: Derived from Browning (2016).

[a] Heavy Duty-Vehicles includes medium-duty trucks, heavy-duty trucks, and buses.

Note: In 2015, EIA changed its methods for estimating AFV fuel consumption. These methodological changes included how vehicle counts are estimated, moving from estimates based on modeling to one that is based on survey data. EIA now publishes data about fuel use and number of vehicles for only four types of AFV fleets: federal government, state government, transit agencies, and fuel providers. These changes were first incorporated in the 2014 Inventory and apply to the 1990 to 2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes. In 2016, estimates of alternative fuel vehicle mileage for the last ten years were revised to reflect updates made to EIA data on alternative fuel use and vehicle counts. These changes were first incorporated in this year's Inventory and apply to the 2005 to 2015 time period.

Table A-99: Detailed Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (10^6 Miles)

Vehicle Type/Year	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Light-Duty Cars	**4.0**	**56.0**	**78.1**	**195.1**	**230.8**	**252.9**	**261.3**	**296.8**	**345.6**	**577.1**	**1,101.2**	**2,335.3**	**3,864.2**	**5,066.7**
Methanol-Flex Fuel ICE	+	48.9	15.2	+	+	+	+	+	+	+	+	+	+	+
Ethanol-Flex Fuel ICE	+	0.3	20.9	51.0	59.2	72.8	84.2	96.2	122.2	118.5	148.9	173.5	135.4	126.5
CNG ICE	+	0.1	5.5	15.9	14.7	14.6	13.1	12.3	11.7	12.3	12.5	13.3	12.6	14.2
CNG Bi-fuel	+	0.2	18.0	40.6	25.4	19.3	13.0	10.1	8.1	7.1	4.5	3.5	2.6	1.7
LPG ICE	1.1	1.2	1.2	0.1	0.2	1.7	1.7	1.7	+	0.2	0.2	0.4	3.5	6.1
LPG Bi-fuel	2.8	3.0	3.0	3.3	3.7	1.7	1.6	1.8	1.2	0.3	0.3	0.2	0.1	+
Biodiesel (BD100)	+	+	1.0	14.6	41.4	50.2	39.1	46.4	39.4	149.4	180.3	310.3	333.2	368.3
NEVs	+	2.0	11.9	67.5	81.7	82.8	87.7	83.7	68.5	97.3	83.8	73.3	64.4	46.7
Electric Vehicle	+	0.2	1.5	2.1	4.5	9.7	20.7	44.1	94.3	169.3	533.5	1,484.1	2,844.9	3,804.9
SI PHEV - Electricity	+	+	+	+	+	+	+	+	+	22.5	137.2	276.5	467.4	698.2
Fuel Cell Hydrogen	+	+	+	+	+	0.3	0.2	0.5	0.2	0.1	0.1	0.1	0.1	0.1
Light-Duty Trucks	**77.4**	**93.3**	**180.9**	**333.1**	**491.8**	**556.3**	**458.8**	**511.5**	**463.7**	**1,223.2**	**1,340.5**	**2,036.7**	**2,058.7**	**2,180.2**
Ethanol-Flex Fuel ICE	+	0.3	23.4	54.5	62.8	77.0	89.6	102.7	130.9	144.2	191.8	227.2	222.3	238.2
CNG ICE	+	0.1	5.6	14.5	15.2	13.7	10.8	10.3	9.2	9.7	9.9	9.5	8.2	9.2
CNG Bi-fuel	+	0.4	47.2	72.8	68.8	61.3	26.3	22.0	20.6	19.7	16.0	17.4	20.9	26.6
LPG ICE	22.4	26.5	27.6	32.6	28.9	23.3	11.6	13.5	10.8	10.6	6.5	6.9	7.8	9.1
LPG Bi-fuel	55.0	65.1	67.7	67.6	54.8	32.0	24.8	28.9	24.9	13.1	5.2	6.3	23.4	46.8
LNG	+	+	0.1	0.3	0.2	0.2	0.3	0.2	+	+	+	+	+	+
Biodiesel (BD100)	+	+	4.1	85.3	253.9	341.1	287.9	326.6	260.2	1,020.9	1,107.2	1,752.0	1,741.4	1,803.3
Electric Vehicle	+	0.8	5.3	5.6	7.1	7.7	7.5	7.3	7.0	4.6	3.7	17.1	34.4	46.6
Fuel Cell Hydrogen	+	+	+	+	+	0.1	0.1	0.2	0.1	0.3	0.2	0.2	0.3	0.3
Medium Duty Trucks	**324.5**	**317.4**	**308.6**	**352.8**	**543.5**	**640.9**	**580.1**	**607.0**	**457.1**	**1,414.9**	**1,475.6**	**2,335.2**	**2,362.7**	**2,499.7**
CNG ICE	+	+	1.1	4.1	2.8	5.8	8.0	6.9	6.6	9.0	10.6	11.1	12.5	13.7
CNG Bi-fuel	+	0.1	10.5	15.5	13.0	11.4	9.7	8.0	7.5	7.3	8.3	8.7	11.9	13.6
LPG ICE	271.5	265.4	242.4	155.6	82.1	61.3	46.5	41.5	36.5	34.1	32.3	29.6	28.7	28.9
LPG Bi-fuel	53.0	51.8	47.3	43.8	23.6	10.3	16.5	8.4	10.3	9.3	12.6	13.7	17.7	24.4
LNG	+	+	+	+	+	+	+	+	+	+	+	0.1	+	+
Biodiesel (BD100)	+	+	7.3	133.7	422.0	552.0	499.4	542.3	396.2	1,355.2	1,411.8	2,271.9	2,291.8	2,419.1
Heavy-Duty Trucks	**130.4**	**127.6**	**137.1**	**440.2**	**1,047.4**	**1,389.7**	**1,181.2**	**1,228.4**	**1,024.7**	**3,370.2**	**3,369.7**	**5,321.9**	**5,297.6**	**5,561.8**
Neat Ethanol ICE	+	+	+	1.9	2.2	2.7	3.1	3.5	4.5	7.0	11.3	15.6	18.7	23.2
CNG ICE	+	+	0.9	1.9	2.7	2.9	2.7	3.4	3.6	3.6	4.1	5.0	5.5	6.0
LPG ICE	122.1	119.5	109.1	87.2	76.6	65.8	56.2	49.6	41.0	43.1	28.0	27.6	22.4	20.4
LPG Bi-fuel	8.3	8.1	7.4	5.4	4.8	4.6	4.6	5.4	5.6	8.3	6.5	7.1	3.1	+
LNG	+	+	+	0.8	0.9	0.9	1.2	1.3	1.5	1.7	1.7	1.5	2.0	2.0
Biodiesel (BD100)	+	+	19.7	343.0	960.2	1,312.8	1,113.4	1,165.1	968.4	3,306.4	3,318.2	5,265.1	5,246.0	5,510.2
Buses	**24.6**	**46.3**	**150.7**	**524.6**	**629.8**	**625.6**	**656.3**	**685.3**	**695.5**	**779.6**	**770.3**	**833.7**	**846.5**	**820.0**
Neat Methanol ICE	7.8	12.7	+	+	+	+	+	+	+	+	+	+	+	+
Neat Ethanol ICE	+	5.9	0.1	+	+	+	+	+	+	+	0.1	0.1	3.3	3.3
CNG ICE	+	1.1	104.1	413.5	481.7	509.8	546.2	581.7	605.4	637.1	628.3	650.1	650.3	617.8
LPG ICE	16.4	15.8	14.4	11.7	13.3	12.3	13.4	9.0	8.1	4.8	4.7	5.0	5.4	6.3

LNG	0.4	8.9	23.2	61.4	66.8	40.2	39.8	36.0	36.8	39.5	41.1	29.4	38.2	35.4
Biodiesel (BD100)	+	+	0.8	13.2	38.9	53.3	46.6	51.7	38.1	90.1	90.7	143.5	142.8	149.5
Electric	+	1.8	8.2	24.8	29.0	9.9	10.2	6.8	7.0	7.7	5.1	5.3	6.1	7.3
Fuel Cell Hydrogen	+	+	+	+	0.1	0.1	0.1	0.1	0.2	0.3	0.3	0.3	0.3	0.3
Total VMT	**560.8**	**640.5**	**855.5**	**1,845.8**	**2,943.3**	**3,465.4**	**3,137.8**	**3,329.0**	**2,986.6**	**7,365.0**	**8,057.3**	**12,862.7**	**14,429.6**	**16,128.5**

1+ Does not exceed 0.05 million vehicle miles traveled
2Note: 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.
3In 2015, EIA changed its methods for estimating AFV fuel consumption. These methodological changes included how vehicle counts are estimated, moving from estimates based on modeling to one that is based on
4survey data. EIA now publishes data about fuel use and number of vehicles for only four types of AFV fleets: federal government, state government, transit agencies, and fuel providers. These changes were first
5incorporated in the 2014 Inventory and apply to the 1990 to 2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes. In 2016, estimates of
6alternative fuel vehicle mileage for the last ten years were revised to reflect updates made to EIA data on alternative fuel use and vehicle counts. These changes were first incorporated in this year's Inventory and
7apply to the 2005 to 2015 time period
8Source: Derived from Browning (2016).
9

Table A-100: Age Distribution by Vehicle/Fuel Type for On-Road Vehicles,[a] 2015

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC
0	7.2%	8.2%	6.5%	13.6%	8.8%	6.2%	7.3%
1	7.1%	7.8%	6.0%	13.3%	8.3%	5.7%	7.1%
2	6.8%	7.3%	5.4%	12.8%	7.9%	5.1%	6.7%
3	6.5%	7.0%	4.9%	12.3%	7.5%	4.8%	6.0%
4	4.0%	4.7%	2.8%	7.6%	5.1%	3.0%	4.8%
5	4.5%	4.1%	1.9%	7.3%	3.0%	2.0%	4.3%
6	4.1%	3.0%	1.7%	4.8%	2.6%	2.4%	4.5%
7	5.1%	5.1%	3.2%	0.4%	6.4%	3.6%	7.9%
8	5.6%	5.3%	2.9%	0.3%	5.7%	7.0%	7.1%
9	5.1%	5.3%	4.1%	5.6%	7.1%	6.0%	6.7%
10	5.1%	5.4%	3.3%	3.8%	6.0%	5.5%	5.9%
11	4.7%	5.2%	4.0%	2.3%	5.3%	3.8%	5.0%
12	4.8%	4.7%	3.5%	3.0%	4.7%	3.4%	4.3%
13	4.5%	4.4%	3.5%	3.1%	4.0%	2.7%	3.7%
14	4.0%	3.8%	2.9%	1.9%	4.5%	3.6%	3.2%
15	3.8%	3.5%	5.6%	1.6%	2.3%	5.5%	2.5%
16	2.9%	2.9%	5.4%	0.9%	3.3%	4.4%	1.9%
17	2.3%	2.3%	2.3%	0.8%	1.2%	2.9%	1.6%
18	2.1%	2.0%	4.2%	0.3%	1.5%	2.8%	1.6%
19	1.7%	1.4%	2.5%	0.3%	1.1%	2.5%	1.4%
20	1.7%	1.4%	3.5%	0.2%	0.8%	3.1%	1.0%
21	1.3%	1.1%	2.7%	0.0%	0.5%	2.3%	1.2%
22	1.1%	0.8%	2.2%	0.1%	0.5%	1.7%	1.0%
23	0.9%	0.6%	1.7%	0.2%	0.5%	1.2%	0.8%
24	0.7%	0.5%	1.3%	0.3%	0.3%	1.1%	0.6%
25	0.6%	0.5%	1.9%	0.1%	0.2%	1.4%	0.5%
26	0.5%	0.5%	2.2%	0.1%	0.2%	1.4%	0.4%
27	0.4%	0.4%	1.8%	0.0%	0.2%	1.2%	0.3%
28	0.3%	0.3%	1.7%	0.7%	0.1%	1.0%	0.3%
29	0.3%	0.3%	1.7%	0.4%	0.2%	0.7%	0.3%
30	0.3%	0.2%	2.9%	1.8%	0.2%	1.6%	0.3%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

Source: EPA (2016b).

Note: This year's Inventory includes updated vehicle population data based on the MOVES 2014a Model.

[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).

Table A-101: Annual Average Vehicle Mileage Accumulation per Vehicle[a] (miles)

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC[b]
0	13,712	15,498	19,032	13,712	15,498	41,675	7,577
1	13,452	15,207	19,036	13,452	15,207	41,413	4,046
2	13,170	14,878	19,039	13,170	14,878	41,193	3,061
3	12,870	14,519	19,043	12,870	14,519	41,921	2,531
4	12,553	14,131	16,772	12,553	14,131	46,741	2,190
5	12,220	13,719	14,489	12,220	13,719	45,576	1,947
6	11,875	13,287	13,981	11,875	13,287	47,032	1,765
7	11,520	12,837	14,612	11,520	12,837	33,200	1,622
8	11,156	12,375	12,219	11,156	12,375	43,952	1,500
9	10,785	11,906	12,380	10,785	11,906	36,876	1,402
10	10,410	11,430	10,491	10,410	11,430	34,839	1,318
11	10,033	10,954	10,254	10,033	10,954	28,657	1,243
12	9,656	10,481	9,092	9,656	10,481	27,572	1,182
13	9,282	10,017	8,282	9,282	10,016	23,494	1,121
14	8,912	9,562	7,056	8,912	9,562	21,260	1,068
15	8,547	9,122	7,299	8,547	9,122	19,488	1,023
16	8,192	8,702	6,145	8,192	8,702	16,393	985

17	7,847	8,304	5,709	7,847	8,304	15,976	947
18	7,514	7,934	5,148	7,514	7,934	11,931	909
19	7,197	7,594	4,864	7,197	7,594	12,666	879
20	6,896	7,289	4,825	6,896	7,289	10,576	849
21	6,616	7,022	4,349	6,616	7,022	9,298	826
22	6,355	6,798	4,341	6,355	6,798	8,711	803
23	6,118	6,621	3,652	6,118	6,621	7,984	758
24	5,907	6,494	3,612	5,907	6,494	7,293	712
25	5,723	6,419	3,385	5,723	6,419	6,242	667
26	5,569	6,405	3,189	5,569	6,405	5,319	614
27	5,447	6,405	2,872	5,447	6,405	4,790	568
28	5,359	6,405	2,642	5,359	6,405	4,535	538
29	5,307	6,405	2,438	5,307	6,405	3,807	500
30	5,307	6,405	2,375	5,307	6,405	2,872	462

Source: EPA (2016b).

[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-102: VMT Distribution by Vehicle Age and Vehicle/Fuel Type, [a] 2015

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC
0	9.21%	10.49%	11.99%	15.60%	11.00%	9.08%	25.10%
1	8.88%	9.77%	11.07%	15.03%	10.24%	8.29%	13.20%
2	8.31%	9.03%	9.97%	14.07%	9.45%	7.40%	9.32%
3	7.84%	8.42%	9.17%	13.29%	8.81%	7.04%	6.89%
4	4.71%	5.45%	4.58%	7.99%	5.84%	4.91%	4.78%
5	5.14%	4.64%	2.63%	7.49%	3.29%	3.16%	3.84%
6	4.52%	3.35%	2.27%	4.78%	2.84%	3.97%	3.61%
7	5.52%	5.47%	4.56%	0.42%	6.67%	4.19%	5.87%
8	5.79%	5.44%	3.50%	0.28%	5.68%	10.81%	4.83%
9	5.15%	5.20%	5.01%	5.09%	6.84%	7.81%	4.28%
10	4.89%	5.07%	3.35%	3.36%	5.56%	6.75%	3.52%
11	4.34%	4.75%	4.05%	1.93%	4.66%	3.86%	2.82%
12	4.29%	4.07%	3.12%	2.40%	4.00%	3.29%	2.29%
13	3.90%	3.67%	2.83%	2.40%	3.24%	2.25%	1.92%
14	3.29%	3.04%	1.99%	1.40%	3.46%	2.68%	1.55%
15	3.03%	2.62%	4.03%	1.12%	1.71%	3.79%	1.18%
16	2.24%	2.10%	3.24%	0.60%	2.29%	2.53%	0.86%
17	1.71%	1.56%	1.27%	0.54%	0.81%	1.65%	0.71%
18	1.46%	1.28%	2.11%	0.19%	0.96%	1.18%	0.65%
19	1.12%	0.89%	1.18%	0.20%	0.70%	1.12%	0.55%
20	1.07%	0.82%	1.63%	0.14%	0.49%	1.14%	0.40%
21	0.79%	0.67%	1.15%	0.02%	0.27%	0.76%	0.45%
22	0.64%	0.46%	0.92%	0.06%	0.28%	0.52%	0.35%
23	0.50%	0.34%	0.60%	0.08%	0.25%	0.33%	0.28%
24	0.41%	0.28%	0.48%	0.16%	0.14%	0.29%	0.21%
25	0.33%	0.25%	0.61%	0.05%	0.11%	0.31%	0.16%
26	0.26%	0.25%	0.68%	0.03%	0.10%	0.25%	0.11%
27	0.20%	0.21%	0.50%	0.01%	0.08%	0.20%	0.08%
28	0.16%	0.16%	0.43%	0.30%	0.03%	0.16%	0.08%
29	0.13%	0.16%	0.40%	0.16%	0.11%	0.10%	0.06%
30	0.16%	0.11%	0.67%	0.81%	0.08%	0.16%	0.05%
Total	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

Model that affects this distribution.

[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).

Note: Estimated by weighting data in by data in Table A-101. This year's Inventory includes updated vehicle population data based on the MOVES 2014a.

Table A-103: Fuel Consumption for Off-Road Sources by Fuel Type (million gallons)

Vehicle Type/Year	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Aircraft[a]	**19,560**	**18,320**	**20,304**	**19,714**	**18,973**	**18,670**	**17,984**	**16,030**	**15,762**	**15,262**	**14,914**	**15,274**	**15,418**	**16,352**
Aviation Gasoline	374	329	302	294	278	263	235	221	225	225	209	186	181	176
Jet Fuel	19,186	17,991	20,002	19,420	18,695	18,407	17,749	15,809	15,537	15,036	14,705	15,088	15,237	16,176
Commercial Aviation[b]	*11,569*	*12,136*	*14,672*	*13,976*	*14,426*	*14,708*	*13,400*	*12,588*	*11,931*	*12,067*	*11,932*	*12,031*	*12,131*	*12,534*
Ships and Boats	**4,507**	**5,789**	**6,407**	**4,858**	**5,120**	**5,723**	**4,860**	**4,289**	**5,740**	**5,915**	**5,340**	**5,293**	**4,329**	**4,719**
Diesel	1,043	1,546	1,750	1,470	1,409	1,489	1,470	1,480	1,446	1,727	1,475	1,499	1,370	1,967
Gasoline	1,403	1,597	1,629	1,607	1,597	1,587	1,577	1,568	1,556	1,545	1,535	1,528	1,522	1,519
Residual	2,061	2,646	3,028	1,781	2,115	2,647	1,812	1,241	2,738	2,643	2,330	2,265	1,437	1,233
Construction/Mining Equipment[c]	**4,160**	**4,835**	**5,523**	**6,617**	**6,755**	**6,785**	**6,939**	**7,066**	**7,312**	**7,418**	**7,586**	**8,187**	**7,949**	**7,869**
Diesel	3,674	4,387	5,181	5,922	6,069	6,216	6,363	6,511	6,658	6,806	6,954	7,102	7,250	7,372
Gasoline	486	448	342	695	686	569	575	556	655	612	632	1,085	698	497
Agricultural Equipment[d]	**3,134**	**3,698**	**3,929**	**4,776**	**5,011**	**4,926**	**4,582**	**4,708**	**4,807**	**4,998**	**5,157**	**5,021**	**5,094**	**4,693**
Diesel	2,321	2,772	3,277	3,699	3,782	3,865	3,948	4,032	4,115	4,199	4,282	4,366	4,450	4,534
Gasoline	813	927	652	1,078	1,229	1,061	634	676	692	799	875	655	644	159
Rail	**3,461**	**3,864**	**4,106**	**4,446**	**4,665**	**4,539**	**4,216**	**3,535**	**3,807**	**3,999**	**3,921**	**4,025**	**4,175**	**4,000**
Diesel	3,461	3,864	4,106	4,446	4,665	4,539	4,216	3,535	3,807	3,999	3,921	4,025	4,175	4,000
Other[e]	**5,916**	**6,525**	**6,798**	**8,255**	**8,370**	**8,229**	**8,360**	**8,455**	**8,804**	**8,768**	**8,703**	**8,800**	**8,952**	**10,042**
Diesel	1,423	1,720	2,050	2,380	2,446	2,512	2,579	2,645	2,711	2,778	2,844	2,910	2,977	2,960
Gasoline	4,493	4,805	4,748	5,875	5,924	5,717	5,782	5,810	6,093	5,990	5,859	5,890	5,975	7,082
Total	**40,738**	**43,031**	**47,067**	**48,666**	**48,894**	**48,872**	**46,941**	**44,083**	**46,233**	**46,359**	**45,622**	**46,600**	**45,917**	**47,675**

[a] For aircraft, this is aviation gasoline. For all other categories, this is motor gasoline.

[b] Commercial aviation, as modeled in FAA's AEDT, consists of passenger aircraft, cargo, and other chartered flights.

[c] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[d] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[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: In 2016, FHWA changed its methods for estimating the share of motor gasoline used in on-highway and off-highway applications. This resulted in an increase in the estimated off-highway motor gasoline consumption and subsequent decrease in the on-highway motor gasoline consumption for 2015.

In 2015, EPA incorporated the NONROAD2008 model into MOVES2014a. This year's inventory uses the NONROAD component of MOVES2014a for years 1999 through 2015.

Sources: AAR (2008 through 2016), APTA (2007 through 2016), BEA (1991 through 2016), Benson (2002 through 2004), DHS (2008), DOC (1991 through 2016), DESC (2016), DOE (1993 through 2016), DOT (1991 through 2016), EIA (2002), EIA (2007b), EIA (2016), EIA (2007 through 2016), EIA (1991 through 2016), EPA (2016d), FAA (2017), Gaffney (2007), and Whorton (2006 through 2014).

Table A-104: 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%	82%	18%	-
1999	-	-	<1%	67%	33%	-
2000	-	-	-	44%	56%	-
2001	-	-	-	3%	97%	-
2002	-	-	-	1%	99%	-
2003	-	-	-	<1%	85%	15%
2004	-	-	-	<1%	24%	76%
2005	-	-	-	-	13%	87%
2006	-	-	-	-	18%	82%
2007	-	-	-	-	4%	96%
2008	-	-	-	-	2%	98%
2009-15	-	-	-	-	-	100%

Sources: EPA (1998), EPA (2016e), and EPA (2016f).

- Not applicable.

Note: Detailed descriptions of emissions control technologies are provided in the following section of this Annex. In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, which emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous Inventories, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore were not included in the engine technology breakouts. For this Inventory, HEVs are now classified as gasoline vehicles across the entire time series.

Table A-105: 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	-	-	-	87%	13%	-
1999	-	-	-	61%	39%	-
2000	-	-	-	63%	37%	-
2001	-	-	-	24%	76%	-
2002	-	-	-	31%	69%	-
2003	-	-	-	25%	69%	6%
2004	-	-	-	1%	26%	73%

2005	-	-	-	-	17%	83%
2006	-	-	-	-	24%	76%
2007	-	-	-	-	14%	86%
2008-2015	-	-	-	-	-	100%

Sources: EPA (1998), EPA (2016e), and EPA (2016f).
- Not applicable.
[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.
Note: In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, which emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous Inventories, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore were not included in the engine technology breakouts. For this Inventory, HEVs are now classified as gasoline vehicles across the entire time series.

Table A-106: 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	-	-	-	-	100%	0%	-
1999	-	-	-	-	98%	2%	-
2000	-	-	-	-	93%	7%	-
2001	-	-	-	-	78%	22%	-
2002	-	-	-	-	94%	6%	-
2003	-	-	-	-	85%	14%	1%
2004	-	-	-	-	0%	33%	67%
2005	-	-	-	-	-	15%	85%
2006	-	-	-	-	-	50%	50%
2007	-	-	-	-	-	0%	100%
2008-2015	-	-	-	-	-	-	100%

Sources: EPA (1998), EPA (2016e), and EPA (2016f).
- Not applicable.
[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.
Note: In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, which emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous Inventories, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore were not included in the engine technology breakouts. For this Inventory, HEVs are now classified as gasoline vehicles across the entire time series.

Table A-107: 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	1996-2015
Diesel Medium- and Heavy-Duty Trucks and Buses	
Uncontrolled	1960-1990
Moderate control	1991-2003
Advanced control	2004-2006
Aftertreatment	2007-2015
Motorcycles	

Uncontrolled	1960-1995
Non-catalyst controls	1996-2015

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

Table A-108: 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).
[a] The categories "EPA Tier 0" and "EPA Tier 1" were substituted for the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the *2006 IPCC Guidelines*. Detailed descriptions of emissions control technologies are provided at the end of this Annex.

Table A-109: Emission Factors for CH_4 and N_2O for Alternative Fuel Vehicles (g/mi)

	N_2O	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-110: Emission Factors for CH_4 and N_2O Emissions from Non-Road Mobile Combustion (g/kg fuel)

Vehicle Type/Fuel Type	N_2O	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[b]		
Gasoline	0.08	0.18
Diesel	0.08	0.18
Other Non-Road		
All "Other" Categories[c]	0.08	0.18
Aircraft		
Jet Fuel[d]	0.10	0.00
Aviation Gasoline	0.04	2.64

Source: IPCC (2006) 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.

[d] Emissions of CH_4 from jet fuels have been zeroed out across the time series. Recent research indicates that modern aircraft jet engines are typically net consumers of methane (Santoni et al. 2011). Methane is emitted at low power and idle operation, but at higher power modes aircraft engines consumer methane. Over the range of engine operating modes, aircraft engines are net consumers of methane on average. Based on this data, CH_4 emissions factors for jet aircraft were changed to zero in this year's Inventory to reflect the latest emissions testing data.

Table A-111: NO_x Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Gasoline On-Road	**5,746**	**4,560**	**3,812**	**3,984**	**3,819**	**3,654**	**3,317**	**2,966**	**2,724**	**2,805**	**2,614**	**2,423**	**2,232**	**1,976**
Passenger Cars	3,847	2,752	2,084	2,174	2,083	1,993	1,810	1,618	1,486	1,530	1,426	1,322	1,217	1,080
Light-Duty Trucks	1,364	1,325	1,303	1,378	1,321	1,264	1,147	1,026	942	970	904	838	772	683
Medium- and Heavy-Duty Trucks and Buses	515	469	411	418	401	383	348	311	286	294	274	254	234	207
Motorcycles	20	14	13	15	14	13	12	11	10	10	10	9	8	7
Diesel On-Road	**2,956**	**3,493**	**3,803**	**3,580**	**3,431**	**3,283**	**2,980**	**2,665**	**2,448**	**2,520**	**2,349**	**2,177**	**2,005**	**1,776**
Passenger Cars	39	19	7	6	6	6	5	5	4	4	4	4	4	3
Light-Duty Trucks	20	12	6	6	6	5	5	4	4	4	4	4	3	3
Medium- and Heavy-Duty Trucks and Buses	2,897	3,462	3,791	3,568	3,420	3,272	2,970	2,656	2,439	2,512	2,341	2,169	1,998	1,769
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**2,160**	**2,483**	**2,584**	**2,731**	**2,490**	**2,249**	**2,226**	**2,166**	**2,118**	**1,968**	**1,908**	**1,848**	**1,788**	**1,420**
Ships and Boats	402	488	506	565	515	465	460	448	438	407	395	382	370	344
Rail	338	433	451	504	460	415	411	400	391	363	352	341	330	307
Aircraft[b]	25	31	40	41	37	34	33	32	32	29	29	28	27	25
Agricultural Equipment[c]	437	478	484	494	450	407	402	392	383	356	345	334	323	301
Construction/Mining Equipment[d]	641	697	697	709	647	584	578	563	550	511	496	480	464	433
Other[e]	318	357	407	418	381	344	341	332	324	301	292	283	274	10
Total	**10,862**	**10,536**	**10,199**	**10,295**	**9,740**	**9,186**	**8,523**	**7,797**	**7,290**	**7,294**	**6,871**	**6,448**	**6,024**	**5,172**

IE (Included Elsewhere)

[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: The source of this data is the National Emissions Inventory. Updates to estimates from MOVES2014a is a change that affects the emissions time series.

Note: Totals may not sum due to independent rounding.

Table A-112: CO Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Gasoline On-Road	**98,328**	**74,673**	**60,657**	**38,265**	**35,781**	**33,298**	**29,626**	**24,515**	**25,235**	**24,442**	**22,805**	**21,167**	**19,529**	**17,739**
Passenger Cars	60,757	42,065	32,867	21,319	19,936	18,552	16,506	13,659	14,060	13,618	12,706	11,793	10,881	9,883
Light-Duty Trucks	29,237	27,048	24,532	15,230	14,242	13,253	11,792	9,758	10,044	9,729	9,077	8,425	7,773	7,061
Medium- and Heavy-Duty Trucks and Buses	8,093	5,404	3,104	1,627	1,521	1,416	1,259	1,042	1,073	1,039	969	900	830	754
Motorcycles	240	155	154	89	83	77	69	57	58	57	53	49	45	41
Diesel On-Road	**1,696**	**1,424**	**1,088**	**586**	**548**	**510**	**454**	**376**	**387**	**375**	**349**	**324**	**299**	**272**
Passenger Cars	35	18	7	4	4	3	3	3	3	3	2	2	2	2
Light-Duty Trucks	22	16	6	4	3	3	3	2	2	2	2	2	2	2
Medium- and Heavy-Duty Trucks and Buses	1,639	1,391	1,075	579	541	504	448	371	382	370	345	320	295	268
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**19,337**	**21,533**	**21,814**	**19,763**	**18,382**	**17,001**	**16,137**	**14,365**	**13,853**	**13,488**	**12,999**	**12,509**	**12,019**	**11,870**
Ships and Boats	1,559	1,781	1,825	1,626	1,512	1,398	1,327	1,182	1,140	1,109	1,069	1,029	989	976
Rail	85	93	90	80	74	69	65	58	56	54	52	50	48	48
Aircraft[b]	217	224	245	207	193	178	169	151	145	141	136	131	126	124
Agricultural Equipment[c]	581	628	626	551	513	474	450	401	386	376	363	349	335	331
Construction/Mining Equipment[d]	1,090	1,132	1,047	924	860	795	755	672	648	631	608	585	562	555
Other[e]	15,805	17,676	17,981	16,375	15,231	14,087	13,371	11,903	11,479	11,176	10,770	10,364	9,959	9,835
Total	**119,360**	**97,630**	**83,559**	**58,615**	**54,712**	**50,809**	**46,217**	**39,256**	**39,475**	**38,305**	**36,153**	**34,000**	**31,848**	**29,881**

IE (Included Elsewhere)

[a] CO 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.

Notes: The source of this data is the National Emissions Inventory. Updates to estimates from MOVES2014a is a change that affects the emissions time series. Totals may not sum due to independent rounding.

Table A-113: NMVOCs Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Gasoline On-Road	**8,110**	**5,819**	**4,615**	**2,979**	**2,997**	**3,015**	**2,641**	**2,384**	**2,393**	**2,485**	**2,292**	**2,099**	**1,906**	**1,716**
Passenger Cars	5,120	3,394	2,610	1,664	1,674	1,684	1,475	1,332	1,336	1,388	1,280	1,172	1,065	958
Light-Duty Trucks	2,374	2,019	1,750	1,157	1,164	1,171	1,025	926	929	965	890	815	740	666
Medium- and Heavy-Duty Trucks and Buses	575	382	232	143	144	145	127	115	115	120	110	101	92	83
Motorcycles	42	24	23	15	15	15	14	12	12	13	12	11	10	9
Diesel On-Road	**406**	**304**	**216**	**144**	**145**	**146**	**128**	**115**	**116**	**120**	**111**	**102**	**92**	**83**
Passenger Cars	16	8	3	2	2	2	2	2	2	2	2	1	1	1
Light-Duty Trucks	14	9	4	3	3	3	2	2	2	2	2	2	2	1
Medium- and Heavy-Duty Trucks and Buses	377	286	209	140	140	141	124	112	112	116	107	98	89	80
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**2,415**	**2,622**	**2,398**	**2,600**	**2,491**	**2,383**	**2,310**	**2,150**	**2,082**	**1,957**	**1,840**	**1,723**	**1,607**	**1,519**
Ships and Boats	608	739	744	798	764	731	709	660	639	600	565	529	493	466
Rail	33	36	35	39	37	35	34	32	31	29	27	26	24	23
Aircraft[b]	28	28	24	21	20	19	19	17	17	16	15	14	13	12
Agricultural Equipment[c]	85	86	76	79	76	73	70	65	63	60	56	52	49	46
Construction/Mining Equipment[d]	149	152	130	137	131	125	121	113	109	103	97	91	84	80
Other[e]	1,512	1,580	1,390	1,527	1,463	1,399	1,356	1,263	1,223	1,149	1,081	1,012	944	892
Total	**10,932**	**8,745**	**7,230**	**5,724**	**5,634**	**5,544**	**5,078**	**4,650**	**4,591**	**4,562**	**4,243**	**3,924**	**3,605**	**3,318**

IE (Included Elsewhere)

[a] NMVOC 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.

Notes: The source of this data is the National Emissions Inventory. Updates to estimates from MOVES2014a is a change that affects the emissions time series. Totals may not sum due to independent rounding.

Definitions of Emission Control Technologies and Standards

The N_2O and CH_4 emission factors used depend on the emission standards in place and the corresponding level of control technology for each vehicle type. Table A-104 through Table A-107 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 and were compiled from EPA (1993, 1994a, 1994b, 1998, 1999a) and IPCC/UNEP/OECD/IEA (1997).

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 percent 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 three 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 NO_x 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 report 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-114 provides estimates of CO_2 from these other mobile sources, developed from EPA's NONROAD components of the MOVES2014a

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-114: CO_2 Emissions from Non-Transportation Mobile Sources (MMT CO_2 Eq.)

Fuel Type/Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Agricultural Equipment[a]	31.0	36.6	39.3	47.4	49.5	48.7	45.7	46.9	47.8	49.6	51.1	50.0	50.8	47.5
Construction/Mining Equipment[b]	42.0	48.9	56.1	66.8	68.1	68.3	69.8	71.1	73.4	74.5	76.1	81.5	79.7	79.2
Other Sources[c]	54.5	59.9	62.6	75.9	77.1	75.7	76.4	77.1	80.0	79.6	79.1	80.1	81.4	90.7
Total	**127.6**	**145.4**	**158.0**	**190.0**	**194.6**	**192.8**	**191.9**	**195.1**	**201.2**	**203.7**	**206.3**	**211.6**	**211.9**	**217.4**

[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.

Note: In 2016, FHWA changed its methods for estimating the share of motor gasoline used in on-highway and off-highway applications. This resulted in an increase in the estimated off-highway motor gasoline consumption and subsequent decrease in the on-highway motor gasoline consumption for 2015.

In 2015, EPA incorporated the NONROAD2008 model into MOVES2014a. This year's Inventory uses the NONROAD component of MOVES2014a for years 1999 through 2015.

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 air-conditioning 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-115 below presents these HFC emissions. Table A-116 presents all transportation and mobile source greenhouse gas emissions, including HFC emissions.

Table A-115: HFC Emissions from Transportation Sources (MMT CO_2 Eq.)

Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Mobile AC	+	**18.9**	**53.5**	**65.0**	**65.6**	**66.0**	**66.3**	**65.2**	**61.7**	**55.7**	**49.9**	**44.0**	**40.9**	**38.3**
Passenger Cars	+	11.2	28.1	31.7	31.7	31.5	31.2	29.9	27.5	23.9	20.6	17.3	16.0	14.9
Light-Duty Trucks	+	7.8	25.4	33.3	33.9	34.5	35.1	35.2	34.2	31.7	29.3	26.7	25.0	23.4
Comfort Cooling for Trains and Buses	+	**+**	**0.1**	**0.3**	**0.3**	**0.4**	**0.4**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
School and Tour Buses	+	+	0.1	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Transit Buses	+	+	+	+	+	+	+	+	+	+	+	+	0.1	0.1
Rail	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Refrigerated Transport	+	**0.2**	**0.8**	**1.8**	**2.0**	**2.3**	**2.6**	**2.9**	**3.5**	**4.1**	**4.7**	**5.3**	**5.8**	**6.4**
Medium- and Heavy-Duty Trucks	+	0.1	0.6	1.5	1.7	1.9	2.2	2.4	2.9	3.4	3.9	4.4	4.4	4.8
Rail	+	0.0	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.7	0.8	0.9	1.4	1.5
Ships and Boats	+	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	+
Total	+	**19.1**	**54.5**	**67.1**	**67.9**	**68.7**	**69.3**	**68.5**	**65.6**	**60.2**	**55.1**	**49.8**	**47.2**	**45.1**

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

Contribution of Transportation and Mobile Sources to Greenhouse Gas Emissions, by Mode/Vehicle Type/Fuel Type

Table A-116 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 2,026.9 MMT CO_2 Eq. in 2015, an increase of 20 percent from 1990. Transportation sources account for 1,807.5 MMT CO_2 Eq. while non-transportation mobile sources account for 219.5 MMT 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 the Substitutes for Ozone Depleting Substances section of the IPPU chapter; and estimates of CO_2 emitted from non-transportation mobile sources reported in Table A-112 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 emission 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 estimates for both jet fuel and aviation gasoline, and CH_4 estimates for aviation gasoline were developed for individual aircraft types by multiplying the emissions estimates for each fuel type (jet fuel and aviation gasoline) by the portion of fuel used by each aircraft type (from FAA 2017 and DESC 2016). Emissions of CH_4 from jet fuels are no longer considered to be emitted from aircraft gas turbine engines burning jet fuel A at higher power settings. This update applies to the entire time series.[56] Recent research indicates that modern aircraft jet engines are typically net consumers of methane (Santoni et al 2011). Methane is emitted at low power and idle operation, but at higher power modes aircraft engines consume methane. Over the range of engine operating modes, aircraft engines are net consumers of methane on average. Based on this data, CH_4 emission factors for jet aircraft were reported as zero to reflect the latest emissions testing data.

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 2016). Carbon dioxide emissions from non-transportation mobile sources are calculated using data from EPA's NONROAD component of MOVES2014a (EPA 2016d). 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 3.9 (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 transport, and the release of CO_2 from lubricants (such as motor oil) used in transportation. Together, transportation sources were responsible for 1,807.5 MMT CO_2 Eq. in 2015.

On-road vehicles were responsible for about 75 percent of all transportation and non-transportation mobile greenhouse gas emissions in 2015. Although passenger cars make up the largest component of on-road vehicle greenhouse gas emissions, medium- and heavy-duty trucks have been the primary sources of growth in on-road vehicle emissions. Between 1990 and 2015, greenhouse gas emissions from passenger cars increased by 14 percent, while emissions from light-duty trucks decreased by one percent.[57] Meanwhile, greenhouse gas emissions from medium- and heavy-duty trucks increased 80 percent between 1990 and 2015, reflecting the increased volume of total freight movement and an increasing share transported by trucks.

[56] Recommended Best Practice for Quantifying Speciated Organic Gas Emissions from Aircraft Equipped with Turbofan, Turbojet and Turboprop Engines," EPA-420-R-09-901, May 27, 2009 (see <http://www.epa.gov/otaq/regs/nonroad/aviation/420r09901.pdf>).

[57] In 2011 FHWA changed how they defined vehicle types for the purposes of reporting VMT for the years 2007-2010. The old approach to vehicle classification was based on body type and split passenger vehicles into "Passenger Cars" and "Other 2 Axle 4-Tire Vehicles". The new approach is a vehicle classification system based on wheelbase. Vehicles with a wheelbase less than or equal to 121 inches are counted as "Light-duty Vehicles –Short Wheelbase". Passenger vehicles with a wheelbase greater than 121 inches are counted as "Light-duty Vehicles - Long Wheelbase". This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this Inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

Greenhouse gas emissions from aircraft decreased 15 percent between 1990 and 2015. Emissions from military aircraft decreased 58 percent between 1990 and 2015. Commercial aircraft emissions rose 27 percent between 1990 and 2007 then dropped 15 percent from 2007 to 2015, a change of approximately 8 percent between 1990 and 2015.

Non-transportation mobile sources, such as construction/mining equipment, agricultural equipment, and industrial/commercial equipment, emitted approximately 219.5 MMT CO_2 Eq. in 2015. Together, these sources emitted more greenhouse gases than ships and boats, and rail combined. Emissions from non-transportation mobile sources increased rapidly, growing approximately 70 percent between 1990 and 2015. Methane 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-117 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 97 percent in 2015). Emissions of CO_2 from transportation and mobile sources increased by 328.1 MMT CO_2 Eq. between 1990 and 2015. In contrast, the combined emissions of CH_4 and N_2O decreased by 29.4 MMT CO_2 Eq. over the same period, due largely to the introduction of control technologies designed to reduce criteria pollutant emissions.[58] Meanwhile, HFC emissions from mobile air-conditioners and refrigerated transport increased from virtually no emissions in 1990 to 45.1 MMT CO_2 Eq. in 2015 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 per UNFCCC reporting requirements.

Greenhouse Gas Emissions from Freight and Passenger Transportation

Table A-118 and Table A-119 present 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-118. 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-119. Commercial aircraft do carry some freight, in addition to passengers, and emissions have been split between passenger and freight 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 emission 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-116. In addition, estimates of fuel consumption from DOE (1993 through 2016) were used to allocate rail emissions between passenger and freight categories.

In 2015, passenger transportation modes emitted 1,251.9 MMT CO_2 Eq., while freight transportation modes emitted 514.8 MMT CO_2 Eq. Between 1990 and 2015, the percentage growth of greenhouse gas emissions from freight sources was 46 percent, while emissions from passenger sources grew by 8 percent. This difference in growth is due largely to the rapid increase in emissions associated with medium- and heavy-duty trucks.

[58] The decline in CFC emissions is not captured in the official transportation estimates.

Table A-116: Total U.S. Greenhouse Gas Emissions from Transportation and Mobile Sources (MMT CO_2 Eq.)

Mode / Vehicle Type / Fuel Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Percent Change 1990-2015
Transportation Total[a]	**1,554.4**	**1698.4**	**1,927.0**	**2,005.9**	**1,999.4**	**1,999.8**	**1,902.5**	**1,824.1**	**1,832.5**	**1,804.3**	**1,784.7**	**1,794.3**	**1,807.5**	**1,807.5**	**16%**
On-Road Vehicles	**1,233.5**	**1,370.4**	**1,572.8**	**1,673.7**	**1,669.7**	**1,664.9**	**1,586.7**	**1,541.1**	**1,542.0**	**1,515.2**	**1,504.7**	**1,504.3**	**1,531.3**	**1,521.0**	**23%**
Passenger Cars	**656.7**	**646.6**	**697.2**	**708.7**	**682.8**	**843.3**	**802.1**	**792.6**	**783.4**	**774.1**	**767.7**	**763.0**	**762.4**	**749.8**	**14%**
Gasoline[b]	648.7	627.6	665.4	672.8	646.9	807.7	767.1	759.1	752.1	746.1	743.0	741.7	742.3	730.6	13%
Diesel[b]	7.9	7.8	3.7	4.2	4.1	4.1	3.7	3.6	3.7	4.1	4.1	4.1	4.1	4.2	-46%
AFVs[c]	+	+	+	+	+	+	+	+	+	+	+	+	0.1	0.1	1,057%
HFCs from Mobile AC	+	11.2	28.1	31.7	31.7	31.5	31.2	29.9	27.5	23.9	20.6	17.3	16.0	14.9	NA
Light-Duty Trucks	**335.2**	**436.5**	**514.9**	**552.2**	**564.8**	**367.3**	**348.0**	**351.4**	**348.7**	**331.5**	**325.1**	**322.2**	**337.2**	**331.5**	**-1%**
Gasoline[b]	323.5	413.6	469.2	492.7	503.6	318.8	300.4	303.7	301.5	286.4	282.6	282.3	297.8	293.1	-9%
Diesel[b]	11.5	14.9	20.1	25.8	26.7	13.5	12.1	12.0	12.5	13.0	12.9	12.9	13.9	14.2	24%
AFVs[c]	0.2	0.2	0.1	0.4	0.5	0.4	0.5	0.5	0.4	0.4	0.2	0.3	0.6	0.9	362%
HFCs from Mobile AC	+	7.8	25.4	33.3	33.9	34.5	35.1	35.2	34.2	31.7	29.3	26.7	25.0	23.4	NA
Medium- and Heavy-Duty Trucks	**231.4**	**276.3**	**347.9**	**399.2**	**408.0**	**432.5**	**415.1**	**376.8**	**390.4**	**389.3**	**389.9**	**397.1**	**408.4**	**416.2**	**80%**
Gasoline[b]	39.5	36.8	37.1	35.8	36.2	47.2	47.4	43.5	43.3	39.7	39.4	40.2	40.6	39.9	1%
Diesel[b]	190.7	238.4	309.5	360.5	369.1	382.5	364.0	329.9	343.1	344.7	344.8	350.4	361.4	369.6	94%
AFVs[c]	1.1	0.9	0.6	1.3	1.1	0.8	1.5	1.0	1.1	1.5	1.8	2.1	1.9	1.8	55%
HFCs from Refrigerated Transport[d]	+	0.1	0.6	1.5	1.7	1.9	2.2	2.4	2.9	3.4	3.9	4.4	4.4	4.8	NA
Buses	**8.5**	**9.2**	**11.0**	**12.0**	**12.2**	**17.6**	**17.1**	**16.0**	**15.9**	**16.7**	**17.8**	**18.0**	**19.4**	**19.7**	**133%**
Gasoline[b]	0.4	0.4	0.4	0.4	0.4	0.7	0.7	0.8	0.7	0.7	0.8	0.9	0.9	0.9	155%
Diesel[b]	8.0	8.7	10.2	10.6	10.6	15.5	14.6	13.6	13.5	14.4	15.4	15.5	16.9	17.3	115%
AFVs[c]	0.1	0.1	0.2	0.8	1.0	1.0	1.3	1.1	1.2	1.1	1.1	1.2	1.2	1.1	1,129%
HFCs from Comfort Cooling	+	+	0.1	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	NA
Motorcycles	**1.8**	**1.8**	**1.9**	**1.7**	**1.9**	**4.3**	**4.4**	**4.2**	**3.7**	**3.6**	**4.2**	**4.0**	**3.9**	**3.8**	**115%**
Gasoline[b]	1.8	1.8	1.9	1.7	1.9	4.3	4.4	4.2	3.7	3.6	4.2	4.0	3.9	3.8	115%
Aircraft	**189.2**	**176.7**	**199.4**	**193.6**	**186.3**	**183.4**	**176.7**	**157.4**	**154.8**	**149.9**	**146.5**	**150.1**	**151.5**	**160.7**	**-15%**
General Aviation Aircraft	**42.9**	**35.8**	**35.9**	**40.1**	**30.1**	**24.4**	**30.5**	**21.2**	**26.7**	**22.5**	**19.9**	**23.6**	**19.7**	**25.7**	**-40%**
Jet Fuel[e]	39.8	33.0	33.4	37.6	27.7	22.2	28.5	19.4	24.8	20.6	18.2	22.0	18.2	24.2	-39%
Aviation Gasoline	3.2	2.8	2.6	2.5	2.4	2.2	2.0	1.9	1.9	1.9	1.8	1.6	1.5	1.5	-53%
Commercial Aircraft	**110.9**	**116.3**	**140.6**	**134.0**	**138.3**	**141.0**	**128.4**	**120.6**	**114.4**	**115.7**	**114.3**	**115.4**	**116.3**	**120.1**	**8%**
Jet Fuel[e]	110.9	116.3	140.6	134.0	138.3	141.0	128.4	120.6	114.4	115.7	114.3	115.4	116.3	120.1	8%
Military Aircraft	**35.3**	**24.5**	**22.9**	**19.5**	**18.0**	**18.0**	**17.7**	**15.5**	**13.7**	**11.7**	**12.2**	**11.1**	**15.5**	14.9	-58%
Jet Fuel[e]	35.3	24.5	22.9	19.5	18.0	18.0	17.7	15.5	13.7	11.7	12.2	11.1	15.5	14.9	-58%
Ships and Boats[f]	**44.9**	**58.5**	**61.1**	**44.9**	**48.0**	**54.7**	**45.3**	**38.6**	**44.7**	**46.4**	**40.1**	**39.4**	**28.6**	**32.2**	**-28%**
Gasoline	12.4	14.1	10.2	14.0	13.8	13.6	13.2	13.0	12.7	12.6	12.5	12.4	12.3	12.3	-1%
Distillate Fuel	9.6	14.9	17.1	11.4	10.8	11.6	11.4	11.5	11.1	14.0	11.4	11.5	10.2	16.2	68%
Residual Fuel[g]	22.9	29.5	33.8	19.6	23.4	29.4	20.7	14.2	20.9	19.8	16.2	15.5	6.0	3.7	-84%

HFCs from Refrigerated Transport[d]	+	+	+	+	+	+	+	+	+	+	+	+	+	+	NA
Rail	**38.9**	**43.1**	**46.1**	**51.1**	**53.0**	**52.2**	**48.5**	**41.3**	**44.2**	**45.8**	**44.6**	**45.5**	**47.6**	**45.6**	**17%**
Distillate Fuel[h]	35.8	40.0	42.5	46.0	48.1	46.7	43.3	36.3	39.0	40.8	39.9	40.5	42.0	40.3	12%
Electricity	3.1	3.1	3.5	4.8	4.6	5.1	4.7	4.5	4.5	4.3	3.9	4.1	4.1	3.8	24%
Other Emissions from Rail Electricity Use[i]	0.1	0.1	+	0.1	+	0.1	+	+	+	+	+	+	+	+	-100%
HFCs from Comfort Cooling	+	+	+	+	+	+	+	+	+	+	+	+	+	+	NA
HFCs from Refrigerated Transport[d]	+	+	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.7	0.8	0.9	1.4	1.5	NA
Pipelines[j]	**36.0**	**38.4**	**35.4**	**32.4**	**32.4**	**34.4**	**35.9**	**37.1**	**37.3**	**38.1**	**40.5**	**46.2**	**39.4**	**38.0**	**5%**
Natural Gas	36.0	38.4	35.4	32.4	32.4	34.4	35.9	37.1	37.3	38.1	40.5	46.2	39.4	38.0	5%
Other Transportation	**11.8**	**11.3**	**12.1**	**10.2**	**9.9**	**10.2**	**9.5**	**8.5**	**9.5**	**9.0**	**8.3**	**8.8**	**9.1**	**10.0**	**-16%**
Lubricants	11.8	11.3	12.1	10.2	9.9	10.2	9.5	8.5	9.5	9.0	8.3	8.8	9.1	10.0	-16%
Non-Transportation Mobile[k] Total	**128.8**	**146.7**	**159.5**	**191.8**	**196.4**	**194.6**	**193.7**	**196.9**	**203.1**	**205.7**	**208.3**	**213.6**	**213.9**	**219.5**	**70%**
Agricultural Equipment[l]	**31.4**	**37.0**	**39.7**	**47.9**	**50.0**	**49.2**	**46.2**	**47.4**	**48.4**	**50.1**	**51.6**	**50.6**	**51.3**	48.0	53%
Gasoline	7.3	8.3	5.8	9.6	11.0	9.4	5.6	5.9	6.0	7.0	7.6	5.7	5.6	1.4	-81%
Diesel	24.1	28.7	33.9	38.3	39.1	39.8	40.6	41.5	42.3	43.2	44.0	44.9	45.7	46.6	94%
Construction/ Mining Equipment[m]	**42.4**	**49.3**	**56.6**	**67.4**	**68.7**	**68.9**	**70.4**	**71.7**	**74.0**	**75.2**	**76.8**	**82.3**	**80.4**	**79.9**	**89%**
Gasoline	4.4	4.0	3.0	6.2	6.1	5.1	5.1	4.9	5.7	5.3	5.5	9.4	6.1	4.3	-1%
Diesel	38.0	45.4	53.6	61.2	62.6	63.9	65.3	66.9	68.3	69.8	71.3	72.8	74.4	75.6	99%
Other Equipment[n]	**55.0**	**60.4**	**63.2**	**76.5**	**77.7**	**76.4**	**77.1**	**77.8**	**80.7**	**80.4**	**79.9**	**80.8**	**82.2**	**91.6**	**67%**
Gasoline	40.3	42.6	42.0	52.0	52.5	50.6	50.6	50.6	52.9	51.9	50.7	50.9	51.7	61.2	52%
Diesel	14.7	17.8	21.2	24.6	25.2	25.8	26.5	27.2	27.8	28.5	29.2	29.9	30.5	30.4	106%
Transportation and Non-Transportation Mobile Total	**1,683.1**	**1,845.1**	**2,086.5**	**2,197.7**	**2,195.9**	**2,194.4**	**2,096.3**	**2,021.0**	**2,035.6**	**2,010.0**	**1,993.0**	**2,007.9**	**2,021.5**	**2,026.9**	**20%**

+ Does not exceed 0.05 MMT CO_2 Eq.

NA - Not Applicable, as there were no HFC emissions allocated to the transport sector in 1990, and thus a growth rate cannot be calculated.

[a] Not including emissions from international bunker fuels.

[b] Gasoline and diesel highway vehicle fuel consumption estimates used to develop CO_2 estimates in this Inventory are based on data from FHWA Highway Statistics Table MF-21, MF-27 and VM-1 (FHWA 1996 through 2016). In 2016, FHWA changed its methods for estimating the share of motor gasoline used in on-highway and off-highway applications. This method change resulted in an increase in the estimated off-highway motor gasoline consumption and subsequent decrease in the on-highway motor gasoline consumption for 2015. Data from Table VM-1 is used to estimate the share of fuel consumption between each on-road vehicle class. Since VM-1 data for 2015 has not been published yet, fuel consumption shares from 2014 are used as a proxy for Public Review. For mobile CH_4 and N_2O emissions estimates, gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2016). Table VM-1 data for 2015 has not been published yet, therefore 2015 mileage data is estimated using the 3.5 percent increase in FHWA Traffic Volume Trends from 2014 to 2015. These fuel consumption and mileage estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is as a proxy.

[c] In 2015, EIA changed its methods for estimating AFV fuel consumption. These methodological changes included how vehicle counts are estimated, moving from estimates based on modeling to one that is based on survey data. EIA now publishes data about fuel use and number of vehicles for only four types of AFV fleets: federal government, state government, transit agencies, and fuel providers. These

changes were first incorporated in the 2014 Inventory and apply to the 1990-2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes.

[d] Updated Commodity Flow Survey data was used to allocate refrigerated transport emissions to the trucking, rail and marine sectors in 2014.

[e] Updates to the jet fuel heat content used in the mobile N_2O emissions estimates for years 1990 through present resulted in small changes to the time series emissions compared to the previous Inventory.

[f] Fluctuations in emission estimates reflect data collection problems. Note that CH_4 and N_2O from U.S. Territories are included in this value, but not CO_2 emissions from U.S. Territories, which are estimated separately in the section on U.S. Territories.

[g] Domestic residual fuel for ships and boats is estimated by taking the total amount of residual fuel and subtracting out an estimate of international bunker fuel use.

[h] Class II and Class II diesel consumption data for 2014 and 2015 is not available yet, therefore 2013 data is used as a proxy.

[i] Other emissions from electricity generation are a result of waste incineration (as the majority of municipal solid waste is combusted in "trash-to-steam" electricity generation plants), electrical transmission and distribution, and a portion of Other Process Uses of Carbonates (from pollution control equipment installed in electricity generation plants).

[j] Includes only CO_2 from natural gas used to power natural gas pipelines; does not include emissions from electricity use or non-CO_2 gases.

[k] In 2016, FHWA changed its methods for estimating the share of motor gasoline used in on-highway and off-highway applications. This method change resulted in an increase in the estimated off-highway motor gasoline consumption and subsequent decrease in the on-highway motor gasoline consumption for 2015.

[l] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[m] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[n] "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.

Notes: Increases to CH_4 and N_2O emissions from mobile combustion relative to previous Inventories are largely due to updates made to the Motor Vehicle Emissions Simulator (MOVES2014a) model that is used to estimate on-road gasoline vehicle distribution and mileage across the time series. See Section 3.1 "CH_4 and N_2O from Mobile Combustion" for more detail. In 2015, EPA incorporated the NONROAD2008 model into MOVES2014a. This year's inventory uses the NONROAD component of MOVES2014a for years 1999 through 2015. In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, which emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous Inventories, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore were not included in the engine technology breakouts. For this Inventory, HEVs are now classified as gasoline vehicles across the entire time series.

Table A-117: Transportation and Mobile Source Emissions by Gas (MMT CO_2 Eq.)

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Percent Change 1990-2015
CO_2	1,636.2	1,769.6	1,979.0	2,091.9	2,091.7	2,094.1	1,997.9	1,925.1	1,943.4	1,924.6	1,915.2	1,937.4	1,955.5	1,964.3	20%
N_2O	41.2	51.2	49.3	35.7	33.5	28.9	26.6	25.0	24.1	22.8	20.4	18.5	16.6	15.4	-63%
CH_4	5.6	5.2	3.7	2.8	2.7	2.5	2.4	2.3	2.3	2.3	2.2	2.1	2.1	2.0	-64%
HFC	+	19.1	54.5	67.1	67.9	68.7	69.3	68.5	65.6	60.2	55.1	49.8	47.2	45.1	NA
Total[a]	**1,683.1**	**1,845.0**	**2,086.5**	**2,197.6**	**2,195.8**	**2,194.3**	**2,096.2**	**2,021.0**	**2,035.5**	**2,009.9**	**1,992.9**	**2,007.8**	**2,021.4**	**2,026.8**	**20%**

+ Does not exceed 0.05 MMT CO_2 Eq.

NA - Not Applicable, as there were no HFC emissions allocated to the transport sector in 1990, and thus a growth rate cannot be calculated.

[a] Total excludes other emissions from electricity generation and CH_4 and N_2O emissions from electric rail.

Note: The current Inventory includes updated vehicle population data based on the MOVES 2014a Model.

Gasoline and diesel highway vehicle fuel consumption estimates used to develop CO_2 estimates in this Inventory are based on data from FHWA Highway Statistics Table MF-21, MF-27 and VM-1 (FHWA 1996 through 2016). In 2016, FHWA changed its methods for estimating the share of motor gasoline used in on-highway and off-highway applications. This resulted in an increase in the estimated off-highway motor gasoline consumption and subsequent decrease in the on-highway motor gasoline consumption for 2015. Data from Table VM-1 is used to estimate the share of fuel consumption between each on-road vehicle class. Since VM-1 data for 2015 has not been published yet, fuel consumption shares from 2014 are used as a proxy for Public Review. For mobile CH_4 and N_2O emissions estimates, gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2016). Table VM-1 data for 2015 has not been published yet, therefore 2015 mileage data is estimated using the 3.5 percent increase in FHWA Traffic Volume Trends from 2014 to 2015. These fuel consumption and mileage estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is as a proxy.

Note: In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, which emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous Inventories, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore were not included in the engine technology breakouts. For this Inventory, HEVs are now classified as gasoline vehicles across the entire time series.

Figure A-4: Domestic Greenhouse Gas Emissions by Mode and Vehicle Type, 1990 to 2015 (MMT CO_2 Eq.)

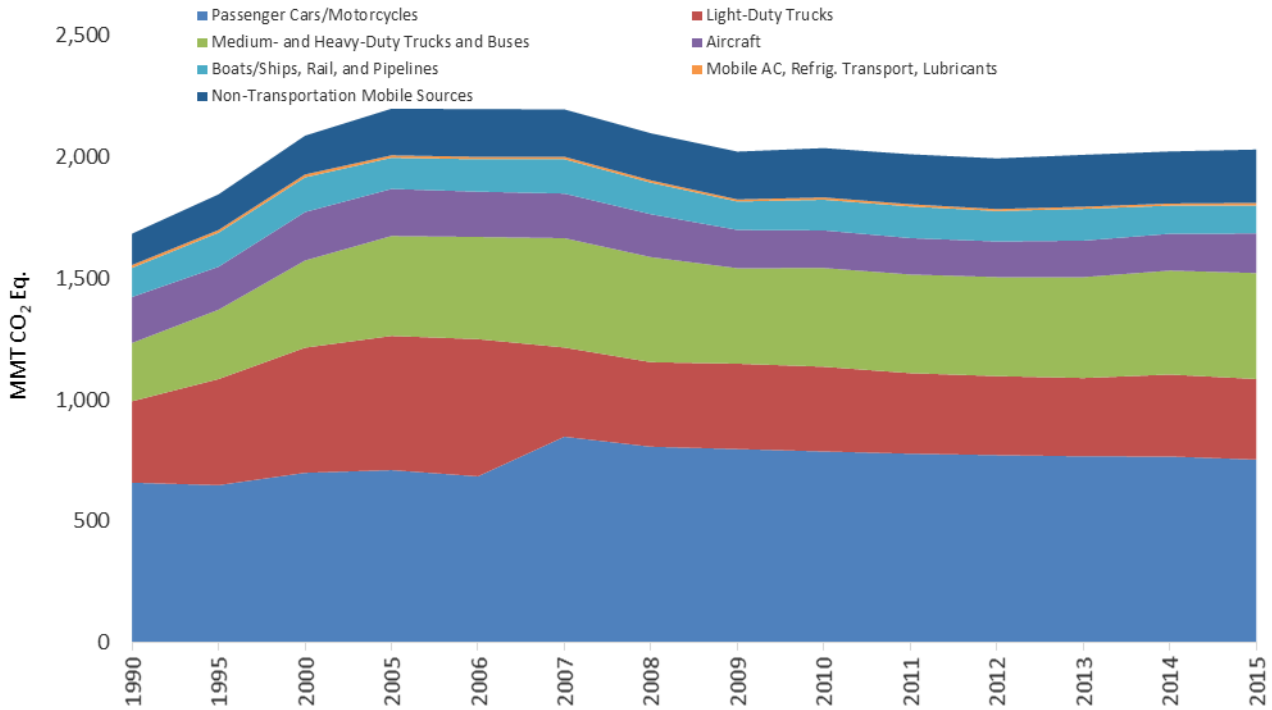

Table A-118: Greenhouse Gas Emissions from Passenger Transportation (MMT CO_2 Eq.)

Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Percent Change 1990-2015
On-Road Vehicles[a,b]	**1,002.1**	**1,094.1**	**1,224.9**	**1,274.5**	**1,261.7**	**1,232.4**	**1,171.6**	**1,164.3**	**1,151.6**	**1,125.9**	**1,114.8**	**1,107.3**	**1,123.0**	**1,104.9**	**10%**
Passenger Cars	656.7	646.6	697.2	708.7	682.8	843.3	802.1	792.6	783.4	774.1	767.7	763.0	762.4	749.8	14%
Light-Duty Trucks	335.2	436.5	514.9	552.2	564.8	367.3	348.0	351.4	348.7	331.5	325.1	322.2	337.2	331.5	-1%
Buses	8.5	9.2	11.0	12.0	12.2	17.6	17.1	16.0	15.9	16.7	17.8	18.0	19.4	19.7	133%
Motorcycles	1.8	1.8	1.9	1.7	1.9	4.3	4.4	4.2	3.7	3.6	4.2	4.0	3.9	3.8	115%
Aircraft	**134.6**	**132.0**	**152.2**	**152.7**	**146.6**	**144.9**	**140.9**	**125.2**	**124.8**	**122.1**	**118.5**	**123.1**	**119.7**	**129.3**	**-4%**
General Aviation	42.9	35.8	35.9	40.1	30.1	24.4	30.5	21.2	26.7	22.5	19.9	23.6	19.7	25.7	-40%
Commercial Aircraft	91.7	96.2	116.3	112.6	116.5	120.4	110.4	103.9	98.0	99.6	98.6	99.5	100.0	103.6	13%
Recreational Boats	**14.3**	**16.4**	**13.0**	**17.2**	**17.1**	**17.0**	**16.6**	**16.5**	**16.3**	**16.2**	**16.2**	**16.3**	**12.3**	**12.3**	**-14%**
Passenger Rail	**4.4**	**4.5**	**5.2**	**6.2**	**6.0**	**6.6**	**6.2**	**6.1**	**6.2**	**5.9**	**5.5**	**5.8**	**5.7**	**5.4**	**24%**
Total	**1,155.4**	**1,247.0**	**1,395.3**	**1,450.6**	**1,431.4**	**1,400.8**	**1,335.4**	**1,312.0**	**1,298.8**	**1,270.2**	**1,255.0**	**1,252.4**	**1,260.7**	**1,251.9**	**8%**

[a] The current Inventory includes updated vehicle population data based on the MOVES 2014a Model.

[b] Gasoline and diesel highway vehicle fuel consumption estimates used to develop CO_2 estimates in this Inventory are based on data from FHWA Highway Statistics Table MF-21, MF-27 and VM-1 (FHWA 1996 through 2016). In 2016, FHWA changed its methods for estimating the share of motor gasoline used in on-highway and off-highway applications. This resulted in an increase in the estimated off-highway motor gasoline consumption and subsequent decrease in the on-highway motor gasoline consumption for 2015. Data from Table VM-1 is used to estimate the share of fuel consumption between each on-road vehicle class. Since VM-1 data for 2015 has not been published yet, fuel consumption shares from 2014 are used as a proxy for Public Review. For mobile CH_4 and N_2O emissions estimates, gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2016). Table VM-1 data for 2015 has not been published yet, therefore 2015 mileage data is estimated using the 3.5 percent increase in FHWA Traffic Volume Trends from 2014 to 2015. These fuel consumption and mileage estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data are used as a proxy.

Notes: Data from DOE (1993 through 2016) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates. In 2015, EPA incorporated the NONROAD2008 model into MOVES2014a. This year's Inventory uses the NONROAD component of MOVES2014a for years 1999 through 2015. In 2015, EIA changed its methods for estimating AFV fuel consumption. These methodological changes included how vehicle counts are estimated, moving from estimates based on modeling to one that is based on survey data. EIA now publishes data about fuel use and number of vehicles for only four types of AFV fleets: federal government, state government, transit agencies, and fuel providers. These changes were first incorporated in the 2014 Inventory and apply to the 1990 through2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes.

Note: In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, which emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous Inventories, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore were not included in the engine technology breakouts. For this Inventory, HEVs are now classified as gasoline vehicles across the entire time series.

Table A-119: Greenhouse Gas Emissions from Domestic Freight Transportation (MMT CO_2 Eq.)

By Mode	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Percent Change 1990-2015
Trucking[a,b]	231.4	276.3	347.9	399.2	408.0	432.5	415.1	376.8	390.4	389.3	389.9	397.1	408.4	416.2	80%
Freight Rail	34.5	38.6	40.9	44.8	47.0	45.6	42.2	35.1	38.0	39.9	39.0	39.7	41.8	40.2	16%
Ships and Non-Recreational Boats	30.6	42.1	48.1	27.8	31.0	37.7	28.7	22.2	28.5	30.2	23.9	27.7	6.3	4.0	-87%
Pipelines[c]	36.0	38.4	35.4	32.4	32.4	34.4	35.9	37.1	37.3	38.1	40.5	46.2	39.4	38.0	5%
Commercial Aircraft	19.2	20.1	24.3	21.4	21.8	20.5	18.0	16.7	16.3	16.0	15.8	15.9	16.2	16.5	-14%
Total	**351.7**	**415.5**	**496.7**	**525.5**	**540.1**	**570.7**	**539.9**	**487.9**	**510.4**	**513.4**	**509.1**	**526.6**	**512.1**	**514.8**	**46%**

[a] The current Inventory includes updated vehicle population data based on the MOVES 2014a Model.

[b] Gasoline and diesel highway vehicle fuel consumption estimates used to develop CO_2 estimates in this Inventory are based on data from FHWA Highway Statistics Table MF-21, MF-27 and VM-1 (FHWA 1996 through 2016). In 2016, FHWA changed its methods for estimating the share of motor gasoline used in on-highway and off-highway applications. This resulted in an increase in the estimated off-highway motor gasoline consumption and subsequent decrease in the on-highway motor gasoline consumption for 2015. Data from Table VM-1 is used to estimate the share of fuel consumption between each on-road vehicle class. Since VM-1 data for 2015 has not been published yet, fuel consumption shares from 2014 are used as a proxy for Public Review. For mobile CH_4 and N_2O emissions estimates, gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2016). Table VM-1 data for 2015 has not been published yet, therefore 2015 mileage data is estimated using the 3.5 percent increase in FHWA Traffic Volume Trends from 2014 to 2015. These fuel consumption and mileage estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is as a proxy.

[c] Pipelines reflect CO_2 emissions from natural gas powered pipelines transporting natural gas.

Notes: Data from DOE (1993 through 2015) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates. In 2015, EPA incorporated the NONROAD2008 model into MOVES2014a. This year's inventory uses the NONROAD component of MOVES2014a for years 1999 through 2015. In 2015, EIA changed its methods for estimating AFV fuel consumption. These methodological changes included how vehicle counts are estimated, moving from estimates based on modeling to one that is based on survey data. EIA now publishes data about fuel use and number of vehicles for only four types of AFV fleets: federal government, state government, transit agencies, and fuel providers. These changes were first incorporated in the 2014 Inventory and apply to the 1990 to 2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes. In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, which emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous Inventories, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore were not included in the engine technology breakouts. For this Inventory, HEVs are now classified as gasoline vehicles across the entire time series.

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3.3. Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption

IPCC Tier 3B Method: Commercial aircraft jet fuel burn and carbon dioxide (CO_2) emissions estimates were developed by the U.S. Federal Aviation Administration (FAA) using radar-informed data from the FAA Enhanced Traffic Management System (ETMS) for 2000 through 2015 as modeled with the Aviation Environmental Design Tool (AEDT). This bottom-up approach is built from modeling dynamic aircraft performance for each flight occurring within an individual calendar year. The analysis incorporates data on the aircraft type, date, flight identifier, departure time, arrival time, departure airport, arrival airport, ground delay at each airport, and real-world flight trajectories. To generate results for a given flight within AEDT, the radar-informed aircraft data is correlated with engine and aircraft performance data to calculate fuel burn and exhaust emissions. Information on exhaust emissions for in-production aircraft engines comes from the International Civil Aviation Organization (ICAO) Aircraft Engine Emissions Databank (EDB). This bottom-up approach is in accordance with the Tier 3B method from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

International Bunkers: The IPCC guidelines define international aviation (International Bunkers) as emissions from flights that depart from one country and arrive in a different country. Bunker fuel emissions estimates for commercial aircraft were developed for this report for 2000 through 2015 using the same radar-informed data modeled with AEDT. Since this process builds estimates from flight-specific information, the emissions estimates for commercial aircraft can include emissions associated with the U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands). However, to allow for the alignment of emissions estimates for commercial aircraft with other data that is provided without the U.S. Territories, this annex includes emissions estimates for commercial aircraft both with and without the U.S. Territories included.

Time Series and Analysis Update: The FAA incrementally improves the consistency, robustness, and fidelity of the CO_2 emissions modeling for commercial aircraft, which is the basis of the Tier 3B inventories presented in this report. While the FAA does not anticipate significant changes to the AEDT model in the future, recommended improvements are limited by budget and time constraints, as well as data availability. For instance, previous reports included reported annual CO_2 emission estimates for 2000 through 2005 that were modeled using the FAA's System for assessing Aviation's Global Emissions (SAGE). That tool and its capabilities were significantly improved after it was incorporated and evolved into AEDT. For this report, the AEDT model was used to generate annual CO_2 emission estimates for 2000, 2005, 2010, 2011, 2012, 2013, 2014 and 2015 only. The reported annual CO_2 emissions values for 2001 through 2004 were estimated from the previously reported SAGE data. Likewise, CO_2 emissions values for 2006 through 2009 were estimated by interpolation to preserve trends from past reports.

Commercial aircraft radar data sets are not available for years prior to 2000. Instead, the FAA applied a Tier3B methodology by developing Official Airline Guide (OAG) schedule-informed estimates modeled with AEDT and great circle trajectories for 1990, 2000 and 2010. The ratios between the OAG schedule-informed and the radar-informed inventories for the years 2000 and 2010 were applied to the 1990 OAG scheduled-informed inventory to generate the best possible CO_2 inventory estimate for commercial aircraft in 1990. The resultant 1990 CO_2 inventory served as the reference for generating the additional 1991-1999 emissions estimates, which were established using previously available trends.

Notes on the 1990 CO_2 Emissions Inventory for Commercial Aircraft: There are uncertainties associated with the modeled 1990 data that do not exist for the modeled 2000 to 2015 data. Radar-based data is not available for 1990. The OAG schedule information generally includes fewer carriers than radar information, and this will result in a different fleet mix, and in turn, different CO_2 emissions than would be quantified using a radar-based data set. For this reason, the FAA adjusted the OAG-informed schedule for 1990 with a ratio based on radar-informed information. In addition, radar trajectories are also generally longer than great circle trajectories. While the 1990 fuel burn data was adjusted to address these differences, it inherently adds greater uncertainty to the revised 1990 commercial aircraft CO_2 emissions as compared to data from 2000 forward. Also, the revised 1990 CO_2 emissions inventory now reflects only commercial aircraft jet fuel consumption, while previous reports may have aggregated jet fuel sales data from non-commercial aircraft into this category. Thus, it would be inappropriate to compare 1990 to future years for other than qualitative purposes.

The 1990 commercial aircraft CO_2 emissions estimate is approximately 8 percent lower than the 2015 CO_2 emissions estimate. It is important to note that the distance flown increased by more than 45 percent over this 25-year period

and that fuel burn and aviation activity trends over the past two decades indicate significant improvements in commercial aviation's ability to provide increased service levels while using less fuel.[59]

Additional information on the AEDT modeling process is available at: <http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/>.

Methane Emissions: Contributions of methane (CH_4) emissions from commercial aircraft are reported as zero. Years of scientific measurement campaigns conducted at the exhaust exit plane of commercial aircraft gas turbine engines have repeatedly indicated that CH_4 emissions are consumed over the full mission flight envelope (Santoni et al. 2011). As a result, the U.S. EPA published that "*…methane is no longer considered to be an emission from aircraft gas turbine engines burning Jet A at higher power settings and is, in fact, consumed in net at these higher powers.*"[60] In accordance with the following statements in the *2006 IPCC Guidelines* (IPCC 2006), the FAA does not calculate CH_4 emissions for either the domestic or international bunker commercial aircraft jet fuel emissions inventories. *"Methane (CH_4) may be emitted by gas turbines during idle and by older technology engines, but recent data suggest that little or no CH_4 is emitted by modern engines." "Current scientific understanding does not allow other gases (e.g., N_2O and CH_4) to be included in calculation of cruise emissions."* (IPCC 1999).

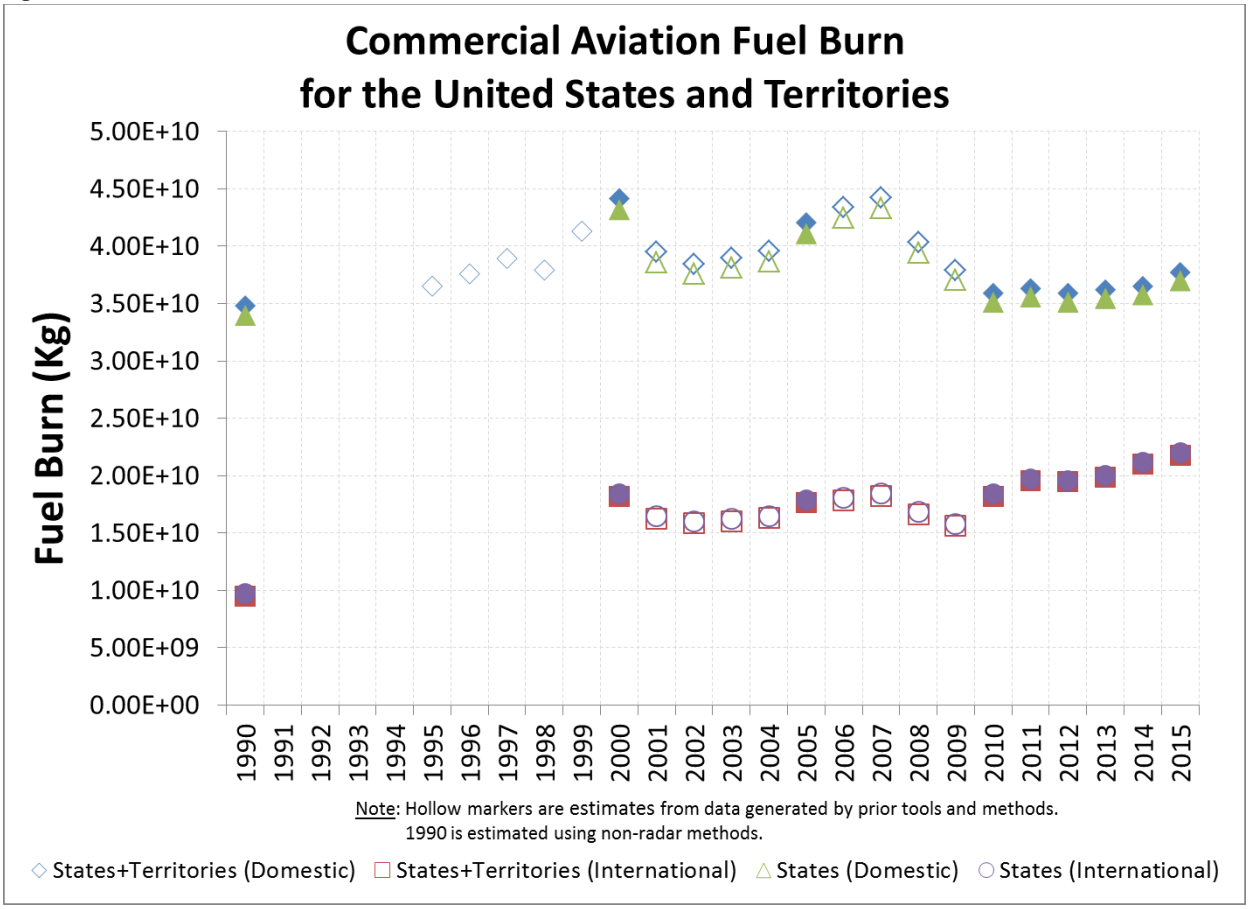
Results: For each inventory calendar year the graph and table below include four jet fuel burn values. These values are comprised of domestic and international fuel burn totals for the U.S. 50 States and the U.S. 50 States + Territories. Data are presented for domestic defined as jet fuel burn from any commercial aircraft flight departing and landing in the U.S. 50 States and for the U.S. 50 States + Territories. The data presented as international is respective of the two different domestic definitions, and represents flights departing from the specified domestic area and landing anywhere in the world outside of that area.

Note that the graph and table present less fuel burn for the international U.S. 50 States + Territories than for the international U.S. 50 States. This is because the flights between the 50 states and U.S. Territories are "international" when only the 50 states are defined as domestic, but they are "domestic" for the U.S. 50 States + Territories definition.

[59] Additional information on the AEDT modeling process is available at: <http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/>.

[60] Recommended Best Practice for Quantifying Speciated Organic Gas Emissions from Aircraft Equipped with Turbofan, Turbojet and Turboprop Engines, EPA-420-R-09-901, May 27, 2009. See <http://www.epa.gov/otaq/aviation.html>.

Figure A-5: Commercial Aviation Fuel Burn for the United States and Territories



Note: Hollow markers are estimates from data generated by prior tools and methods. 1990 is estimated using non-radar methods.

Table A-120: Commercial Aviation Fuel Burn for the United States and Territories

Year	Region	Distance Flown (nmi)	Fuel Burn (M Gallon)	Fuel Burn (Tbtu)	Fuel Burn (Kg)	CO_2 (MMT)
1990	Domestic U.S. 50 States and U.S. Territories	4,057,195,988	11,568	1,562	34,820,800,463	109.9
	International U.S. 50 States and U.S. Territories	599,486,893	3,155	426	9,497,397,919	30.0
	Domestic U.S. 50 States	3,984,482,217	11,287	1,524	33,972,832,399	107.2
	International U.S. 50 States	617,671,849	3,228	436	9,714,974,766	30.7
1995*	Domestic U.S. 50 States and U.S. Territories	N/A	12,136	1,638	36,528,990,675	115.2
1996*	Domestic U.S. 50 States and U.S. Territories	N/A	12,492	1,686	37,600,624,534	118.6
1997*	Domestic U.S. 50 States and U.S. Territories	N/A	12,937	1,747	38,940,896,854	122.9
1998*	Domestic U.S. 50 States and U.S. Territories	N/A	12,601	1,701	37,930,582,643	119.7
1999*	Domestic U.S. 50 States and U.S. Territories	N/A	13,726	1,853	41,314,843,250	130.3
2000	Domestic U.S. 50 States and U.S. Territories	5,994,679,944	14,672	1,981	44,161,841,348	139.3
	International U.S. 50 States and U.S. Territories	1,309,565,963	6,040	815	18,181,535,058	57.4
	Domestic U.S. 50 States	5,891,481,028	14,349	1,937	43,191,000,202	136.3
	International U.S. 50 States	1,331,784,289	6,117	826	18,412,169,613	58.1
2001*	Domestic U.S. 50 States and U.S. Territories	5,360,977,447	13,121	1,771	39,493,457,147	124.6
	International U.S. 50 States and U.S. Territories	1,171,130,679	5,402	729	16,259,550,186	51.3
	Domestic U.S. 50 States	5,268,687,772	12,832	1,732	38,625,244,409	121.9
	International U.S. 50 States	1,191,000,288	5,470	739	16,465,804,174	51.9
2002*	Domestic U.S. 50 States and U.S. Territories	5,219,345,344	12,774	1,725	38,450,076,259	121.3
	International U.S. 50 States and U.S. Territories	1,140,190,481	5,259	710	15,829,987,794	49.9
	Domestic U.S. 50 States	5,129,493,877	12,493	1,687	37,604,800,905	118.6

	International U.S. 50 States	1,159,535,153	5,326	719	16,030,792,741	50.6
2003*	Domestic U.S. 50 States and U.S. Territories	5,288,138,079	12,942	1,747	38,956,861,262	122.9
	International U.S. 50 States and U.S. Territories	1,155,218,577	5,328	719	16,038,632,384	50.6
	Domestic U.S. 50 States	5,197,102,340	12,658	1,709	38,100,444,893	120.2
	International U.S. 50 States	1,174,818,219	5,396	728	16,242,084,008	51.2
2004*	Domestic U.S. 50 States and U.S. Territories	5,371,498,689	13,146	1,775	39,570,965,441	124.8
	International U.S. 50 States and U.S. Territories	1,173,429,093	5,412	731	16,291,460,535	51.4
	Domestic U.S. 50 States	5,279,027,890	12,857	1,736	38,701,048,784	122.1
	International U.S. 50 States	1,193,337,698	5,481	740	16,498,119,309	52.1
2005	Domestic U.S. 50 States and U.S. Territories	6,476,007,697	13,976	1,887	42,067,562,737	132.7
	International U.S. 50 States and U.S. Territories	1,373,543,928	5,858	791	17,633,508,081	55.6
	Domestic U.S. 50 States	6,370,544,998	13,654	1,843	41,098,359,387	129.7
	International U.S. 50 States	1,397,051,323	5,936	801	17,868,972,965	56.4
2006*	Domestic U.S. 50 States and U.S. Territories	5,894,323,482	14,426	1,948	43,422,531,461	137.0
	International U.S. 50 States and U.S. Territories	1,287,642,623	5,939	802	17,877,159,421	56.4
	Domestic U.S. 50 States	5,792,852,211	14,109	1,905	42,467,943,091	134.0
	International U.S. 50 States	1,309,488,994	6,015	812	18,103,932,940	57.1
2007*	Domestic U.S. 50 States and U.S. Territories	6,009,247,818	14,707	1,986	44,269,160,525	139.7
	International U.S. 50 States and U.S. Territories	1,312,748,383	6,055	817	18,225,718,619	57.5
	Domestic U.S. 50 States	5,905,798,114	14,384	1,942	43,295,960,105	136.6
	International U.S. 50 States	1,335,020,703	6,132	828	18,456,913,646	58.2
2008*	Domestic U.S. 50 States and U.S. Territories	5,475,092,456	13,400	1,809	40,334,124,033	127.3
	International U.S. 50 States and U.S. Territories	1,196,059,638	5,517	745	16,605,654,741	52.4
	Domestic U.S. 50 States	5,380,838,282	13,105	1,769	39,447,430,318	124.5
	International U.S. 50 States	1,216,352,196	5,587	754	16,816,299,099	53.1
2009*	Domestic U.S. 50 States and U.S. Territories	5,143,268,671	12,588	1,699	37,889,631,668	119.5
	International U.S. 50 States and U.S. Territories	1,123,571,175	5,182	700	15,599,251,424	49.2
	Domestic U.S. 50 States	5,054,726,871	12,311	1,662	37,056,676,966	116.9
	International U.S. 50 States	1,142,633,881	5,248	709	15,797,129,457	49.8
2010	Domestic U.S. 50 States and U.S. Territories	5,652,264,576	11,931	1,611	35,912,723,830	113.3
	International U.S. 50 States and U.S. Territories	1,474,839,733	6,044	816	18,192,953,916	57.4
	Domestic U.S. 50 States	5,554,043,585	11,667	1,575	35,116,863,245	110.8
	International U.S. 50 States	1,497,606,695	6,113	825	18,398,996,825	58.0
2011	Domestic U.S. 50 States and U.S. Territories	5,767,378,664	12,067	1,629	36,321,170,730	114.6
	International U.S. 50 States and U.S. Territories	1,576,982,962	6,496	877	19,551,631,939	61.7
	Domestic U.S. 50 States	5,673,689,481	11,823	1,596	35,588,754,827	112.3
	International U.S. 50 States	1,596,797,398	6,554	885	19,727,043,614	62.2
2012	Domestic U.S. 50 States and U.S. Territories	5,735,605,432	11,932	1,611	35,915,745,616	113.3
	International U.S. 50 States and U.S. Territories	1,619,012,587	6,464	873	19,457,378,739	61.4
	Domestic U.S. 50 States	5,636,910,529	11,672	1,576	35,132,961,140	110.8
	International U.S. 50 States	1,637,917,110	6,507	879	19,587,140,347	61.8
2013	Domestic U.S. 50 States and U.S. Territories	5,808,034,123	12,031	1,624	36,212,974,471	114.3
	International U.S. 50 States and U.S. Territories	1,641,151,400	6,611	892	19,898,871,458	62.8
	Domestic U.S. 50 States	5,708,807,315	11,780	1,590	35,458,690,595	111.9
	International U.S. 50 States	1,661,167,498	6,657	899	20,036,865,038	63.2
2014	Domestic U.S. 50 States and U.S. Territories	5,825,999,388	12,131	1,638	36,514,970,659	115.2
	International U.S. 50 States and U.S. Territories	1,724,559,209	6,980	942	21,008,818,741	66.3
	Domestic U.S. 50 States	5,725,819,482	11,882	1,604	35,764,791,774	112.8
	International U.S. 50 States	1,745,315,059	7,027	949	21,152,418,387	66.7
	Domestic U.S. 50 States and U.S. Territories	5,900,440,363	12,534	1,692	37,727,860,796	119.0
2015	International U.S. 50 States and U.S. Territories	1,757,724,661	7,227	976	21,752,301,359	68.6
	Domestic U.S 50 States	5,801,594,806	12,291	1,659	36,997,658,406	116.7
	International U.S. 50 States	1,793,787,700	7,310	987	22,002,733,062	69.4

*Estimates for these years were derived from previously reported tools and methods

References – TO BE UPDATED FOR FINAL INVENTORY REPORT

3.4. Methodology for Estimating CH_4 Emissions from Coal Mining

The methodology for estimating CH_4 emissions from coal mining consists of two steps:

- **Estimate emissions from underground mines.** These emissions have two sources: ventilation systems and degasification systems. They are estimated using mine-specific data, then summed to determine total CH_4 liberated. The CH_4 recovered and used is then subtracted from this total, resulting in an estimate of net emissions to the atmosphere.
- **Estimate emissions from surface mines and post-mining activities.** This step does not use mine-specific data; rather, it consists of multiplying coal-basin-specific coal production by coal-basin-specific gas content and an emission factor.

Step 1: Estimate CH_4 Liberated and CH_4 Emitted from Underground Mines

Underground mines generate CH_4 from ventilation systems and from degasification systems. Some mines recover and use the generated CH_4, 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 use ventilation systems to ensure that CH_4 levels remain within safe concentrations. Many coal mines do not have detectable levels of CH_4; 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 (MSHA 2016).[61] Based on the four quarterly measurements, MSHA estimates average daily CH_4 liberated at each of these underground mines.

For 1990 through 1999, average daily CH_4 emissions from MSHA 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 2015, 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.

Since 2011, the nation's "gassiest" underground coal mines—those that liberate more than 36,500,000 actual cubic feet of CH_4 per year (about 14,700 MT CO_2 Eq.)—have been required to report to the EPA's GHGRP (EPA 2016).[62] Mines that report to EPA's GHGRP must report quarterly measurements of CH_4 emissions from ventilation systems to EPA; they have the option of recording their own measurements, or using the measurements taken by MSHA as part of that agency's quarterly safety inspections of all mines in the U.S. with detectable CH_4 concentrations.[63]

Since 2013, ventilation emission estimates have been calculated based on both EPA's GHGRP data submitted by underground mines, and on quarterly measurement data obtained directly from MSHA for the remaining mines. The quarterly measurements are used to determine the average daily emissions rate for the reporting year quarter. The CH_4 liberated from ventilation systems was estimated by summing the emissions from the EPA's GHGRP mines and emissions based on MSHA quarterly measurements for the remaining mines not reporting to EPA's GHGRP.

[61] 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.

[62] Underground coal mines report to EPA under Subpart FF of the GHGRP. In 2015, 123 underground coal mines reported to the program.

[63] MSHA records coal mine CH_4 readings with concentrations of greater than 50 ppm (parts per million) CH_4. Readings below this threshold are considered non-detectable.

Table A-121: 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)**
2010	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)**
2011	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)**
2012	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)**
2013	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2014	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2015	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% 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 types of degasification systems to remove CH_4, including pre-mining vertical and horizontal wells (to recover CH_4 before mining) and post-mining vertical wells and horizontal boreholes (to recover CH_4 during mining of the coal seam). Post-mining 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).

Twenty-six mines employed degasification systems in 2015, and the CH_4 liberated through these systems was reported to the EPA's GHGRP (EPA 2016). Sixteen of these mines reported CH_4 recovery and use projects, and the other ten reported emitting CH_4 from degasification systems to the atmosphere. Several of the mines venting CH_4 from degasification systems use a small portion of the gas to fuel gob well blowers or compressors in remote locations where electricity is not available. However, this CH_4 use is not considered to be a formal recovery and use project.

Degasification information reported to EPA's GHGRP by underground coal mines is the primary source of data used to develop estimates of CH_4 liberated from degasification systems. Data reported to EPA's GHGRP were used to estimate CH_4 liberated from degasification systems at 21 of the 26 mines that used degasification systems in 2015.

Degasification volumes for the life of any pre-mining wells are attributed to the mine as emissions in the year in which the well is mined through.[64] EPA's GHGRP does not require gas production from virgin coal seams (coalbed methane) to be reported by coal mines under subpart FF. Most pre-mining wells drilled from the surface are considered coalbed methane wells and are reported under another subpart of the program (subpart W, "Petroleum and Natural Gas Systems"). As a result, for the 5 mines with degasification systems that include pre-mining wells, EPA's GHGRP information was supplemented with historical data from state gas well production databases (DMME 2016, GSA 2016; WVGES 2016), as well as with mine-specific information regarding the dates on which pre-mining wells are mined through (JWR 2010; El

[64] A well is "mined through" when coal mining development or the working face intersects the borehole or well.

Paso 2009). For pre-mining wells, the cumulative CH_4 production from the well is totaled using gas sales data, and considered liberated from the mine's degasification system the year in which the well is mined through.

EPA's GHGRP reports with CH_4 liberated from degasification systems are reviewed for errors in reporting. For some mines, EPA's GHGRP data are corrected for the inventory based on expert judgment. Common errors include reporting CH_4 liberated as CH_4 destroyed and vice versa. Other errors include reporting CH_4 destroyed without reporting any CH_4 liberated by degasification systems. In the rare cases where EPA's GHGRP data are inaccurate and gas sales data unavailable, estimates of CH_4 liberated are based on historical CH_4 liberation rates.

Step 1.3: Estimate CH_4 Recovered from Ventilation and Degasification Systems, and Utilized or Destroyed (Emissions Avoided)

Of the 16 active coal mines with operational CH_4 recovery and use projects in 2015, 14 sold the recovered CH_4 to a pipeline, including one that also used CH_4 to fuel a thermal coal dryer. Uses at other mines include electrical power generation (one mine) and heating mine ventilation air (one mine).

Ten of the 16 mines deployed degasification systems in 2015; for those mines, estimates of CH_4 recovered from the systems were exclusively based on EPA's GHGRP data. Based on weekly measurements of gas flow and CH_4 concentrations, the GHGRP summary data for degasification destruction at each mine were added together to estimate the CH_4 recovered and used from degasification systems.

Of the 16 mines with methane recovery in 2015, four intersected pre-mining wells in 2015. EPA's GHGRP and supplemental data were used to estimate CH_4 recovered and used at two of these mines, while supplemental data alone were used at the other two mines, that reported as a single entity to EPA's GHGRP. Supplemental information was used for these four mines because estimating CH_4 recovery and use from pre-mining wells requires additional data (not reported under subpart FF of EPA's GHGRP; see discussion in step 1.2 above) to account for the emissions avoided. The supplemental data came from state gas production databases (GSA 2016; WVGES 2015), as well as mine-specific information on the timing of mined-through pre-mining wells (JWR 2010; El Paso 2009). For pre-mining wells, the cumulative CH_4 production from the wells was totaled using gas sales data, and considered to be CH_4 recovered and used from the mine's degasification system the year in which the well is mined through.

For one mine, due to a lack of mine-provided information used in prior years and a GHGRP reporting discrepancy, the CH_4 liberated was based on an estimate from historical mine-provided CH_4 recovery and use rates and state gas sales records (DMME 2016). In 2015 the availability of the Virginia Division of Gas and Oil Data Information System made it possible to estimate recovered degasification emissions for this mine based on published well production.

EPA's GHGRP reports with CH_4 recovered and used from degasification systems are reviewed for errors in reporting. For some mines, EPA's GHGRP data are corrected for the inventory based on expert judgment (see further discussion in Step 1.2). In 2015, EPA's GHGRP information was not used to estimate CH_4 recovered and used at two mines because of a lack of mine-provided information used in prior years and GHGRP reporting discrepancies.

In 2015, one mine destroyed a portion of its CH_4 emissions from ventilation systems using thermal oxidation technology. The amount of CH_4 recovered and destroyed by the project was determined through publicly available emission reduction project information (ACR 2016).

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, basin-specific coal production obtained from the Energy Information Administration's *Annual Coal Report* was multiplied by basin-specific gas contents and a 150 percent emission factor (to account for CH_4 from over- and under-burden) to estimate CH_4 emissions (see King 1994; Saghafi 2013). For post-mining activities, basin-specific coal production was multiplied by basin-specific gas contents and a mid-range 32.5 percent emission factor accounting for CH_4 desorption during coal transportation and storage (Creedy 1993). Basin-specific *in situ* gas content data were compiled from AAPG (1984) and USBM (1986). Beginning in 2006, revised data on *in situ* CH_4 content and emissions factors have been used (EPA 1996, 2005).

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-122, which presents coal basin definitions by basin and by state.

The Energy Information Administration's *Annual Coal Report* (EIA 2016) 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-122. For two states—West Virginia and Kentucky—county-level production data were used for the basin assignments because coal production occurred in geologically distinct coal basins within these states. Table A-123 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 analyses conducted in Canada and Australia on coals similar to those present in the U.S. (King 1994; Saghafi 2013), the surface mining emission factor used was conservatively estimated to be 150 percent of the *in situ* CH_4 content of 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-124 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 from surface mines and post-mining activities was calculated by multiplying the coal production in each basin by the appropriate emission factors.

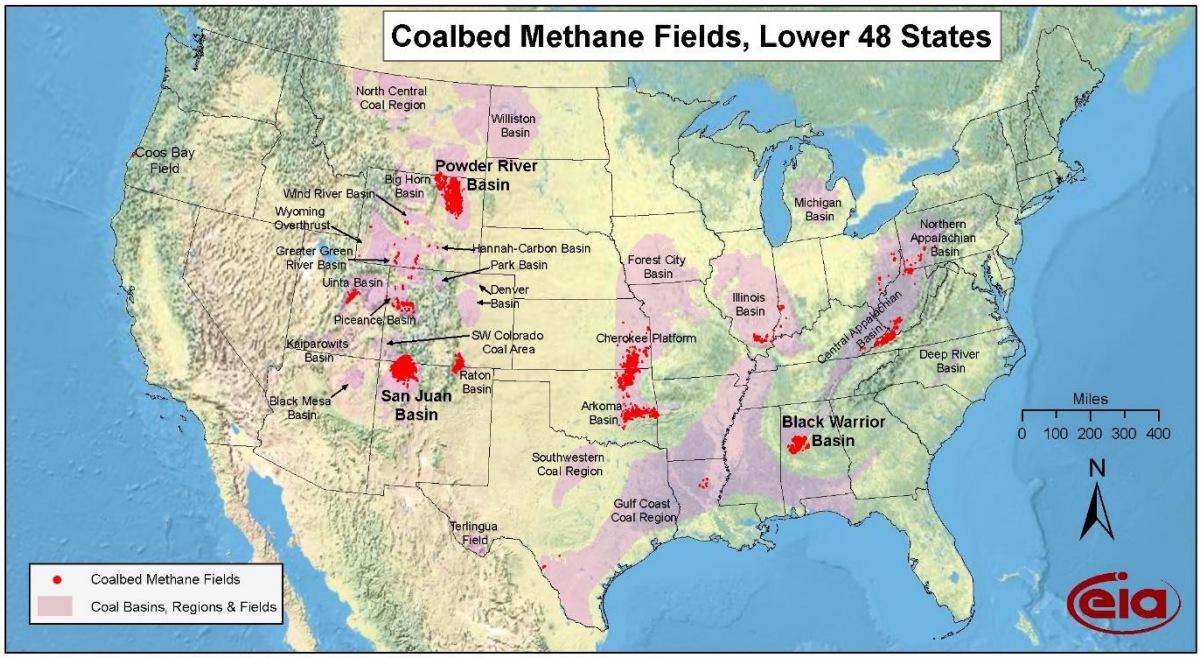
Table A-122 lists each of the major coal mine basins in the United States and the states in which they are located. As shown in Figure A-6, several coal basins span several states. Table A-123 shows annual underground, surface, and total coal production (in short tons) for each coal basin. Table A-124 shows the surface, post-surface, and post-underground emission factors used for estimating CH_4 emissions for each of the categories. Table A-125 presents annual estimates of CH_4 emissions for ventilation and degasification systems, and CH_4 used and emitted by underground coal mines. Table A-126 presents annual estimates of total CH_4 emissions from underground, post-underground, surface, and post-surface activities. Table A-127 provides the total net CH_4 emissions by state.

Table A-122: 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

Figure A-6: Locations of U.S Coal Basins



Source: Energy Information Administration based on data from USGS and various published studies
Updated: April 8, 2009

Table A-123: Annual Coal Production (Thousand Short Tons)

Basin	1990	2005	2008	2009	2010	2011	2012	2013	2014	2015
Underground Coal Production	**423,556**	**368,611**	**357,074**	**332,061**	**337,155**	**345,607**	**342,387**	**341,216**	**354,705**	**306,820**
N. Appalachia	103,865	111,151	105,228	99,629	103,109	105,752	103,408	104,198	116,700	103,578
Cent. Appalachia	198,412	123,083	114,998	98,689	96,354	94,034	78,067	70,440	64,219	53,230
Warrior	17,531	13,295	12,281	11,505	12,513	10,879	12,570	13,391	12,516	9,897
Illinois	69,167	59,180	64,609	67,186	72,178	81,089	92,500	98,331	105,211	96,361
S. West/Rockies	32,754	60,865	55,781	50,416	44,368	45,139	45,052	41,232	44,302	33,762
N. Great Plains	1,722	572	3,669	4,248	8,208	8,179	10,345	13,126	11,272	9,510
West Interior	105	465	508	388	425	535	445	498	485	482
Northwest	0	0	0	0	0	0	0	0	0	0
Surface Coal Production	**602,753**	**762,191**	**813,321**	**740,175**	**764,709**	**754,871**	**672,748**	**640,740**	**643,721**	**588,774**
N. Appalachia	60,761	28,873	30,413	26,552	26,082	26,382	21,411	19,339	17,300	13,491
Cent. Appalachia	94,343	112,222	118,962	97,778	89,788	90,778	69,721	57,173	52,399	37,278
Warrior	11,413	11,599	11,172	10,731	11,406	10,939	9,705	8,695	7,584	6,437
Illinois	72,000	33,702	34,266	34,837	32,911	34,943	34,771	33,798	31,969	27,360
S. West/Rockies	43,863	42,756	34,283	32,167	28,889	31,432	30,475	28,968	27,564	26,020
N. Great Plains	249,356	474,056	538,387	496,290	507,995	502,734	455,320	444,740	458,112	436,928
West Interior	64,310	52,263	44,361	39,960	46,136	55,514	49,293	46,477	47,201	40,083
Northwest	6,707	6,720	1,477	1,860	2,151	2,149	2,052	1,550	1,502	1,177
Total Coal Production	**1,026,309**	**1,130,802**	**1,170,395**	**1,072,236**	**1,101,864**	**1,100,478**	**1,015,135**	**981,956**	**998,426**	**895,594**
N. Appalachia	164,626	140,024	135,641	126,181	129,191	132,134	124,819	123,537	134,000	117,069
Cent. Appalachia	292,755	235,305	233,960	196,467	186,142	184,812	147,788	127,613	116,618	90,508
Warrior	28,944	24,894	23,453	22,236	23,919	21,818	22,275	22,086	20,100	16,334
Illinois	141,167	92,882	98,875	102,023	105,089	116,032	127,271	132,129	137,180	123,721
S. West/Rockies	76,617	103,621	90,064	82,583	73,257	76,571	75,527	70,200	71,956	59,782
N. Great Plains	251,078	474,628	542,056	500,538	516,203	510,913	465,665	457,866	469,384	446,438
West Interior	64,415	52,728	44,869	40,348	46,561	56,049	49,738	46,975	47,686	40,565
Northwest	6,707	6,720	1,477	1,860	2,151	2,149	2,052	1,550	1,502	1,177

Source for 1990–2015 data: EIA (1990 through 2015), *Annual Coal Report.* Table 1. U.S. Department of Energy.
Source for 2015 data: spreadsheet for the 2015 *Annual Coal Report*.
Note: Totals may not sum due to independent rounding.

Table A-124: Coal Underground, Surface, and Post-Mining CH_4 Emission Factors (ft^3 per Short Ton)

Basin	Surface Average *In Situ* Content	Underground Average *In Situ* Content	Surface Mine Factors	Post-Mining Surface Factors	Post Mining Underground
Northern Appalachia	59.5	138.4	89.3	19.3	45.0
Central Appalachia (WV)	24.9	136.8	37.4	8.1	44.5
Central Appalachia (VA)	24.9	399.1	37.4	8.1	129.7
Central Appalachia (E KY)	24.9	61.4	37.4	8.1	20.0
Warrior	30.7	266.7	46.1	10.0	86.7
Illinois	34.3	64.3	51.5	11.1	20.9
Rockies (Piceance Basin)	33.1	196.4	49.7	10.8	63.8
Rockies (Uinta Basin)	16.0	99.4	24.0	5.2	32.3
Rockies (San Juan Basin)	7.3	104.8	11.0	2.4	34.1
Rockies (Green River Basin)	33.1	247.2	49.7	10.8	80.3
Rockies (Raton Basin)	33.1	127.9	49.7	10.8	41.6
N. Great Plains (WY, MT)	20.0	15.8	30.0	6.5	5.1
N. Great Plains (ND)	5.6	15.8	8.4	1.8	5.1
West Interior (Forest City, Cherokee Basins)	34.3	64.3	51.5	11.1	20.9
West Interior (Arkoma Basin)	74.5	331.2	111.8	24.2	107.6
West Interior (Gulf Coast Basin)	11.0	127.9	16.5	3.6	41.6
Northwest (AK)	16.0	160.0	24.0	1.8	52.0
Northwest (WA)	16.0	47.3	24.0	5.2	15.4

Sources: 1986 USBM Circular 9067, *Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins*; U.S. DOE Report DOE/METC/83-76, *Methane Recovery from Coalbeds: A Potential Energy Source;* 1986–1988 Gas Research Institute Topical Report, *A Geologic Assessment of Natural Gas from Coal Seams;* 2005 U.S. EPA Draft Report, *Surface Mines Emissions Assessment*.

Table A-125: Underground Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	2005	2008	2009	2010	2011	2012	2013	2014	2015
Ventilation Output	112	75	100	114	117	97	90	89	89	84
Adjustment Factor for Mine Data*	98%	98%	99%	99%	99%	99%	99%	100%	100%	100%
Adjusted Ventilation Output	114	77	101	115	118	98	91	89	89	84
Degasification System Liberated	54	48	49	49	58	48	45	45	42	41
Total Underground Liberated	168	124	150	163	177	147	137	134	131	126
Recovered & Used	(14)	(37)	(40)	(40)	(49)	(42)	(38)	(38)	(35)	(33)
Total	**154**	**87**	**110**	**123**	**128**	**104**	**98**	**96**	**96**	**93**

* Refer to Table A-121.

Note: Totals may not sum due to independent rounding

Table A-126: Total Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	2005	2008	2009	2010	2011	2012	2013	2014	2015
Underground Mining	154	87	110	123	128	104	98	96	96	93
Surface Mining	22	25	27	24	24	24	21	20	20	18
Post-Mining (Underground)	19	16	15	14	14	14	14	14	14	12
Post-Mining (Surface)	5	5	6	5	5	5	5	4	4	4
Total	**200**	**132**	**157**	**166**	**171**	**148**	**138**	**134**	**135**	**126**

Note: Totals may not sum due to independent rounding.

Table A-127: Total Coal Mining CH_4 Emissions by State (Million Cubic Feet)

State	1990	2005	2008	2009	2010	2011	2012	2013	2014	2015
Alabama	32,097	15,789	20,992	22,119	21,377	18,530	18,129	17,486	16,301	12,675
Alaska	50	42	43	54	63	63	60	45	44	34
Arizona	151	161	107	100	103	108	100	101	107	91
Arkansas	5	+	237	119	130	348	391	214	176	559
California	1	0	0	0	0	0	0	0	0	0
Colorado	10,187	13,441	12,871	13,999	16,470	11,187	9,305	4,838	4,038	3,248
Illinois	10,180	6,488	7,568	7,231	8,622	7,579	9,763	8,920	9,217	10,547
Indiana	2,232	3,303	5,047	5,763	5,938	6,203	7,374	6,427	7,159	6,891
Iowa	24	0	0	0	0	0	0	0	0	0
Kansas	45	11	14	12	8	2	1	1	4	12
Kentucky	10,018	6,898	9,986	12,035	12,303	10,592	7,993	8,098	8,219	6,377
Louisiana	64	84	77	73	79	168	80	56	52	69
Maryland	474	361	263	219	238	263	197	166	169	170
Mississippi	0	199	159	193	224	154	165	200	209	176

Missouri	166	3	15	28	29	29	26	26	23	9
Montana	1,373	1,468	1,629	1,417	1,495	1,445	1,160	1,269	1,379	1,353
New Mexico	363	2,926	3,411	3,836	3,956	4,187	2,148	2,845	2,219	2,648
North Dakota	299	306	303	306	296	289	281	282	298	294
Ohio	4,406	3,120	3,686	4,443	3,614	3,909	3,389	3,182	3,267	2,718
Oklahoma	226	825	932	624	436	360	499	282	112	735
Pennsylvania	21,864	17,904	20,684	22,939	23,372	17,708	17,773	20,953	19,803	19,587
Tennessee	276	115	86	69	67	60	35	31	22	40
Texas	1,119	922	783	704	823	922	887	854	876	721
Utah	3,587	4,787	5,524	5,449	5,628	3,651	3,624	2,733	1,605	1,737
Virginia	46,041	8,649	9,223	8,042	9,061	8,526	6,516	8,141	6,980	6,386
Washington	146	154	0	0	0	0	0	0	0	0
West Virginia	48,335	29,745	36,421	40,452	40,638	35,709	33,608	32,998	38,023	35,784
Wyoming	6,671	14,745	16,959	15,627	16,032	15,916	14,507	14,025	14,339	13,624
Total	**200,399**	**132,481**	**157,112**	**165,854**	**171,000**	**147,908**	**138,012**	**134,173**	**134,643**	**126,483**

+ 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.

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3.5. Methodology for Estimating CH_4 and CO_2 Emissions from Petroleum Systems

For this public review draft, this annex is available at https://www.epa.gov/ghgemissions/updates-under-consideration-petroleum-and-natural-gas-systems-1990-2015-ghg-inventory.

The annex contains tables presenting methane emissions (in kt CH_4), activity data, average emission factors (in kg CH_4/unit) for the full 1990-2015 time series, and a short description of data sources and methods for each source, also in tabular format. Previous GHG Inventory annexes included the most recent year of information on activity data and average emission factors, and text describing data sources and methods for activity data and emission factors. EPA is seeking stakeholder feedback on the presentation of information in this format versus the previous annex discussion text. For information on CO_2 emissions, which have not been updated in this public review draft, please see the annexes of the 2016 GHG Inventory (1990-2014).

3.6. Methodology for Estimating CH_4 and CO_2 Emissions from Natural Gas Systems

For this public review draft, this annex is available at https://www.epa.gov/ghgemissions/updates-under-consideration-petroleum-and-natural-gas-systems-1990-2015-ghg-inventory.

The annex contains tables presenting methane emissions (in kt CH_4), activity data, average emission factors (in kg CH_4/unit) for the full 1990-2015 time series, and a short description of data sources and methods for each source, also in tabular format. Previous GHG Inventory annexes included the most recent year of information on activity data and average emission factors, and text describing data sources and methods for activity data and emission factors. EPA is seeking stakeholder feedback on the presentation of information in this format versus the previous annex discussion text. For information on CO_2 emissions, which have not been updated in this public review draft, please see the annexes of the 2016 GHG Inventory (1990-2014).

3.7. Methodology for Estimating CO_2, CH_4, and N_2O 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 CH_4 and N_2O. The emission estimates are calculated for all four sources on a mass-basis based on the data available. 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 2014), *Advancing Sustainable Materials Management: Facts and Figures – Assessing Trends in Material Generation, Recycling and Disposal in the United States* (EPA 2015, 2016) the flows of plastics in the U.S. waste stream are reported for seven resin categories. For 2015, the quantity generated, recovered, and discarded for each resin is shown in Table A-128. The data set for 1990 through 2015 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), and Shin (2014). 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-128: 2015 Plastics in the Municipal Solid Waste Stream by Resin (kt)

Waste Pathway	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Generation	4,600	5,289	762	6,995	6,450	2,114	3,955	**30,164**
Recovery	880	553	0	408	54	27	953	**2,876**
Discard	3,720	4,736	762	6,586	6,396	2,087	3,003	**27,289**
Landfill	3,437	4,376	704	6,086	5,910	1,928	2,775	**25,215**
Combustion	283	360	58	501	486	159	228	**2,074**
Recovery[a]	19%	10%	0%	6%	1%	1%	24%	**10%**
Discard[a]	81%	90%	100%	94%	99%	99%	76%	**90%**
Landfill[a]	75%	83%	92%	87%	92%	91%	70%	**84%**
Combustion[a]	6%	7%	8%	7%	8%	8%	6%	**7%**

[a] 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-129). 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-129: 2015 Plastics Incinerated (kt), Carbon Content (%), Fraction Oxidized (%) and Carbon Incinerated (kt)

Factor	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Quantity Combusted	283	360	58	501	486	159	228	**2,074**
Carbon Content of Resin	63%	86%	38%	86%	86%	92%	66%	**-**
Fraction Oxidized	98%	98%	98%	98%	98%	98%	98%	**-**
Carbon in Resin Combusted	173	302	22	420	408	143	147	**1,617**
Emissions (MMT CO_2 Eq.)	**0.6**	**1.1**	**0.1**	**1.5**	**1.5**	**0.5**	**0.5**	**5.9**

[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. "2014 U.S. Scrap Tire Management Summary" (RMA 2016) reports that 1,923 thousand of the 3,551 thousand tons of scrap tires generated in 2015 (approximately 54 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.[65] Table A-130 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 the mass of scrap tires incinerated by the total C content of the synthetic rubber, C black portions of scrap tires, and then by a 98 percent oxidation factor, yielded CO_2 emissions, as shown in Table A-131. The disposal rate of rubber in tires (0.3 MMT C/year) is smaller than the consumption rate for tires based on summing the elastomers listed in Table A-128 (1.3 MMT/year); 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 2015 were taken from RMA 2006, RMA 2009, RMA 2011; RMA 2014a; RMA2016; where 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.

In 2009, RMA 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, 2014b, 2016).

Table A-130: Elastomers Consumed in 2002 (kt)

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**	**NA**	**1,950**
For Tires	**1,307**	**NA**	**1,174**

* Used to calculate C content of non-tire rubber products in municipal solid waste.
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

[65] The carbon content of tires (1,174 kt C) divided by the mass of rubber in tires (1,307 kt) equals 90 percent.

Table A-131: Scrap Tire Constituents and CO_2 Emissions from Scrap Tire Incineration in 2015

Material	Weight of Material (MMT)	Fraction Oxidized	Carbon Content	Emissions (MMT CO_2 Eq.)
Synthetic Rubber	0.3	98%	90%	1.2
Carbon Black	0.4	98%	100%	1.4
Total	**0.8**	**NA**	**NA**	**2.7**

NA (Not Applicable)

CO_2 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[66] provided in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2014), *Advancing Sustainable Materials Management: Facts and Figures: Assessing Trends in Material Generation, Recycling and Disposal in the United States* (EPA 2015, 2016), 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 (2016) did not report rubber found in the product category "containers and packaging;" however, containers and packaging from miscellaneous material types were reported for 2009 through 2015. As a result, EPA assumes that rubber containers and packaging are reported under the "miscellaneous" category; and therefore, the quantity reported for 2009 through 2015 were 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 percent was assigned to each product type, as shown in Table A-132.[67] 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-132: Rubber and Leather in Municipal Solid Waste in 2014

Product Type	Incinerated (kt)	Synthetic Rubber (%)	Carbon Content (%)	Fraction Oxidized (%)	Emissions (MMT CO_2 Eq.)
Durables (not Tires)	**259**	**70%**	**85%**	**98%**	**0.8**
Non-Durables	**79**	**-**	**-**	**-**	**0.2**
Clothing and Footwear	60	70%	85%	98%	0.2
Other Non-Durables	19	70%	85%	98%	0.1
Containers and Packaging	**2**	**70%**	**85%**	**98%**	**0.0**
Total	**341**	**-**	**-**	**-**	**1.1**

- Not Applicable

CO_2 from Incineration of Synthetic Fibers

Carbon dioxide emissions from synthetic fibers were estimated as the product of the amount of synthetic fiber discarded annually and the average 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 2014) and *Advancing Sustainable Materials Management: Facts and Figures – Assessing Trends in Material Generation, Recycling and Disposal in the United States* (EPA 2015, 2016) 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-133). 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), and Shin (2014). 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). The average C content of 71 percent was assigned to synthetic fiber using the production-weighted average of the C contents of the four major fiber types (polyester, nylon, olefin, and acrylic) based on 2015 fiber production (see Table A-134). The equation relating CO_2 emissions to the amount of textiles combusted is shown below.

[66] Discards = Generation minus recycling.

[67] As a sustainably harvested biogenic material, the incineration of leather is assumed to have no net CO_2 emissions.

CO_2 Emissions from the Incineration of Synthetic Fibers = Annual Textile Incineration (kt) × (Percent of Total Fiber that is Synthetic) × (Average C Content of Synthetic Fiber) × (44 g CO_2/12 g C)

Table A-133: Synthetic Textiles in MSW (kt)

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	4,706	655	4,051	417
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	5,714	913	4,800	480
2006	5,893	933	4,959	479
2007	6,041	953	5,088	470
2008	6,305	968	5,337	470
2009	6,424	978	5,446	458
2010	6,508	998	5,510	441
2011	6,513	1,003	5,510	419
2012	7,114	1,117	5,997	456
2013	7,496	894	6,602	502
2014	8,052	1,301	6,751	513
2015	8,052	1,301	6,751	513

Table A-134: Synthetic Fiber Production in 2015

Fiber	Production (MMT)	Carbon Content
Polyester	1.2	63%
Nylon	0.5	64%
Olefin	1.0	86%
Acrylic	-	68%
Total	**2.8**	**71%**

CH_4 and N_2O 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 2014), *Advancing Sustainable Materials Management: Facts and Figures: Assessing Trends in Material Generation, Recycling and Disposal in the United States* (EPA 2015, 2016) 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 results of the biannual national survey of Municipal Solid Waste (MSW) Generation and Disposition in the U.S., published in *BioCycle* (van Haaren et al. 2010), and Shin (2014). 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 IPCC 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 1990 through 2008. Data for 2011 were derived from information in Shin (2014). For waste incineration in the United States, an emission factor of 0.20 kg CH_4/kt 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 for 2012 through 2015, so these values were assumed to be equal to the 2011 value.

Despite the differences in methodology and data sources, the two series of references (EPA 2014; van Haaren, Rob, Themelis, N., and Goldstein, N. 2010) provide estimates of total solid waste incinerated that are relatively consistent (see Table A-135).

Table A-135: 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
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	22,714,122[e]
2010	26,544,672	21,741,734[e]
2011	26,544,672	20,756,870
2012	26,544,672	20,756,870[f]
2013	29,629,152	20,756,870[f]
2014	30,136,361	20,756,870[f]
2015	30,136,361[g]	20,756,870[f]

[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
[e] Interpolated between 2011 and 2008 values
[f] Set equal to the 2011 value
[g] Set equal to the 2014 value.

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3.8. Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military

Bunker fuel emissions estimates for the Department of Defense (DoD) were developed using data generated by the Defense Logistics Agency Energy (DLA Energy) for aviation and naval fuels. DLA Energy prepared a special report based on data in the Fuels Automated System (FAS) for calendar year 2015 fuel sales in the Continental United States (CONUS).[68] The following steps outline the methodology used for estimating emissions from international bunker fuels used by the U.S. Military.

Step 1: Omit Extra-Territorial Fuel Deliveries

Beginning with the complete FAS data set for each year, the first step in quantifying DoD-related emissions from international bunker fuels was to identify data that would be representative of international bunker fuel consumption as 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[69] and NATO[70] 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 of 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 Military Service data and expert judgment, a small fraction of the total JP8 use (i.e., between 1.78 and 2.7 times the quantity of diesel fuel used, depending on the Service) was reallocated from the aviation subtotal to a new land-based jet fuel category for 1997 and subsequent years. As a result of this reallocation, the JP8 use reported for aviation was reduced and the total fuel use for land-based equipment increased. DoD's total fuel use did not change.

Table A-136 displays DoD's consumption of transportation fuels, summarized by fuel type, that remain at the completion of Step 1, and 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 omitted for the purpose of calculating international bunker fuels. The remaining fuels, listed below, were considered potential DoD international bunker fuels.

- **Aviation:** jet fuels (JP8, JP5, JP4, JAA, JA1, and JAB).
- **Marine:** naval distillate fuel (F76), marine gas oil (MGO), and intermediate fuel oil (IFO).

Step 4: Omit Fuel Transactions Received by Military Services that are not considered to be International Bunker Fuels

Only Navy and Air Force were deemed to be users of military international bunker fuels after sorting the data by Military Service and applying the following assumptions regarding fuel use by Service.

- 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.

[68] FAS contains data for 1995 through 2015, but the dataset was not complete for years prior to 1995. Using DLA aviation and marine fuel procurement data, fuel quantities from 1990 to 1994 were estimated based on a back-calculation of the 1995 data in the legacy database, the Defense Fuels Automated Management System (DFAMS). 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.

[69] DoD Directive 4140.25-M-V1, Fuel Standardization and Cataloging, 2013; DoD Directive 4140.25, DoD Management Policy for Energy Commodities and Related Services, 2004.

[70] NATO Standard Agreement NATO STANAG 4362, Fuels for Future Ground Equipments Using Compression Ignition or Turbine Engines, 2012.

- Based on previous discussions with the Army staff, only an extremely small percentage of Army aviation emissions, and none of Army 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 research, Army bunker fuel emissions were assumed to be zero.

- Marine Corps aircraft operating while embarked consumed fuel that was 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 DLA Energy were assumed to be zero.

Step 5: Determine Bunker Fuel Percentages

It was necessary to determine what percent of the aviation and marine 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). Methods for quantifying aviation and marine bunker fuel percentages are described below.

- **Aviation:** The Air Force Aviation bunker fuel percentage was determined to be 13.2 percent. 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. 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 was calculated to be 40.4 percent by 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. This Naval Aviation bunker fuel percentage was then multiplied by total annual Navy aviation fuel delivered for U.S. activities, yielding total Navy aviation bunker fuel consumed.

- **Marine:** For marine bunkers, fuels consumed while ships were underway were assumed to be bunker fuels. The Navy maritime bunker fuel percentage was determined to be 79 percent because the Navy reported that 79 percent of vessel operations were underway, while the remaining 21 percent of operations occurred in port (i.e., pierside) in the year 2000.[71]

Table A-137 and Table A-138 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 greenhouse gas 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-137 and Table A-138, below. CO_2 emissions from aviation bunkers and distillate marine bunkers are presented in Table A-141, and are based on emissions from fuels tallied in Table A-137 and Table A-138.

[71] Note that 79 percent is used because it is based on Navy data, but the percentage of time underway may vary from year-to-year depending on vessel operations. For example, for years prior to 2000, the bunker fuel percentage was 87 percent.

Table A-136: Transportation Fuels from Domestic Fuel Deliveries[a] (Million Gallons)

Vehicle Type/Fuel	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Aviation	**4,598.4**	**3,099.9**	**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**	**1,814.5**	**1,663.9**	**1,405.0**	**1,449.7**	**1,336.4**	**1,796.2**	**1,773.8**
Total Jet Fuels	4,598.4	3,099.9	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	1,814.3	1,663.7	1,404.8	1,449.5	1,336.2	1,795.9	1,773.6
JP8	*285.7*	*2,182.8*	*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*	*1,358.2*	*1,100.1*	*882.8*	*865.2*	*718.0*	*546.6*	*126.6*
JP5	*1,025.4*	*691.2*	*472.1*	*503.2*	*442.2*	*409.1*	*433.7*	*421.6*	*325.5*	*376.1*	*362.2*	*361.2*	*399.3*	*372.3*	*362.5*	*316.4*	*311.0*	*316.4*
Other Jet Fuels	*3,287.3*	*225.9*	*69.6*	*71.2*	*76.1*	*111.4*	*143.2*	*77.6*	*57.0*	*86.3*	*89.2*	*94.8*	*164.3*	*149.7*	*221.8*	*301.7*	*938.3*	*1,330.6*
Aviation Gasoline	+	+	+	+	0.1	0.1	+	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.3	0.2	0.3	0.3
Marine	**686.8**	**438.9**	**454.4**	**418.4**	**455.8**	**609.1**	**704.5**	**604.9**	**531.6**	**572.8**	**563.4**	**485.8**	**578.8**	**489.9**	**490.4**	**390.4**	**427.9**	**421.7**
Middle Distillate (MGO)	+	+	48.3	33.0	41.2	88.1	71.2	54.0	45.8	45.7	55.2	56.8	48.4	37.3	52.9	40.9	62.0	56.0
Naval Distillate (F76)	686.8	438.9	398.0	369.1	395.1	460.9	583.5	525.9	453.6	516.0	483.4	399.0	513.7	440.0	428.4	345.7	362.7	363.3
Intermediate Fuel Oil (IFO)[b]	+	+	8.1	16.3	19.5	60.2	49.9	25.0	32.2	11.1	24.9	30.0	16.7	12.5	9.1	3.8	3.2	2.4
Other[c]	**717.1**	**310.9**	**248.2**	**109.8**	**211.1**	**221.2**	**170.9**	**205.6**	**107.3**	**169.0**	**173.6**	**206.8**	**224.0**	**208.6**	**193.8**	**180.6**	**190.7**	**181.1**
Diesel	93.0	119.9	126.6	26.6	57.7	60.8	46.4	56.8	30.6	47.3	49.1	58.3	64.1	60.9	57.9	54.9	57.5	54.8
Gasoline	624.1	191.1	74.8	24.7	27.5	26.5	19.4	24.3	11.7	19.2	19.7	25.2	25.5	22.0	19.6	16.9	16.5	16.2
Jet Fuel[d]	+	+	46.7	58.4	125.9	133.9	105.1	124.4	65.0	102.6	104.8	123.3	134.4	125.6	116.2	108.8	116.7	110.1
Total (Including Bunkers)	**6,002.4**	**3,849.8**	**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**	**2,507.1**	**2,466.7**	**2,103.5**	**2,133.9**	**1,907.5**	**2,414.9**	**2,376.6**

+ Indicates value does not exceed 0.05 million gallons.

[a] Includes fuel distributed 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. Datasets 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. Since 2001, other gasoline and diesel fuel totals were generated by DLA Energy.

[d] The fraction of jet fuel consumed in land-based vehicles was estimated based on DLA Energy data as well as Military Service and expert judgment.

Note: Totals may not sum due to independent rounding.

Table A-137: Total U.S. Military Aviation Bunker Fuel (Million Gallons)

Fuel Type/Service	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jet Fuels																		
JP8	**56.7**	**300.4**	**307.6**	**341.2**	**309.5**	**305.1**	**309.8**	**285.6**	**262.5**	**249.1**	**229.4**	**211.4**	**182.5**	**143.4**	**141.2**	**122.0**	**71.8**	**13.1**
Navy	56.7	38.3	53.4	73.8	86.6	76.3	79.2	70.9	64.7	62.7	59.2	55.4	60.8	47.1	50.4	48.9	19.8	0.8
Air Force	+	262.2	254.2	267.4	222.9	228.7	230.6	214.7	197.8	186.5	170.3	156.0	121.7	96.2	90.8	73.0	52.0	12.3
JP5	**370.5**	**249.8**	**160.3**	**169.7**	**158.3**	**146.1**	**157.9**	**160.6**	**125.0**	**144.5**	**139.2**	**137.0**	**152.5**	**144.9**	**141.2**	**124.9**	**121.9**	**124.1**
Navy	365.3	246.3	155.6	163.7	153.0	141.3	153.8	156.9	122.8	141.8	136.5	133.5	149.7	143.0	139.5	123.6	120.2	122.6
Air Force	5.3	3.5	4.7	6.1	5.3	4.9	4.1	3.7	2.3	2.7	2.6	3.5	2.8	1.8	1.7	1.3	1.6	1.5
JP4	**420.8**	**21.5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Navy	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Air Force	420.8	21.5	+	+	+	+	+	+	+	+	+	+	0.1	+	+	+	+	+
JAA	**13.7**	**9.2**	**12.5**	**12.6**	**13.7**	**21.7**	**30.0**	**15.5**	**11.7**	**15.6**	**16.8**	**18.1**	**31.4**	**31.1**	**38.6**	**46.5**	**124.5**	**189.8**
Navy	8.5	5.7	7.9	8.0	9.8	15.5	21.5	11.6	9.1	11.7	12.5	12.3	13.7	14.6	14.8	13.4	32.2	62.1
Air Force	5.3	3.5	4.5	4.6	3.8	6.2	8.6	3.9	2.6	3.9	4.3	5.9	17.7	16.5	23.8	33.1	92.3	127.7
JA1	+	+	+	0.1	0.6	0.2	0.5	0.5	0.4	1.1	1.0	0.6	0.3	-+	-+	0.6	0.3	0.3
Navy	+	+	+	+	+	+	+	+	+	0.1	0.1	0.1	0.1	-+	-+	0.6	-+	+
Air Force	+	+	+	0.1	0.6	0.2	0.5	0.5	0.4	1.0	0.8	0.5	0.1	-+	-+	+	0.3	0.3
JAB	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Navy	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Air Force	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Navy Subtotal	**430.5**	**290.2**	**216.9**	**245.5**	**249.4**	**233.1**	**254.4**	**239.4**	**196.6**	**216.3**	**208.3**	**201.3**	**224.4**	**204.3**	**204.5**	**186.5**	**172.3**	**185.5**
Air Force Subtotal	**431.3**	**290.7**	**263.5**	**278.1**	**232.7**	**239.9**	**243.7**	**222.9**	**203.1**	**194.0**	**178.1**	**165.9**	**142.4**	**114.5**	**116.3**	**107.4**	**146.2**	**141.9**
Total	**861.8**	**580.9**	**480.4**	**523.6**	**482.1**	**473.0**	**498.1**	**462.3**	**399.7**	**410.3**	**386.3**	**367.2**	**366.7**	**318.8**	**320.8**	**293.9**	**318.5**	**327.4**

+ Does not exceed 0.05 million gallons.

The negative values in this table represent returned products.

Note: Totals may not sum due to independent rounding.

Table A-138: Total U.S. DoD Maritime Bunker Fuel (Million Gallons)

Marine Distillates	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Navy – MGO	0.0	0.0	23.8	22.5	27.1	63.7	56.2	38.0	33.0	31.6	40.9	39.9	32.9	25.5	36.5	32.3	43.3	37.8
Navy – F76	522.4	333.8	298.6	282.6	305.6	347.8	434.4	413.1	355.9	404.1	376.9	311.4	402.2	346.6	337.9	273.1	286.2	286.7
Navy – IFO	0.0	0.0	6.4	12.9	15.4	47.5	39.4	19.7	25.4	8.8	19.0	23.1	12.9	9.5	6.1	3.0	1.5	1.9
Total	**522.4**	**333.8**	**328.8**	**318.0**	**348.2**	**459.0**	**530.0**	**470.7**	**414.3**	**444.4**	**436.7**	**374.4**	**448.0**	**381.5**	**380.6**	**308.5**	**331.0**	**326.3**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 million gallons.

Table A-139: Aviation and Marine Carbon Contents (MMT 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-140: Annual Variable Carbon Content Coefficient for Jet Fuel (MMT Carbon/QBtu)

Fuel	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
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	19.70	19.70

Source: EPA (2010)

Table A-141: Total U.S. DoD CO_2 Emissions from Bunker Fuels (MMT CO_2 Eq.)

Mode	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Aviation	8.1	5.5	4.7	5.1	4.7	4.6	4.8	4.5	3.9	4.0	3.8	3.6	3.6	3.1	3.1	2.9	3.1	3.2
Marine	5.4	3.4	3.4	3.3	3.6	4.7	5.4	4.8	4.2	4.6	4.5	3.8	4.6	3.9	3.9	3.2	3.4	3.3
Total	**13.4**	**9.0**	**8.0**	**8.3**	**8.3**	**9.3**	**10.3**	**9.3**	**8.1**	**8.5**	**8.2**	**7.4**	**8.2**	**7.0**	**7.0**	**6.0**	**6.5**	**6.6**

Note: Totals may not sum due to independent rounding.

References

DLA Energy (2016) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, D.C.

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

3.9. 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: refrigeration and air-conditioning, foams, aerosols, solvents, and fire-extinguishing. Within these sectors, there are 65 independently modeled end-uses. The model requires information on the market growth for each of the end-uses, a history of the market transition from ODS to alternatives, and 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, the Greenhouse Gas Reporting Program maintained by the Climate Change 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 and other regulations.

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-142, 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-142: 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								1.6%
	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								1.5%
	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								1.5%
	HCFC-22	1991	1994	16%	HFC-134a	2000	2010	100%	None				
	HCFC-123	1993	1994	31%	Unknown								
CFC-114	HFC-236fa	1993	1996	100%	HFC-134a	1998	2009	100%	None				1.4%
Cold Storage													
CFC-12	HCFC-22	1990	1993	65%	R-404A	1996	2010	75%	None				3.1%
					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				3.0%
					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				2.6%
					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				1.3%
					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				1.3%
					R-410A	2001	2005	18%	None				
					R-410A	2006	2009	8%	None				
					R-410A	2009	2010	71%	None				
Dehumidifiers													

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	HFC-134a	1997	1997	89%	None								1.3%
	R-410A	2007	2010	11%	None								
Ice Makers													
CFC-12	HFC-134a	1993	1995	25%	None								2.1%
	R-404A	1993	1995	75%									
Industrial Process Refrigeration													
CFC-11	HCFC-123	1992	1994	70%	Unknown								3.2%
	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				3.1%
					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	HFC-134a	1995	2009	2%	None								3.0%
	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%	HFO-1234yf	2012	2015	1%	None				0.3%
					HFO-1234yf	2016	2021	99%	None				
Mobile Air Conditioners (Light Duty Trucks)													
CFC-12	HFC-134a	1993	1994	100%	HFO-1234yf	2012	2015	1%	None				1.4%
					HFO-1234yf	2016	2021	99%	None				
Mobile Air Conditioners (School and Tour Buses)													
CFC-12	HCFC-22	1994	1995	0.5%	HFC-134a	2006	2007	100%	None				0.3%
	HFC-134a	1194	1997	99.5%	None								
Mobile Air Conditioners (Transit Buses)													
HCFC-22	HFC-134a	1995	2009	100%	None								0.3%
Mobile Air Conditioners (Trains)													
HCFC-22	HFC-134a	2002	2009	50%	None								0.3%
	R-407C	2002	2009	50%	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	
Packaged Terminal Air Conditioners and Heat Pumps													
HCFC-22	R-410A	2006	2009	10%	None								3.0%
	R-410A	2009	2010	90%	None								
Positive Displacement Chillers													
HCFC-22	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	None				2.5%
					R-410A	2010	2020	40%	None				
	R-407C	2000	2009	1%	None								
	HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	None				
									R-410A	2010	2020	40%	
					R-407C	2009	2010	9%	None				
CFC-12	HCFC-22	1993	1993	100%	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	2.5%
									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%	None								1.7%
Residential Unitary Air Conditioners													
HCFC-22	HCFC-22	2006	2006	70%	R-410A	2007	2010	29%	None				1.3%
					R-410A	2010	2010	71%	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; Technology Transition)													
DX[1]	DX	2000	2006	67.5%	DX	2006	2015	35%	None				1.7%
					DR[2]	2000	2015	23%	None				
					SLS[3]	2000	2015	15%	None				
	DR	2001	2006	22.5%	None								
	SLS	2001	2006	10%	None								
Retail Food (Large; Refrigerant Transition)													
CFC-12	R-404A	1995	2000	17.5%	R-404A	2000	2000	3.3%	None				1.7%
R-502[4]					R-407A	2011	2015	63.3%	None				
	R-507	1995	2000	7.5%	R-507	2001	2005	70%	R-404A	2006	2010	29%	
									R-407A	2006	2010	71%	
					R-407A	2006	2010	30%	None				
	HCFC-22	1995	2000	75%	R-404A	2006	2010	13.3%	R-407A	2011	2015	100%	
					R-407A	2001	2005	1.3%	None				
					R-404A	2001	2005	12%	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	
					R-507	2001	2005	6.7%	R-407A	2011	2015	100%	
					R-404A	2006	2010	34%	R-407A	2011	2015	100%	
					R-404A	2006	2010	7.3%	None				
					R-407A	2006	2010	25.3%	None				
Retail Food (Large Condensing Units)													
HCFC-22	R-402A	1995	2005	5%	R-404A	2006	2006	100%	None				1.5%
	R-404A	1995	2005	25%	None								
	R-507	1995	2005	10%	None								
	R-404A	2008	2010	45%	None								
	R-507	2008	2010	15%	None								
Retail Food (Small Condensing Units)													
HCFC-22	R-401A	1995	2005	6%	HFC-134a	2006	2006	100%	None				1.6%
	R-402A	1995	2005	4%	HFC-134a	2006	2006	100%	None				
	HFC-134a	1993	2005	30%									
	R-404A	1995	2005	30%									
	R-404A	2008	2010	30%									
Retail Food (Small)													
CFC-12	HCFC-22	1990	1993	91%	HFC-134a	1993	1995	91%	CO_2	2012	2015	1%	2.2%
									Non-ODP/GWP	2012	2015	3.7%	
									CO_2	2016	2016	11%	
									Non-ODP/GWP	2016	2016	17.3%	
					HFC-134a	2000	2009	9%					
					Non-								
	R-404A	1990	1993	9%	ODP/GWP	2016	2016	30%					
Retail Food (Vending Machines)													
CFC-12	HFC-134a	1995	1998	90%	CO_2	2012	2012	1%	None				-0.03%
					CO_2	2013	2017	39%	None				
					Propane	2014	2014	1%	None				
					Propane	2015	2015	49%	None				
					R-450A	2019	2019	5%	None				
					R-513A	2019	2019	5%	None				
	R-404A	1995	1998	10%	R-450A	2019	2019	50%	None				
					R-513A	2019	2019	50%	None				
Transport Refrigeration (Road Transport)													
CFC-12	HFC-134a	1993	1995	10%	None								5.5%
	R-404A	1993	1995	60%	None								
	HCFC-22	1993	1995	30%	R-410A	2000	2003	5%	CO_2	2017	2021	5%	
					R-404A	2006	2010	95%	CO_2	2017	2021	5%	

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	
Transport Refrigeration (Intermodal Containers)													
CFC-12	HFC-134a	1993	1993	60%	CO_2	2017	2021	5%	None				7.3%
	R-404A	1993	1993	5%	CO_2	2017	2021	5%	None				
	HCFC-22	1993	1993	35%	HFC-134a	2000	2010	10%	CO_2	2017	2021	5%	
Transport Refrigeration (Merchant Fishing Transport)													
HCFC-22	HFC-134a	1993	1995	10%	None								5.7%
	R-507	1994	1995	10%	None								
	R-404A	1993	1995	10%	None								
	HCFC-22	1993	1995	70%	R-407C	2000	2005	3%	R-410A	2005	2007	100%	
					R-507	2006	2010	49%	None				
					R-404	2006	2010	49%	None				
Transport Refrigeration (Reefer Ships)													
HCFC-22	HFC-134a	1993	1995	3.3%	None								4.2%
	R-507	1994	1995	3.3%	None								
	R-404A	1993	1995	3.3%	None								
	HCFC-22	1993	1995	90%	HFC-134a	2006	2010	25%	None				
					R-507	2006	2010	25%	None				
					R-404A	2006	2010	25%	None				
					R-407C	2006	2010	25%	None				
Transport Refrigeration (Vintage Rail Transport)													
CFC-12	HCFC-22	1993	1995	100%	HFC-134a	1996	2000	100%	None				-100%
Transport Refrigeration (Modern Rail Transport)													
HFC-134a	R-404A	1999	1999	50%	None								0.3%
	HFC-134A	2005	2005	50%	None								
Water-Source and Ground-Source Heat Pumps													
HCFC-22	R-407C	2000	2006	5%	None								1.3%
	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-410A	2008	2009	10%	None								4.0%
	R-410A	2009	2010	90%	None								

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[1] DX refers to direct expansion systems where the compressors are mounted together in a rack and share suction and discharge refrigeration lines that run throughout the store, feeding refrigerant to the display cases in the sales area.

[2] DR refers to distributed refrigeration systems that consist of multiple smaller units that are located close to the display cases that they serve such as on the roof above the cases, behind a nearby wall, or on top of or next to the case in the sales area.

[3] SLS refers to secondary loop systems wherein a secondary fluid such as glycol or carbon dioxide is cooled by the primary refrigerant in the machine room and then pumped throughout the store to remove heat from the display equipment.

[4] The CFC-12 large retail food market for new systems transitioned to R-502 from 1998 to 1990, and subsequently transitioned to HCFC-22 from 1990 to 1993. These transitions are not shown in the table in order to provide the HFC transitions in greater detail.

[5] HCFC-22 for new equipment after 2010 is assumed to be reclaimed material.

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Table A-143 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-143: 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	8	3.0
Industrial Process Refrigeration	25	3.6 – 12.3
Mobile Air Conditioners	5 –16	2.3 – 18.0
Positive Displacement Chillers	20	0.5 – 1.5
PTAC/PTHP	12	3.9
Retail Food	10 – 20	1.0 – 25
Refrigerated Appliances	14	0.6
Residential Unitary A/C	15	11.8
Transport Refrigeration	9 – 40	19.4 – 36.4
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 continued to use CFCs as propellants because their use was deemed essential. Essential use exemptions granted to the United States under the Montreal Protocol for CFC use in MDIs were 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-144.

Table A-144: Aerosol Product Transition Assumptions

Initial Market Segment	Primary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Growth Rate
MDIs									
CFC Mix[a]	HFC-134a	1997	1997	6%	None				0.8%
	Non-ODP/GWP	1998	2007	7%	None				
	CFC Mix[a]	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[b]	HFC-152a	1990	1991	50%	None				2.0%
	HFC-134a	1995	1995	50%	HFC-152a	1997	1998	44%	
					HFC-152a	2001	2005	36%	

[a] 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.

[b] 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-145.

Table A-145: Solvent Market Transition Assumptions

Initial Market Segment	Primary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Growth Rate
Adhesives									
CH_3CCl_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-43-10mee	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_3CCl_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_3CCl_3	Non-ODP/GWP	1992	1996	100%	None				2.0%
CFC-113	Non-ODP/GWP	1992	1996	100%	None				2.0%
CCl_4	Non-ODP/GWP	1992	1996	100%	None				2.0%
Precision									
CH_3CCl_3	Non-ODP/GWP	1995	1996	99.3%	None				2.0%
	HFC-43-10mee	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 zero 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.

$$E_j = \mathrm{r} \times \sum Qc_{j\text{-}i+1} \quad for\ i=1 \rightarrow k$$

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-146.

Table A-146: Fire Extinguishing Market Transition Assumptions

	Primary Substitute				Secondary Substitute				Growth Rate
Initial Market Segment	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	1995	0.1%	None				
	Halotron	1996	2000	5.4%	Non-ODP/GWP	2020	2020	56%	
	Non-ODP/GWP	1993	1994	56%	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.

$$Ep_j = lp \times \sum Qc_{j-m} \quad for\ m=k \rightarrow k+26$$

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 thirteen foam types, whose transition assumptions away from ODS and growth rates are presented in Table A-147. The emission profiles of these thirteen foam types are shown in Table A-148.

Table A-147: 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				

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	
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				
	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-245fa/CO_2 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				

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	
					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				

1

Table A-148: Emission Profile for the Foam End-Uses

Foam End-Use	Loss at Manufacturing (%)	Annual Leakage Rate (%)	Leakage Lifetime (years)	Loss at Disposal (%)	Total[a] (%)
Flexible PU Foam: Slabstock Foam, Moulded Foam	100	0	1	0	100
Commercial Refrigeration	4	0.25	15	92.25	100
Rigid PU: Spray Foam	15	1.5	50	10.0	100
Rigid PU: Slabstock and Other	32.5	0.875	15	54.375	100
Phenolic Foam	28	0.875	32	44.0	100
Polyolefin Foam	40	3	20	0	100
Rigid PU: One Component Foam	95	2.5	2	0	100
XPS: Sheet Foam[a]	50	25	2	0	100
XPS: Boardstock Foam	25	0.75	25	56.25	100
Flexible PU Foam: Integral Skin Foam	95	2.5	2	0	100
Rigid PU: Domestic Refrigerator and Freezer Insulation[a]	3.75-6.5	0.25-0.5	14	39.9-37.2	47.15
PU and PIR Rigid: Boardstock	6	1	25	69.0	100
PU Sandwich Panels: Continuous and Discontinuous	8.5-11.25	0.5	50	63.75-66.5	100

PIR (Polyisocyanurate)
PU (Polyurethane)
XPS (Extruded Polystyrene)
[a] In general, total emissions from foam end-uses are assumed to be 100 percent.. In the Rigid PU Domestic Refrigerator and Freezer Insulation 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.

Sterilization

Sterilants kill microorganisms on medical equipment and devices. The principal ODS used in this sector was a blend of 12 percent ethylene oxide (EtO) and 88 percent 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 one sterilization end-use, whose transition assumptions away from ODS and growth rates are presented in Table A-149.

Table A-149: Sterilization 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	
12/88	EtO	1994	1995	95%	None								2.0%
	Non-ODP/GWP	1994	1995	1%	None								
	HCFC/EtO Blends	1993	1994	4%	Non-ODP/GWP	2010	2010	100%	None				

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 million metric tons of CO_2 equivalent (MMT CO_2 Eq.). The conversion of metric tons of chemical to MMT 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-150 provides the bank for ODS and ODS substitutes by chemical grouping in metric tons (MT) for 1990 to 2015.

Table A-150. Banks of ODS and ODS Substitutes, 1990-2015 (MT)

Year	CFC	HCFC	HFC
1990	683,218	281,698	872
1995	760,787	508,167	49,281
2000	635,772	938,108	182,151
2001	607,568	1,007,660	210,081
2002	583,423	1,061,037	237,950
2003	559,499	1,097,836	271,580
2004	535,143	1,135,490	306,730
2005	505,684	1,176,739	344,095
2006	475,707	1,213,944	387,333
2007	448,358	1,242,230	431,796
2008	426,222	1,259,372	472,808
2009	413,431	1,251,425	518,528
2010	376,199	1,214,311	583,367
2011	339,448	1,166,817	647,323
2012	302,837	1,118,161	718,171
2013	267,100	1,064,634	790,721
2014	231,330	1,009,540	863,268
2015	195,498	955,581	932,649

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.

3.10. Methodology for Estimating CH_4 Emissions from Enteric Fermentation

Methane emissions from enteric fermentation were estimated for seven livestock categories: cattle, horses, sheep, swine, goats, American bison, and the non-horse equines (mules and asses). Emissions from cattle represent the majority of U.S. emissions from enteric fermentation; consequently, a more detailed IPCC Tier 2 methodology was used to estimate emissions from cattle. The IPCC Tier 1 methodology was used to estimate emissions for the other types of livestock, including horses, goats, sheep, swine, American bison, and mules and asses (IPCC 2006).

Estimate Methane Emissions from Cattle

This section describes the process used to estimate CH_4 emissions from enteric fermentation from cattle using the Cattle Enteric Fermentation Model (CEFM). The CEFM was developed based on recommendations provided in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and uses information on population, energy requirements, digestible energy, and CH_4 conversion rates to estimate CH_4 emissions.[72] 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 CEFM's state-level cattle population estimates are based on data obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service Quick Stats database (USDA 2016). State-level cattle population estimates are shown by animal type for 2015 in Table A-151. A national-level summary of the annual average populations upon which all livestock-related emissions are based is provided in Table A-152. Cattle populations used in the Enteric Fermentation source category 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 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-151: 2015 Cattle Population Estimates from the CEFM Transition Matrix, by Animal Type and State (1,000 head)

State	Dairy Calves	Dairy Cows	Dairy Repl. Heif. 7-11 Months	Dairy Repl. Heif. 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Repl. Heif. 7-11 Months	Beef Repl. Heif. 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
Alabama	4	8	1	2	45	336	652	27	63	24	16	5
Alaska	0	0	0	0	2	2	4	0	1	0	0	0
Arizona	100	195	20	46	20	90	175	8	19	132	11	254
Arkansas	4	7	1	3	55	445	863	36	84	63	27	11
California	911	1,780	232	541	70	304	590	31	73	265	73	438
Colorado	74	145	30	70	55	374	725	41	96	375	244	927
Conn.	10	19	2	6	1	3	5	1	1	1	0	0
Delaware	3	5	1	2	0	1	3	0	0	1	0	0
Florida	63	124	11	25	60	467	906	31	73	12	16	3
Georgia	41	81	8	19	28	247	479	22	51	22	16	4
Hawaii	1	2	0	1	4	35	69	3	6	4	3	1
Idaho	296	579	96	225	40	238	461	29	67	135	88	241
Illinois	48	94	16	37	25	189	366	15	36	101	51	234
Indiana	93	181	24	56	17	103	199	12	28	56	23	101
Iowa	107	210	39	91	60	464	900	44	101	620	328	1,210
Kansas	73	143	27	63	95	736	1,427	70	163	909	692	2,149
Kentucky	32	63	14	32	65	514	997	34	79	96	55	15
Louisiana	7	14	2	4	30	240	466	18	42	12	12	3

[72] Additional information on the Cattle Enteric Fermentation Model can be found in ICF (2006).

Maine	15	30	5	11	2	6	11	1	3	2	1	0
Maryland	25	49	8	18	4	22	42	2	5	7	5	10
Mass.	6	13	2	5	1	3	6	0	1	1	1	0
Michigan	206	403	50	117	15	55	107	6	13	82	18	156
Minn.	235	460	84	197	35	175	340	22	51	240	83	379
Miss.	6	12	2	4	38	241	468	23	55	27	17	6
Missouri	46	89	18	42	110	955	1,851	83	194	192	117	70
Montana	7	14	2	5	100	772	1,496	105	245	84	103	42
Nebraska	28	54	6	14	95	906	1,756	102	236	1,121	666	2,484
Nevada	14	28	3	6	12	109	212	9	21	21	15	4
N. Hamp.	7	14	2	4	1	2	3	0	1	0	0	0
N. Jersey	4	7	1	3	1	4	8	0	1	1	0	0
N. Mexico	165	323	33	77	35	210	407	21	48	46	36	10
New York	315	615	105	246	15	54	105	10	23	17	23	25
N. Car.	24	47	5	13	29	187	363	17	39	17	14	4
N. Dakota	8	16	2	4	50	461	894	41	95	103	96	42
Ohio	137	268	38	88	25	145	282	12	28	94	26	166
Oklahoma	20	40	8	18	140	970	1,880	102	236	418	190	262
Oregon	64	125	18	42	40	271	525	27	62	79	55	82
Penn	271	530	92	214	25	77	150	13	31	70	29	93
R.Island	0	1	0	0	0	1	2	0	0	0	0	0
S. Car.	8	15	2	4	14	88	170	7	17	4	6	1
S. Dakota	51	99	20	46	100	831	1,611	98	228	327	255	379
Tenn.	24	47	8	18	60	450	873	34	79	58	34	9
Texas	241	470	75	176	320	2,131	4,130	181	422	1,212	723	2,474
Utah	49	96	14	34	22	167	324	19	44	38	33	24
Vermont	68	132	17	39	3	6	12	1	2	2	3	1
Virginia	48	93	13	30	40	329	637	27	62	75	22	20
Wash.	142	277	41	96	18	102	198	13	30	84	70	205
W. Virg.	5	9	1	3	13	95	185	8	19	21	10	4
Wisconsin	653	1,275	220	513	35	142	275	18	42	180	23	257
Wyoming	3	6	2	4	40	358	694	47	109	65	74	74

Table A-152: Cattle Population Estimates from the CEFM Transition Matrix for 1990–2015 (1,000 head)

Livestock Type	1990	1995	2000	2005	2011	2012	2013	2014	2015
Dairy									
Dairy Calves (0–6 months)	5,369	5,091	4,951	4,628	4,709	4,770	4,758	4,727	4,764
Dairy Cows	10,015	9,482	9,183	9,004	9,156	9,236	9,221	9,208	9,307
Dairy Replacements 7–11 months	1,214	1,216	1,196	1,257	1,362	1,348	1,341	1,356	1,417
Dairy Replacements 12–23 months	2,915	2,892	2,812	2,905	3,215	3,233	3,185	3,190	3,310
Beef									
Beef Calves (0–6 months)	16,909	18,177	17,431	16,918	15,817	15,288	14,859	14,946	15,117
Bulls	2,160	2,385	2,293	2,214	2,165	2,100	2,074	2,038	2,109
Beef Cows	32,455	35,190	33,575	32,674	30,913	30,282	29,631	29,085	29,302
Beef Replacements 7–11 months	1,269	1,493	1,313	1,363	1,232	1,263	1,291	1,342	1,473
Beef Replacements 12–23 months	2,967	3,637	3,097	3,171	2,889	2,968	3,041	3,113	3,422
Steer Stockers	10,321	11,716	8,724	8,185	7,568	7,173	7,457	7,411	7,517
Heifer Stockers	5,946	6,699	5,371	5,015	4,752	4,456	4,455	4,384	4,402
Feedlot Cattle	9,549	11,064	13,006	12,652	13,601	13,328	13,267	13,222	12,883

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.[73] 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 profiles vary both between and within each cattle type, these monthly age groups are tracked in the enteric fermentation

[73] Mature animal populations are not assumed to have significant monthly fluctuations, and therefore the populations utilized are the January estimates downloaded from USDA (2016).

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 calves, replacements, stockers, 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, described in further detail below.

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., calves are usually weaned between 4 and 6 months of age), each is modeled on a per-month basis. The type of cattle also influences 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 and bulls are tabulated for both dairy and beef stock. The transition matrix estimates total monthly populations for all cattle subtypes. These populations are then reallocated to the state level based on the percent of the cattle type reported in each state in the January 1 USDA data. Each lifecycle is discussed separately below, and the categories tracked are listed in Table A-153.

Table A-153: Cattle Population Categories Used for Estimating CH_4 Emissions

Dairy Cattle	Beef Cattle
Calves	Calves
Heifer Replacements	Heifer Replacements
Cows	Heifer and Steer Stockers
	Animals in Feedlots (Heifers & Steer)
	Cows
	Bulls[a]

[a] Bulls (beef and dairy) are accounted for in a single category.

The key variables tracked for each of these cattle population categories are as follows:

Calves. Although enteric emissions are only calculated for 4- to 6-month old calves, it is necessary to calculate populations from birth as emissions from manure management require total calf populations and the estimates of populations for older cattle rely on the available supply of calves from birth. 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 per month. Annual birth information for each year was taken from USDA (2016). For dairy cows, the number of births is assumed to be distributed equally throughout the year (approximately 8.3 percent per month) while beef births are distributed according to Table A-154, based on approximations 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 (approximately 61 pounds per month). The 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 6 months of age). An example of a transition matrix for calves is shown in

Table **A-155**. Note that 1- to 6-month old calves in January of each year have been tracked through the model based on births and death loss from the previous year.

Table A-154: 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-155: Example of Monthly Average Populations from Calf Transition Matrix (1,000 head)

Age (month)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6	1,138	1,131	1,389	1,612	1,554	1,538	2,431	4,488	7,755	6,298	2,971	1,522
5	1,131	1,389	1,612	1,554	1,538	2,431	4,488	7,755	6,298	2,971	1,522	1,153
4	1,389	1,612	1,554	1,538	2,431	4,488	7,755	6,298	2,971	1,522	1,153	1,144
3	1,612	1,554	1,538	2,431	4,488	7,755	6,298	2,971	1,522	1,153	1,144	1,402
2	1,554	1,538	2,431	4,488	7,755	6,298	2,971	1,522	1,153	1,144	1,402	1,625
1	1,538	2,431	4,488	7,755	6,298	2,971	1,522	1,153	1,144	1,402	1,625	1,565
0	2,431	4,488	7,755	6,298	2,971	1,522	1,153	1,144	1,402	1,625	1,565	1,547

Note: The cohort starting at age 0 months on January 1 is tracked in order to illustrate how a single cohort moves through the transition matrix. Each month, the cohort reflects the decreases in population due to the estimated 0.35 percent annual death loss, and between months 4 and 5, a more significant loss is seen than in other months due to estimated veal slaughter.

Replacements and Stockers. At 7 months of age, calves "graduate" and are separated into the applicable cattle types: replacements (cattle raised to give birth), or stockers (cattle held for conditioning and growing on grass or other forage diets). 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. Based on the USDA estimates for "replacement beef heifers" and "replacement dairy heifers," the transition matrix for the replacements is back-calculated from the known animal totals from USDA, and the number of calves needed to fill that requirement for each month is subtracted from the known supply of female calves. All female calves remaining after those needed for beef and dairy replacements are removed and become "stockers" that can be placed in feedlots (along with all male calves). During the stocker phase, animals are subtracted out of the transition matrix for placement into feedlots based on feedlot placement statistics from USDA (2016).

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 (added in month 7, bottom row of Table A-156) and subtraction through death loss and animals placed in feedlots. Eventually, an entire cohort population of stockers may reach zero, indicating that the complete cohort has been transitioned into feedlots. An example of the transition matrix for stockers is shown in Table A-156.

Table A-156: Example of Monthly Average Populations from Stocker Transition Matrix (1,000 head)

Age (month)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
23	185	180	104	37	15	9	8	8	6	3	1	0
22	320	146	49	19	12	9	9	9	6	3	17	181
21	260	69	25	14	11	11	11	8	6	68	218	313
20	123	35	19	14	14	13	10	8	133	331	387	254
19	63	27	19	17	16	13	10	196	472	615	318	120
18	48	27	23	20	16	13	241	610	900	514	149	61
17	47	33	27	19	15	295	709	1,179	759	237	129	47
16	58	38	26	19	363	828	1,380	1,000	348	340	47	46
15	67	36	25	452	977	1,619	1,172	456	603	47	46	57
14	65	36	599	1,172	1,921	1,378	534	862	47	46	57	66
13	64	845	1,478	2,309	1,639	629	1,117	47	46	57	66	63
12	982	1,602	2,556	1,858	755	1,512	214	46	57	66	63	63
11	1,814	2,770	2,056	855	1,872	277	138	76	89	81	80	1,016
10	3,133	2,255	945	2,241	385	189	184	231	209	185	1,135	2,445
9	2,545	1,062	2,502	484	335	341	420	372	371	1,292	2,786	5,299
8	1,200	2,951	664	482	557	759	658	649	1,503	3,247	5,984	4,877
7	3,381	800	794	956	1,160	1,109	1,100	1,876	3,666	6,504	5,243	2,353

Note: The cohort starting at age 7 months on January 1 is tracked in order to illustrate how a single cohort moves through the transition matrix. Each month, the cohort reflects the decreases in population due to the estimated 0.35 percent annual death loss and loss due to placement in feedlots (the latter resulting in the majority of the loss from the matrix).

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 (2016). 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 one lower weight category. 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 pounds. 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) and increased during the time series through 2007.[74] Bull mature weight was calculated as 1.5 times the beef cow mature weight (Doren et al. 1989). 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 pounds for all years, based on a personal communication with Kris Johnson (2010) and an estimate from Holstein Association USA (2010).[75] Dairy replacement weight at 15 months was assumed to be 875 pounds and 1,300 pounds at 24 months. Live slaughter weights were estimated from dressed slaughter weight (USDA 2016) 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). The annual typical animal mass for each livestock type are presented in Table A-157.

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. Interim years were calculated linearly, as shown in Table A-158, and weight gain was held constant starting in 2000. Table A-158 provides weight gains that vary by year in the CEFM.

[74] Mature beef weight is held constant after 2007 but future inventory submissions will incorporate known trends through 2007 and extrapolate to future years, as noted in the Planned Improvements section of 5.1 Enteric Fermentation.

[75] Mature dairy weight is based solely on Holstein weight, so could be higher than the national average. Future Inventory submissions will consider other dairy breeds, as noted in the Planned Improvements section of 5.1 Enteric Fermentation.

Table A-157: Typical Animal Mass (lbs)

Year/Cattle Type	Calves	Dairy Cows[a]	Dairy Replacements[b]	Beef Cows[a]	Bulls[a]	Beef Replacements[b]	Steer Stockers[b]	Heifer Stockers[b]	Steer Feedlot[b]	Heifer Feedlot[b]
1990	269	1,500	899	1,221	1,832	819	691	651	923	845
1991	270	1,500	897	1,225	1,838	821	694	656	933	855
1992	269	1,500	897	1,263	1,895	840	714	673	936	864
1993	270	1,500	898	1,280	1,920	852	721	683	929	863
1994	270	1,500	897	1,280	1,920	853	720	688	943	875
1995	270	1,500	897	1,282	1,923	857	735	700	947	879
1996	269	1,500	898	1,285	1,928	858	739	707	939	878
1997	270	1,500	899	1,286	1,929	860	736	707	938	876
1998	270	1,500	896	1,296	1,944	865	736	709	956	892
1999	270	1,500	899	1,292	1,938	861	730	708	959	894
2000	270	1,500	896	1,272	1,908	849	719	702	960	898
2001	270	1,500	897	1,272	1,908	850	725	707	963	900
2002	270	1,500	896	1,276	1,914	851	725	707	981	915
2003	270	1,500	899	1,308	1,962	871	718	701	972	904
2004	270	1,500	896	1,323	1,985	877	719	702	966	904
2005	270	1,500	894	1,327	1,991	879	717	706	974	917
2006	270	1,500	897	1,341	2,012	889	724	712	983	925
2007	270	1,500	896	1,348	2,022	894	720	706	991	928
2008	270	1,500	897	1,348	2,022	894	720	704	999	938
2009	270	1,500	895	1,348	2,022	894	730	715	1007	947
2010	270	1,500	897	1,348	2,022	896	726	713	996	937
2011	270	1,500	897	1,348	2,022	891	721	712	989	932
2012	270	1,500	899	1,348	2,022	892	714	706	1003	945
2013	270	1,500	898	1,348	2,022	892	718	709	1016	958
2014	270	1,500	895	1,348	2,022	888	722	714	1022	962
2015	270	1,500	896	1,348	2,022	891	717	713	1037	982

[a] Input into the model.
[b] Annual average calculated in model based on age distribution.

Table A-158: 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–onwards	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 (e.g., more grain than forage, along with new dietary supplements), during this time weight gain is estimated to be 2.7 to 3 pounds per day (Johnson 1999). Animals are then switched to a finishing diet (concentrated, high energy) for a period of time before they are slaughtered. Weight gain during finishing diets is estimated to be 2.9 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 (categories displayed in Table A-159) 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-159 provides a summary of the reported feedlot placement statistics for 2015.

Table A-159: Feedlot Placements in the United States for 2015 (Number of animals placed/1,000 Head)

Weight Placed When:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
< 600 lbs	410	330	365	320	360	350	365	395	405	645	470	375
600 – 700 lbs	340	265	275	240	260	250	235	215	290	530	387	355
700 – 800 lbs	474	396	449	348	389	336	327	362	416	431	310	357
> 800 lbs	565	560	720	640	710	545	620	660	830	680	435	440
Total	**1,789**	**1,551**	**1,809**	**1,548**	**1,719**	**1,481**	**1,547**	**1,632**	**1,941**	**2,286**	**1,602**	**1,527**

Source: USDA (2016).
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 pounds per animal per month. The monthly estimates for daily milk production by beef cows are shown in Table A-160. Annual estimates for dairy cows were taken from USDA milk production statistics. Dairy lactation estimates for 1990 through 2015 are shown in Table A-161. 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-160: Estimates of Average Monthly Milk Production by Beef Cows (lbs/cow)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beef Cow Milk Production (lbs/ head)	3.3	5.1	8.7	12.0	13.6	13.3	11.7	9.3	6.9	4.4	3.0	2.8

Table A-161: Dairy Lactation Rates by State (lbs/ year/cow)

State/Year	1990	1995	2000	2005	2011	2012	2013	2014	2015
Alabama	12,214	14,176	13,920	14,000	14,300	13,000	13,000	13,625	12,625
Alaska	13,300	17,000	14,500	12,273	13,800	14,250	10,667	11,667	11,667
Arizona	17,500	19,735	21,820	22,679	23,473	23,979	23,626	24,368	24,477
Arkansas	11,841	12,150	12,436	13,545	11,917	13,300	11,667	13,714	13,000
California	18,456	19,573	21,130	21,404	23,438	23,457	23,178	23,786	23,002
Colorado	17,182	18,687	21,618	22,577	23,430	24,158	24,292	24,951	25,685
Connecticut	15,606	16,438	17,778	19,200	19,000	19,889	20,556	20,158	20,842
Delaware	13,667	14,500	14,747	16,622	18,300	19,542	19,521	20,104	19,700
Florida	14,033	14,698	15,688	16,591	19,067	19,024	19,374	20,390	20,656
Georgia	12,973	15,550	16,284	17,259	18,354	19,138	19,600	20,877	21,651
Hawaii	13,604	13,654	14,358	12,889	14,421	14,200	13,409	13,591	15,909
Idaho	16,475	18,147	20,816	22,332	22,926	23,376	23,440	24,127	24,126
Illinois	14,707	15,887	17,450	18,827	18,510	19,061	19,063	19,681	20,128
Indiana	14,590	15,375	16,568	20,295	20,657	21,440	21,761	21,865	22,143
Iowa	15,118	16,124	18,298	20,641	21,191	22,015	22,149	22,449	22,943
Kansas	12,576	14,390	16,923	20,505	21,016	21,683	21,881	22,085	22,231
Kentucky	10,947	12,469	12,841	12,896	14,342	15,135	15,070	15,905	17,607
Louisiana	11,605	11,908	12,034	12,400	12,889	13,059	12,875	13,600	13,429
Maine	14,619	16,025	17,128	18,030	18,688	18,576	19,548	19,967	19,800
Maryland	13,461	14,725	16,083	16,099	18,654	19,196	19,440	19,740	20,061
Massachusetts	14,871	16,000	17,091	17,059	16,923	18,250	17,692	17,923	18,083
Michigan	15,394	17,071	19,017	21,635	23,164	23,976	24,116	24,638	25,130
Minnesota	14,127	15,894	17,777	18,091	18,996	19,512	19,694	19,841	20,578
Mississippi	12,081	12,909	15,028	15,280	14,571	14,214	13,286	14,462	15,000
Missouri	13,632	14,158	14,662	16,026	14,611	14,979	14,663	15,539	15,511
Montana	13,542	15,000	17,789	19,579	20,571	21,357	21,286	21,500	21,357
Nebraska	13,866	14,797	16,513	17,950	20,579	21,179	21,574	22,130	22,930
Nevada	16,400	18,128	19,000	21,680	22,966	22,931	22,034	23,793	23,069
New Hampshire	15,100	16,300	17,333	18,875	20,429	19,643	20,923	20,143	20,143
New Jersey	13,538	13,913	15,250	16,000	16,875	18,571	18,143	18,143	18,143
New Mexico	18,815	18,969	20,944	21,192	24,854	24,694	24,944	25,093	24,245
New York	14,658	16,501	17,378	18,639	21,046	21,623	22,070	22,325	22,816
North Carolina	15,220	16,314	16,746	18,741	20,089	20,435	20,326	20,891	20,979
North Dakota	12,624	13,094	14,292	14,182	18,158	19,278	18,944	20,250	20,750
Ohio	13,767	15,917	17,027	17,567	19,194	19,833	20,178	20,318	20,573
Oklahoma	12,327	13,611	14,440	16,480	17,415	17,896	17,311	18,150	18,462
Oregon	16,273	17,289	18,222	18,876	20,488	20,431	20,439	20,565	20,408
Pennsylvania	14,726	16,492	18,081	18,722	19,495	19,549	19,797	20,121	20,387
Rhode Island	14,250	14,773	15,667	17,000	17,909	16,636	19,000	19,000	17,667
South Carolina	12,771	14,481	16,087	16,000	17,438	17,250	16,500	16,438	17,400
South Dakota	12,257	13,398	15,516	17,741	20,582	21,391	21,521	21,753	22,255
Tennessee	11,825	13,740	14,789	15,743	16,200	16,100	15,938	16,196	16,489
Texas	14,350	15,244	16,503	19,646	22,232	22,009	21,991	22,268	22,235
Utah	15,838	16,739	17,573	18,875	22,161	22,863	22,432	22,989	23,146
Vermont	14,528	16,210	17,199	18,469	18,940	19,316	19,448	20,197	20,197
Virginia	14,213	15,116	15,833	16,990	17,906	17,990	18,337	19,129	19,462
Washington	18,532	20,091	22,644	23,270	23,727	23,794	23,820	24,088	23,848
West Virginia	11,250	12,667	15,588	14,923	15,700	15,400	15,200	15,556	15,667
Wisconsin	13,973	15,397	17,306	18,500	20,599	21,436	21,693	21,869	22,697
Wyoming	12,337	13,197	13,571	14,878	20,517	20,650	21,367	21,583	22,567

Source: USDA (2016).

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, the USDA, expert opinion, and other literature sources. The designated regions for this analysis for dairy cattle for all years and

foraging beef cattle from 1990 through 2006 are shown in Table A-162. For foraging beef cattle from 2007 onwards, the regional designations were revised based on data available from the NAHMS 2007–2008 survey on cow-calf system management practices (USDA:APHIS:VS 2010) and are shown in and Table A-163. 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 DE and Y_m for each animal type.

Table A-162: Regions used for Characterizing the Diets of Dairy Cattle (all years) and Foraging Cattle from 1990–2006

West	California	Northern Great Plains	Midwestern	Northeast	Southcentral	Southeast
Alaska	California	Colorado	Illinois	Connecticut	Arkansas	Alabama
Arizona		Kansas	Indiana	Delaware	Louisiana	Florida
Hawaii		Montana	Iowa	Maine	Oklahoma	Georgia
Idaho		Nebraska	Michigan	Maryland	Texas	Kentucky
Nevada		North Dakota	Minnesota	Massachusetts		Mississippi
New Mexico		South Dakota	Missouri	New Hampshire		North Carolina
Oregon		Wyoming	Ohio	New Jersey		South Carolina
Utah			Wisconsin	New York		Tennessee
Washington				Pennsylvania		Virginia
				Rhode Island		
				Vermont		
				West Virginia		

Source: USDA (1996).

Table A-163: Regions used for Characterizing the Diets of Foraging Cattle from 2007–2015

West	Central	Northeast	Southeast
Alaska	Illinois	Connecticut	Alabama
Arizona	Indiana	Delaware	**Arkansas**
California	Iowa	Maine	Florida
Colorado	**Kansas**	Maryland	Georgia
Hawaii	Michigan	Massachusetts	Kentucky
Idaho	Minnesota	New Hampshire	**Louisiana**
Montana	Missouri	New Jersey	Mississippi
Nevada	**Nebraska**	New York	North Carolina
New Mexico	**North Dakota**	Pennsylvania	**Oklahoma**
Oregon	Ohio	Rhode Island	South Carolina
Utah	**South Dakota**	Vermont	Tennessee
Washington	Wisconsin	West Virginia	**Texas**
Wyoming			Virginia

Source: Based on data from USDA:APHIS:VS (2010).
Note: States in **bold** represent a change in region from the 1990–2006 assessment.

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, DE and Y_m values unique to the United States were developed for dairy and beef cattle. Digestible energy and Y_m values were estimated across the time series for each cattle population category 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), which represents physiological processes in the ruminant animals, as well as diet characteristics from USDA (1996). The Donovan and Baldwin model is able to account 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 2009 across 23 states—the review indicated highly variable diets, both temporally and spatially. 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, so COWPOLL was used to determine the Y_m value associated with each of the evaluated diets. The statistical analysis of the resulting Y_m estimates showed a downward trend in predicting Y_m, which inventory team experts modeled using the following best-fit non-liner curve:

$$Y_m = 4.52e^{\left(\frac{1.22}{Year-1980}\right)}$$

The team determined that the most comprehensive approach to estimating annual, region-specific Y_m values was to use the 1990 baseline Y_m values derived from Donovan and Baldwin and then scale these Y_m values for each year beyond 1990 with a factor based on this function. The scaling factor is the ratio of the Y_m value for the year in question to the 1990 baseline Y_m value. The scaling factor for each year was multiplied by the baseline Ym value. The resulting Y_m equation (incorporating both Donovan and Baldwin (1999) and COWPOLL) is shown below (and described in ERG 2016):

$$Y_m = Y_m(1990)EXP\left(\frac{1.22}{(Year-1980)}\right) / EXP\left(\frac{1.22}{(1990-1980)}\right)$$

DE values for dairy cows were estimated from the literature search based on the annual trends observed in the data collection effort. The regional variability observed in the literature search was not statistically significant, and therefore DE was not varied by region, but did vary over time, and was grouped by the following years 1990–1993, 1994–1998, 1999–2003, 2004–2006, 2007, and 2008 onwards.

Considerably less data was available for dairy heifers and dairy calves. Therefore, for dairy heifers assumptions were based on the relationship of the collected data in the 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. The forage portion makes up an estimated 85 to 95 percent of grazing beef cattle diets, and there is considerable variation of both forage type and quality across the United States. Currently there is no comprehensive survey of this data, so for this analysis two regional DE values were developed to account for the generally lower forage quality in the "West" region of the United States versus all other regions in Table A-162 (California, Northern Great Plains, Midwestern, Northeast, Southcentral, Southeast) and Table A-163 (Central, Northeast, and Southeast). For all non-western grazing cattle, the forage DE was an average of the estimated seasonal values for grass pasture diets for a calculated DE of 64.2 percent. For foraging cattle in the west, the forage DE was calculated as the seasonal average for grass pasture, meadow and range diets, for a calculated DE of 61.3 percent. The assumed specific components of each of the broad forage types, along with their corresponding DE value and the calculated regional DE values can be found in Table A-164. In addition, beef cattle are assumed to be fed a supplemental diet, consequently, two sets of supplemental diets were developed, one for 1990 through 2006 (Donovan 1999) and one for 2007 onwards (Preston 2010, Archibeque 2011, USDA:APHIS:VS 2010) as shown in Table A-165 and Table A-166 along with the percent of each total diet that is assumed to be made up of the supplemental portion. By weighting the calculated DE values from the forage and supplemental diets, the DE values for the composite diet were calculated.[76] These values are used for steer and heifer stockers and beef replacements. Finally, for mature beef cows and bulls, the DE value was adjusted downward by two percent to reflect the lower digestibility diets of mature cattle based on Johnson (2002). Y_m values for all grazing beef cattle were set at 6.5 percent based on Johnson (2002). The Y_m values and the resulting final weighted DE values by region for 2007 onwards are shown in Table A-167.

For feedlot animals, DE and Y_m are adjusted over time as diet compositions in actual feedlots are adjusted based on new and improved nutritional information and availability of feed types. Feedlot diets are assumed to not differ significantly by state, and therefore only a single set of national diet values is utilized for each year. The DE and Y_m values for 1990 were estimated by Dr. Don Johnson (1999). In the CEFM, the DE values for 1991 through 1999 were linearly extrapolated based on values for 1990 and 2000. DE and Y_m values from 2000 through the current year were estimated using the MOLLY model as described in Kebreab et al. (2008), based on a series of average diet feed compositions from Galyean and Gleghorn (2001) for 2000 through 2006 and Vasconcelos and Galyean (2007) for 2007 onwards. 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.

For calves aged 4 through 6 months, a gradual weaning from milk is simulated, with calf diets at 4 months assumed to be 25 percent forage, increasing to 50 percent forage at age 5 months, and 75 percent forage at age 6 months. The portion of the diet allocated to milk results in zero emissions, as recommended by the IPCC (2006). For calves, the DE for the remainder of the diet is assumed to be similar to that of slightly older replacement heifers (both beef and dairy are calculated separately). The Y_m for beef calves is also assumed to be similar to that of beef replacement heifers (6.5 percent), as literature

[76] For example, the West has a forage DE of 61.3 which makes up 90 percent of the diet and a supplemented diet DE of 67.4 percent was used for 10 percent of the diet, for a total weighted DE of 61.9 percent, as shown in Table A-167.

does not provide an alternative Y_m for use in beef calves. For dairy calves, the Y_m is assumed to be 7.8 percent at 4 months, 8.03 percent at 5 months, and 8.27 percent at 6 months based on estimates provided by Soliva (2006) for Y_m at 4 and 7 months of age and a linear interpolation for 5 and 6 months.

Table A-168 shows the regional DE and Y_m for U.S. cattle in each region for 2015.

Table A-164: Feed Components and Digestible Energy Values Incorporated into Forage Diet Composition Estimates

Forage Type	DE (% of GE)	Grass pasture - Spring	Grass pasture - Summer	Grass pasture - Fall	Range June	Range July	Range August	Range September	Range Winter	Meadow - Spring	Meadow - Fall
Bahiagrass Paspalum notatum, fresh	61.38			x							
Bermudagrass Cynodon dactylon, fresh	66.29		x								
Bremudagrass, Coastal Cynodon dactylon, fresh	65.53		x								
Bluegrass, Canada Poa compressa, fresh, early vegetative	73.99	x									
Bluegrass, Kentucky Poa pratensis, fresh, early vegetative	75.62	x									
Bluegrass, Kentucky Poa pratensis, fresh, mature	59.00		x	x							
Bluestem Andropagon spp, fresh, early vegetative	73.17				x						
Bluestem Andropagon spp, fresh, mature	56.82					x	x	x	x		x
Brome Bromus spp, fresh, early vegetative	78.57	x									
Brome, Smooth Bromus inermis, fresh, early vegetative	75.71	x									
Brome, Smooth Bromus inermis, fresh, mature	57.58		x	x					x		
Buffalograss, Buchloe dactyloides, fresh	64.02				x	x					
Clover, Alsike Trifolium hybridum, fresh, early vegetative	70.62	x									
Clover, Ladino Trifolium repens, fresh, early vegetative	73.22	x									
Clover, Red Trifolium pratense, fresh, early bloom	71.27	x									
Clover, Red Trifolium pratense, fresh, full bloom	67.44		x		x						
Corn, Dent Yellow Zea mays indentata, aerial part without ears, without husks, sun-cured, (stover)(straw)	55.28			x							
Dropseed, Sand Sporobolus cryptandrus, fresh, stem cured	64.69				x	x	x			x	
Fescue Festuca spp, hay, sun-cured, early vegetative	67.39	x									
Fescue Festuca spp, hay, sun-cured, early bloom	53.57			x							
Grama Bouteloua spp, fresh, early vegetative	67.02	x									
Grama Bouteloua spp, fresh, mature	63.38		x	x						x	
Millet, Foxtail Setaria italica, fresh	68.20	x			x						
Napiergrass Pennisetum purpureum, fresh, late bloom	57.24		x	x							
Needleandthread Stipa comata, fresh, stem cured	60.36					x	x	x			
Orchardgrass Dactylis glomerata, fresh, early vegetative	75.54	x									
Orchardgrass Dactylis glomerata, fresh, midbloom	60.13		x								
Pearlmillet Pennisetum glaucum, fresh	68.04	x									
Prairie plants, Midwest, hay, sun-cured	55.53			x							x
Rape Brassica napus, fresh, early bloom	80.88	x									
Rye Secale cereale, fresh	71.83	x									
Ryegrass, Perennial Lolium perenne, fresh	73.68	x									
Saltgrass Distichlis spp, fresh, post ripe	58.06		x	x							
Sorghum, Sudangrass Sorghum bicolor sudanense, fresh, early vegetative	73.27	x									
Squirreltail Stanion spp, fresh, stem-cured	62.00		x			x					

Forage Type	DE (% of GE)	Grass pasture - Spring	Grass pasture - Summer	Grass pasture - Fall	Range June	Range July	Range August	Range September	Range Winter	Meadow - Spring	Meadow - Fall
Summercypress, Gray Kochia vestita, fresh, stem-cured	65.11			x	x	x					
Timothy Phleum pratense, fresh, late vegetative	73.12	x									
Timothy Phleum pratense, fresh, midbloom	66.87		x								
Trefoil, Birdsfoot Lotus corniculatus, fresh	69.07	x									
Vetch Vicia spp, hay, sun-cured	59.44			x							
Wheat Triticum aestivum, straw	45.77			x							
Wheatgrass, Crested Agropyron desertorum, fresh, early vegetative	79.78	x									
Wheatgrass, Crested Agropyron desertorum, fresh, full bloom	65.89		x			x					
Wheatgrass, Crested Agropyron desertorum, fresh, post ripe	52.99			x					x		x
Winterfat, Common Eurotia lanata, fresh, stem-cured	40.89								x		
Weighted Average DE		**72.99**	**62.45**	**57.26**	**67.11**	**62.70**	**60.62**	**58.59**	**52.07**	**64.03**	**55.11**
Forage Diet for West	**61.3**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**
Forage Diet for All Other Regions	**64.2**	**33.3%**	**33.3%**	**33.3%**	**-**	**-**	**-**	**-**	**-**	**-**	**-**

Sources: Preston (2010) and Archibeque (2011).
Note that forages marked with an x indicate that the DE from that specific forage type is included in the general forage type for that column (e.g., grass pasture, range, meadow or meadow by month or season).

Table A-165: DE Values with Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 1990–2006

Feed	Source of DE (NRC 1984)	Unweighted DE (% of GE)	California*	Northern West	Great Plains	Southcentral	Northeast	Midwest	Southeast
Alfalfa Hay	Table 8, feed #006	61.79	65%	30%	30%	29%	12%	30%	
Barley		85.08	10%	15%					
Bermuda	Table 8, feed #030	66.29							35%
Bermuda Hay	Table 8, feed #031	50.79				40%			
Corn	Table 8, feed #089	88.85	10%	10%	25%	11%	13%	13%	
Corn Silage	Table 8, feed #095	72.88			25%		20%	20%	
Cotton Seed Meal						7%			
Grass Hay	Table 8, feed #126, 170, 274	58.37		40%				30%	
Orchard	Table 8, feed #147	60.13							40%
Soybean Meal Supplement		77.15		5%	5%				5%
Sorghum	Table 8, feed #211	84.23							20%
Soybean Hulls		66.86						7%	
Timothy Hay	Table 8, feed #244	60.51					50%		
Whole Cotton Seed		75.75	5%				5%		
Wheat Middlings	Table 8, feed #257	68.09			15%	13%			
Wheat	Table 8, feed #259	87.95	10%						
Weighted Supplement DE (%)			**70.1**	**67.4**	**73.0**	**62.0**	**67.6**	**66.9**	**68.0**
Percent of Diet that is Supplement			**5%**	**10%**	**15%**	**10%**	**15%**	**10%**	**5%**

Source of representative regional diets: Donovan (1999).
* Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above.

Table A-166: DE Values and Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 2007–2015

Feed	Source of DE (NRC1984)	Unweighted DE (% of GE)	West[a]	Central[a]	Northeast[a]	Southeast[a]
Alfalfa Hay	Table 8, feed #006	61.79	65%	30%	12%	
Bermuda	Table 8, feed #030	66.29				20%
Bermuda Hay	Table 8, feed #031	50.79				20%
Corn	Table 8, feed #089	88.85	10%	15%	13%	10%
Corn Silage	Table 8, feed #095	72.88		35%	20%	
Grass Hay	Table 8, feed #126, 170, 274	58.37	10%			
Orchard	Table 8, feed #147	60.13				30%
Protein supplement (West)	Table 8, feed #082, 134, 225[b]	81.01	10%			
Protein Supplement (Central and Northeast)	Table 8, feed #082, 134, 225[b]	80.76		10%	10%	
Protein Supplement (Southeast)	Table 8, feed #082, 134, 101[b]	77.89				10%
Sorghum	Table 8, feed #211	84.23		5%		10%
Timothy Hay	Table 8, feed #244	60.51			45%	
Wheat Middlings	Table 8, feed #257	68.09		5%		
Wheat	Table 8, feed #259	87.95	5%			
Weighted Supplement DE			**67.4**	**73.1**	**68.9**	**66.6**
Percent of Diet that is Supplement			**10%**	**15%**	**5%**	**15%**

Sources of representative regional diets: Donovan (1999), Preston (2010), Archibeque (2011), and USDA:APHIS:VS (2010).
[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.
[b] Not in equal proportions.

Table A-167: Foraging Animal DE (% of GE) and Y_m Values for Each Region and Animal Type for 2007–2015

Animal Type	Data	West[a]	Central	Northeast	Southeast
Beef Repl. Heifers	DE[b]	61.9	65.6	64.5	64.6
	Y_m[c]	6.5%	6.5%	6.5%	6.5%
Beef Calves (4–6 mo)	DE	61.9	65.6	64.5	64.6
	Y_m	6.5%	6.5%	6.5%	6.5%
Steer Stockers	DE	61.9	65.6	64.5	64.6
	Y_m	6.5%	6.5%	6.5%	6.5%
Heifer Stockers	DE	61.9	65.6	64.5	64.6
	Y_m	6.5%	6.5%	6.5%	6.5%
Beef Cows	DE	59.9	63.6	62.5	62.6
	Y_m	6.5%	6.5%	6.5%	6.5%
Bulls	DE	59.9	63.6	62.5	62.6
	Y_m	6.5%	6.5%	6.5%	6.5%

[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. To see the regional designation per state, please see Table A-163.
[b] DE is the digestible energy in units of percent of GE (MJ/Day).
[c] Y_m is the methane conversion rate, the fraction of GE in feed converted to methane.

Table A-168: Regional DE (% of GE) and Y_m Rates for Dairy and Feedlot Cattle by Animal Type for 2015

Animal Type	Data	California[a]	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Dairy Repl. Heifers	DE[b]	63.7	63.7	63.7	63.7	63.7	63.7	63.7
	Ym[c]	6.0%	6.0%	5.7%	6.5%	6.4%	5.7%	7.0%
Dairy Calves (4–6 mo)	DE	63.7	63.7	63.7	63.7	63.7	63.7	63.7
	Ym	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Dairy Cows	DE	66.7	66.7	66.7	66.7	66.7	66.7	66.7
	Ym	5.9%	5.9%	5.6%	6.4%	6.3%	5.6%	6.9%
Steer Feedlot	DE	82.5	82.5	82.5	82.5	82.5	82.5	82.5
	Ym	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%
Heifer Feedlot	DE	82.5	82.5	82.5	82.5	82.5	82.5	82.5
	Ym	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%

[a] Note that emissions are currently calculated on a state-by-state basis, but diets are applied in Table A-162 by the regions shown in the table above. To see the regional designation for foraging cattle per state, please see Table A-162.
[b] DE is the digestible energy in units of percent of GE (MJ/Day).
[c] Y_m is the methane conversion rate, the fraction of GE in feed converted to methane.

Step 3: Estimate CH_4 Emissions from Cattle

Emissions by state were estimated in three steps: a) determine gross energy (GE) intake using the Tier 2 IPCC (2006) equations, b) determine an emission factor using the GE values, Y_m and a conversion factor, 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)[77]
- Standard Reference Weight (kg)[78]
- Milk Production (kg/day)
- Milk Fat (percent of fat in milk = 4)
- Pregnancy (percent of population that is pregnant)
- DE (percent of GE intake digestible)
- Y_m (the fraction of GE converted to CH_4)
- Population

Step 3a: Determine Gross Energy, GE

As shown in the following equation, 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). Calculated GE values for 2015 are shown by state and animal type in Table A-169.

$$GE = \left[\frac{\left(\frac{NE_m + NE_a + NE_l + NE_{work} + NE_p}{REM} \right) + \left(\frac{NE_g}{REG} \right)}{\frac{DE\%}{100}} \right]$$

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)

Table A-169: Calculated Annual GE by Animal Type and State, for 2015 (MJ/1,000 head)

State	Dairy Calves	Dairy Cows	Dairy Replacement Heifers 7-11 Months	Dairy Replacement Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replacement Heifers 7-11 Months	Beef Replacement Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
Alabama	35	902	41	146	3,749	3,017	52,535	1,385	3,732	1,188	801	227

[77] 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 (IPCC 2006).

[78] 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.

Alaska	1	32	1	5	213	21	370	12	32	8	3	1
Arizona	852	30,695	897	3,164	1,779	874	15,053	453	1,216	7,034	604	11,759
Arkansas	31	781	55	195	4,582	3,993	69,536	1,854	4,998	3,090	1,362	513
California	7,779	267,829	10,630	37,484	6,226	2,947	50,750	1,734	4,648	14,069	4,026	19,832
Colorado	634	23,528	1,381	4,868	4,892	3,621	62,362	2,267	6,078	19,952	13,517	43,396
Conn.	83	2,713	110	389	42	23	404	31	84	48	13	7
Delaware	22	691	35	122	33	12	202	9	23	52	19	8
Florida	542	17,979	483	1,704	4,999	4,192	73,000	1,607	4,331	594	801	156
Georgia	354	12,068	373	1,314	2,333	2,216	38,595	1,113	2,999	1,070	801	212
Hawaii	10	271	14	49	356	344	5,918	147	393	230	144	40
Idaho	2,530	90,326	4,418	15,578	3,558	2,302	39,654	1,600	4,290	7,162	4,889	11,432
Illinois	411	13,154	718	2,531	2,036	1,650	28,830	771	2,081	4,867	2,577	10,732
Indiana	791	26,794	1,104	3,894	1,385	897	15,675	602	1,626	2,688	1,145	4,666
Iowa	918	31,762	1,795	6,328	4,887	4,057	70,894	2,168	5,854	29,897	16,397	56,928
Kansas	625	21,219	1,242	4,381	7,738	6,432	112,406	3,493	9,431	43,803	34,617	101,724
Kentucky	275	8,363	621	2,191	5,415	4,613	80,333	1,731	4,664	4,753	2,803	700
Louisiana	61	1,586	69	243	2,499	2,156	37,548	915	2,466	570	614	133
Maine	131	4,159	221	779	125	51	889	56	150	107	67	20
Maryland	214	6,844	345	1,217	334	195	3,394	112	301	358	241	467
Mass.	55	1,647	97	341	84	26	444	25	67	48	27	8
Michigan	1,761	64,494	2,305	8,130	1,222	482	8,428	277	748	3,940	911	7,466
Minn.	2,010	65,205	3,865	13,631	2,851	1,533	26,782	1,084	2,927	11,588	4,164	17,965
Miss.	52	1,467	83	292	3,166	2,165	37,709	1,199	3,232	1,331	881	252
Missouri	389	10,804	828	2,921	8,959	8,343	145,805	4,156	11,220	9,270	5,856	3,266
Montana	61	2,028	97	341	8,894	7,472	128,681	5,801	15,552	4,476	5,695	1,866
Nebraska	236	8,165	276	974	7,738	7,915	138,321	5,059	13,659	54,000	33,315	118,056
Nevada	122	4,249	124	438	1,067	1,059	18,236	493	1,323	1,126	834	187
N. Hamp.	61	1,960	76	268	42	14	242	12	33	24	13	4
N. Jersey	31	924	52	185	84	35	606	16	43	48	24	8
N. Mexico	1,412	50,542	1,519	5,355	3,113	2,033	35,009	1,134	3,039	2,430	2,013	467
New York	2,688	92,703	4,832	17,038	1,253	487	8,484	508	1,370	834	1,178	1,213
N. Car.	205	6,876	248	876	2,416	1,680	29,249	865	2,332	856	721	178
N. Dakota	70	2,279	83	292	4,072	4,030	70,421	2,036	5,496	4,983	4,815	2,053
Ohio	1,171	37,983	1,726	6,085	2,036	1,271	22,213	602	1,626	4,519	1,301	7,933
Oklahoma	175	5,340	345	1,217	11,664	8,698	151,480	5,192	13,993	20,677	9,745	12,366
Oregon	546	17,633	828	2,921	3,558	2,622	45,159	1,467	3,933	4,221	3,020	3,966
Penn.	2,316	74,719	4,211	14,848	2,089	696	12,120	682	1,838	3,457	1,473	4,200
R. Island	4	117	7	24	8	7	121	6	17	12	5	2
S. Car.	66	1,979	69	243	1,166	787	13,698	371	1,000	214	320	59
S. Dakota	433	14,700	897	3,164	8,145	7,262	126,900	4,879	13,171	15,760	12,754	17,965
Tenn.	205	6,028	345	1,217	4,999	4,039	70,341	1,731	4,664	2,852	1,735	524
Texas	2,054	69,866	3,451	12,170	26,661	19,109	332,772	9,272	24,988	59,892	37,111	117,123
Utah	420	14,598	663	2,337	1,957	1,618	27,869	1,040	2,789	1,995	1,841	1,120
Vermont	577	18,509	773	2,726	251	56	970	50	134	95	134	25
Virginia	406	13,038	594	2,093	3,333	2,947	51,326	1,360	3,665	3,684	1,121	933
Wash.	1,211	42,903	1,877	6,621	1,601	989	17,031	720	1,931	4,476	3,883	9,799
W. Virg.	39	1,098	55	195	1,086	859	14,948	409	1,108	1,049	536	187
Wisconsin	5,572	191,584	10,078	35,537	2,851	1,240	21,662	903	2,439	8,691	1,171	12,132
Wyoming	26	898	69	243	3,558	3,466	59,696	2,574	6,900	3,453	4,084	3,500

Step 3b: Determine Emission Factor

The daily emission factor (DayEmit) was determined using the GE 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 GE 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 annual national emission factors are shown by animal type in Table A-170. State-level emission factors are shown by animal type for 2015 in Table A- 171.

Table A-170: Calculated Annual National Emission Factors for Cattle by Animal Type, for 2015 (kg CH_4/head/year)

Cattle Type	1990	1995	2000	2005	2010	2011	2012	2013	2014	2015
Dairy										
Calves	12	12	12	12	12	12	12	12	12	12
Cows	124	125	132	133	142	142	144	144	145	146
Replacements 7–11 months	48	46	46	45	46	46	46	46	46	46
Replacements 12–23 months	73	69	70	67	69	69	69	69	69	69
Beef										
Calves	11	11	11	11	11	11	11	11	11	11
Bulls	91	94	94	97	98	98	98	98	98	98
Cows	89	92	91	94	95	95	95	95	95	95
Replacements 7–11 months	54	57	56	59	60	60	60	60	60	60
Replacements 12–23 months	63	66	66	68	70	70	70	70	70	70
Steer Stockers	55	57	58	58	58	58	58	58	58	58
Heifer Stockers	52	56	60	60	60	60	60	60	60	60
Feedlot Cattle	39	38	39	39	42	42	42	43	43	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).

Table A- 171: Emission Factors for Cattle by Animal Type and State, for 2015 (kg CH_4/head/year)

State	Dairy Calves	Dairy Cows	Dairy Replacement Heifers 7-11 Months	Dairy Replacement Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replacement Heifers 7-11 Months	Beef Replacement Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
Alabama	12	128	53	80	97	10	94	60	69	58	60	33
Alaska	12	103	46	69	104	11	100	64	74	62	65	33
Arizona	12	154	46	69	104	11	100	64	74	62	65	34
Arkansas	12	117	49	74	97	10	94	60	69	58	60	33
California	12	147	46	69	104	11	100	64	74	62	65	33
Colorado	12	150	43	65	104	11	100	64	74	62	65	34
Conn.	12	148	48	73	98	11	94	60	69	58	60	34
Delaware	12	143	48	73	98	11	94	60	69	58	60	35
Florida	12	165	53	80	97	10	94	60	69	58	60	34
Georgia	12	169	53	80	97	10	94	60	69	58	60	35
Hawaii	12	120	46	69	104	11	100	64	74	62	65	36
Idaho	12	152	46	69	104	11	100	64	74	62	65	35
Illinois	12	129	43	65	95	10	92	58	68	56	58	34
Indiana	12	137	43	65	95	10	92	58	68	56	58	34
Iowa	12	140	43	65	95	10	92	58	68	56	58	34
Kansas	12	137	43	65	95	10	92	58	68	56	58	35
Kentucky	12	151	53	80	97	10	94	60	69	58	60	33
Louisiana	12	119	49	74	97	10	94	60	69	58	60	35
Maine	12	143	48	73	98	11	94	60	69	58	60	34
Maryland	12	144	48	73	98	11	94	60	69	58	60	34
Mass.	12	136	48	73	98	11	94	60	69	58	60	36
Michigan	12	148	43	65	95	10	92	58	68	56	58	35
Minn.	12	131	43	65	95	10	92	58	68	56	58	35
Miss.	12	139	53	80	97	10	94	60	69	58	60	33
Missouri	12	112	43	65	95	10	92	58	68	56	58	34
Montana	12	134	43	65	104	11	100	64	74	62	65	32
Nebraska	12	140	43	65	95	10	92	58	68	56	58	35
Nevada	12	148	46	69	104	11	100	64	74	62	65	34

N. Hamp.	12	145	48	73	98	11	94	60	69	58	60	34
N. Jersey	12	136	48	73	98	11	94	60	69	58	60	34
N. Mexico	12	153	46	69	104	11	100	64	74	62	65	35
New York	12	156	48	73	98	11	94	60	69	58	60	35
N. Car.	12	166	53	80	97	10	94	60	69	58	60	34
N. Dakota	12	132	43	65	95	10	92	58	68	56	58	35
Ohio	12	131	43	65	95	10	92	58	68	56	58	35
Oklahoma	12	140	49	74	97	10	94	60	69	58	60	34
Oregon	12	138	46	69	104	11	100	64	74	62	65	35
Penn.	12	146	48	73	98	11	94	60	69	58	60	33
R. Island	12	135	48	73	98	11	94	60	69	58	60	34
S. Car.	12	150	53	80	97	10	94	60	69	58	60	33
S. Dakota	12	137	43	65	95	10	92	58	68	56	58	35
Tenn.	12	146	53	80	97	10	94	60	69	58	60	40
Texas	12	156	49	74	97	10	94	60	69	58	60	35
Utah	12	149	46	69	104	11	100	64	74	62	65	34
Vermont	12	145	48	73	98	11	94	60	69	58	60	34
Virginia	12	159	53	80	97	10	94	60	69	58	60	34
Wash.	12	151	46	69	104	11	100	64	74	62	65	35
W. Virg.	12	126	48	73	98	11	94	60	69	58	60	33
Wisconsin	12	139	43	65	95	10	92	58	68	56	58	34
Wyoming	12	138	43	65	104	11	100	64	74	62	65	34

Note: To convert to a daily emission factor, the yearly emission factor can be divided by 365 (the number of days in a year).

For quality assurance purposes, U.S. emission factors for each animal type were compared to estimates provided by the other Annex I member countries of the United Nations Framework Convention on Climate Change (UNFCCC) (the most recently available summarized results for Annex I countries are through 2012 only). Results, presented in Table A-172, indicate that U.S. emission factors are comparable to those of other Annex I countries. Results in Table A-172 are presented along with Tier I emission factors provided by IPCC (2006). Throughout the time series, beef cattle in the United States generally emit more enteric CH_4 per head than other Annex I member countries, while dairy cattle in the United States generally emit comparable enteric CH_4 per head.

Table A-172: Annex I Countries' Implied Emission Factors for Cattle by Year (kg CH_4/head/year)[79]

	Dairy Cattle		Beef Cattle	
Year	United States Implied Emission Factor	Mean of Implied Emission Factors for Annex I countries (excluding U.S.)	United States Implied Emission Factor	Mean of Implied Emission Factors for Annex I countries (excluding U.S.)
1990	107	96	71	53
1991	107	97	71	53
1992	107	96	72	54
1993	106	97	72	54
1994	106	98	73	54
1995	106	98	72	54
1996	105	99	73	54
1997	106	100	73	54
1998	107	101	73	55
1999	110	102	72	55
2000	111	103	72	55
2001	110	104	73	55
2002	111	105	73	55
2003	111	106	73	55
2004	109	107	74	55
2005	110	109	74	55
2006	110	110	74	55
2007	114	111	75	55
2008	115	112	75	55
2009	115	112	75	56

[79] Excluding calves.

2010	115	113	75	55
2011	116	113	75	55
2012	117	112	75	51
2013	117	NA	75	NA
2014	118	NA	74	NA
2015	117	NA	75	NA
Tier I EFs For North America, from IPCC (2006)		**121**		**53**

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:

$$Emissions_{state} = DayEmit_{state} \times Days/Month \times SubPop_{state}$$

where,

$Emissions_{state}$ = Emissions for state during the month (kg CH_4)
$DayEmit_{state}$ = Emission factor for the subcategory and state (kg CH_4/head/day)
Days/Month = Number of days in the month
$SubPop_{state}$ = Number of animals in the subcategory and state during the month

This process was repeated for each month, and the monthly 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-173. The emissions for each subcategory were then aggregated to estimate total emissions from beef cattle and dairy cattle for the entire year.

Table A-173: CH_4 Emissions from Cattle (kt)

Cattle Type	1990	1995	2000	2005	2011	2012	2013	2014	2015
Dairy	**1,574**	**1,498**	**1,519**	**1,503**	**1,645**	**1,670**	**1,664**	**1,679**	**1,706**
Calves (4–6 months)	62	59	59	54	57	58	58	58	58
Cows	1,242	1,183	1,209	1,197	1,302	1,326	1,325	1,337	1,355
Replacements 7–11 months	58	56	55	56	63	62	61	63	65
Replacements 12–23 months	212	201	196	196	223	224	220	221	228
Beef	**4,763**	**5,419**	**5,070**	**5,007**	**4,873**	**4,763**	**4,722**	**4,660**	**4,724**
Calves (4–6 months)	182	193	186	179	166	161	157	156	159
Bulls	196	225	215	214	212	206	203	200	207
Cows	2,884	3,222	3,058	3,056	2,927	2,868	2,806	2,754	2,774
Replacements 7–11 months	69	85	74	80	74	76	78	83	89
Replacements 12–23 months	188	241	204	217	202	208	213	218	239
Steer Stockers	563	662	509	473	436	413	431	426	434
Heifer Stockers	306	375	323	299	283	266	267	256	264
Feedlot Cattle	375	416	502	488	573	565	568	567	558
Total	**6,338**	**6,917**	**6,589**	**6,510**	**6,518**	**6,433**	**6,386**	**6,339**	**6,430**

Notes: Totals may not sum due to independent rounding.

Emission Estimates from Other Livestock

"Other livestock" include horses, sheep, swine, goats, American bison, and mules and asses. All livestock population data, except for American bison for years prior to 2002, were taken from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) agricultural statistics database (USDA 2016) or earlier census data (USDA 1992, 1997). The Manure Management Annex discusses the methods for obtaining annual average populations and disaggregating into state data where needed and provides the resulting population data for the other livestock that were used for estimating all livestock-related emissions (see Table A-175). For each animal category, the USDA publishes monthly, annual, or multi-year livestock population and production estimates. American bison estimates prior to 2002 were estimated using data from the National Bison Association (1999).

Methane emissions from sheep, goats, swine, horses, mules and asses were estimated by multiplying national population estimates by the default IPCC emission factor (IPCC 2006). For American bison the emission factor for buffalo (IPCC 2006) was used and adjusted based on the ratio of live weights of 300 kg for buffalo (IPCC 2006) and 1,130 pounds (513 kg) for American Bison (National Bison Association 2011) to the 0.75 power. This methodology for determining emission factors is recommended by IPCC (2006) for animals with similar digestive systems. Table A-174 shows the

emission factors used for these other livestock. National enteric fermentation emissions from all livestock types are shown in Table A-175 and Table A-176. Enteric fermentation emissions from most livestock types, broken down by state, for 2015 are shown in Table A-177 and Table A-182. Livestock populations are shown in Table A-179.

Table A-174: Emission Factors for Other Livestock (kg CH_4/head/year)

Livestock Type	Emission Factor
Swine	1.5
Horses	18
Sheep	8
Goats	5
American Bison	82.2
Mules and Asses	10.0

Source: IPCC (2006), except American Bison, as described in text.

Table A-175: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	1995	2000	2005	2011	2012	2013	2014	2015
Beef Cattle	119.1	135.5	126.7	125.2	121.8	119.1	118.0	116.5	118.1
Dairy Cattle	39.4	37.5	38.0	37.6	41.1	41.7	41.6	42.0	42.6
Swine	2.0	2.2	2.2	2.3	2.5	2.5	2.5	2.4	2.6
Horses	1.0	1.2	1.5	1.7	1.7	1.6	1.6	1.6	1.5
Sheep	2.3	1.8	1.4	1.2	1.1	1.1	1.1	1.0	1.1
Goats	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3
American Bison	0.1	0.2	0.4	0.4	0.3	0.3	0.3	0.3	0.3
Mules and Asses	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1
Total	**164.2**	**178.7**	**170.6**	**168.9**	**168.9**	**166.7**	**165.5**	**164.2**	**166.5**

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

Table A-176: CH_4 Emissions from Enteric Fermentation (kt)

Livestock Type	1990	1995	2000	2005	2011	2012	2013	2014	2015
Beef Cattle	4,763	5,419	5,070	5,007	4,873	4,763	4,722	4,660	4,724
Dairy Cattle	1,574	1,498	1,519	1,503	1,645	1,670	1,664	1,679	1,706
Swine	81	88	88	92	98	100	98	96	102
Horses	40	47	61	70	67	65	64	62	61
Sheep	91	72	56	49	44	43	43	42	42
Goats	13	12	12	14	14	13	13	12	12
American Bison	4	9	16	17	14	13	13	12	12
Mules and Asses	1	1	1	2	3	3	3	3	3
Total	**6,566**	**7,146**	**6,824**	**6,755**	**6,757**	**6,670**	**6,619**	**6,572**	**6,661**

Note: Totals may not sum due to independent rounding.

Table A-177: CH_4 Emissions from Enteric Fermentation from Cattle (metric tons), by State, for 2015

State	Dairy Calves	Dairy Cows	Dairy Replacement Heifers 7-11 Months	Dairy Replacement Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replacement Heifers 7-11 Months	Beef Replacement Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot	Total
Alabama	50	1,025	48	169	4,379	3,523	61,361	1,617	4,359	1,388	936	215	79,069
Alaska	2	31	1	5	249	25	432	14	38	9	3	1	810
Arizona	1,216	29,979	893	3,147	2,078	1,021	17,582	530	1,420	8,216	705	11,002	77,789
Arkansas	44	819	59	208	5,352	4,664	81,219	2,166	5,837	3,609	1,590	496	106,063
California	11,102	261,579	10,573	37,283	7,272	3,442	59,276	2,025	5,429	16,433	4,703	18,975	438,091
Colorado	904	21,739	1,300	4,585	5,714	4,229	72,840	2,648	7,099	23,305	15,788	40,154	200,306
Conn.	119	2,806	116	410	49	27	472	36	98	56	16	7	4,211
Delaware	31	715	36	128	39	14	236	10	27	61	22	7	1,327
Florida	773	20,432	558	1,967	5,839	4,896	85,266	1,877	5,059	694	936	144	128,440
Georgia	505	13,714	430	1,517	2,725	2,589	45,080	1,300	3,502	1,249	936	191	73,738
Hawaii	14	264	14	48	416	401	6,912	171	459	269	168	35	9,172
Idaho	3,611	88,218	4,394	15,494	4,155	2,689	46,316	1,869	5,011	8,366	5,711	10,421	196,256
Illinois	586	12,154	676	2,384	2,378	1,927	33,674	900	2,431	5,685	3,010	10,129	75,935
Indiana	1,129	24,757	1,040	3,668	1,617	1,048	18,309	704	1,899	3,140	1,338	4,377	63,026
Iowa	1,310	29,347	1,690	5,961	5,708	4,738	82,805	2,533	6,837	34,920	19,152	52,417	247,419
Kansas	892	19,606	1,170	4,127	9,038	7,513	131,292	4,080	11,016	51,162	40,433	93,069	373,397
Kentucky	393	9,504	717	2,529	6,325	5,388	93,830	2,022	5,448	5,552	3,274	670	135,652
Louisiana	87	1,664	74	260	2,919	2,518	43,856	1,069	2,880	666	717	122	56,832
Maine	187	4,301	232	820	146	60	1,038	65	176	125	78	18	7,247
Maryland	306	7,079	363	1,281	390	228	3,964	130	351	418	282	429	15,220
Mass.	78	1,703	102	359	98	30	519	29	78	56	31	8	3,090
Michigan	2,514	59,590	2,172	7,658	1,427	563	9,845	324	874	4,602	1,064	6,775	97,405
Minn.	2,869	60,246	3,641	12,839	3,330	1,790	31,282	1,266	3,419	13,535	4,864	16,426	155,507
Miss.	75	1,667	96	337	3,698	2,529	44,044	1,401	3,775	1,555	1,029	241	60,447
Missouri	555	9,983	780	2,751	10,465	9,745	170,302	4,854	13,105	10,828	6,840	3,046	243,254
Montana	87	1,874	91	321	10,389	8,727	150,301	6,776	18,165	5,229	6,651	1,839	210,450
Nebraska	337	7,544	260	917	9,038	9,245	161,561	5,910	15,954	63,073	38,913	107,555	420,306
Nevada	175	4,150	124	436	1,247	1,237	21,299	576	1,545	1,315	974	172	33,249
N. Hamp.	87	2,027	80	282	49	16	283	14	39	28	16	4	2,925
N. Jersey	44	955	55	195	98	41	708	19	51	56	28	8	2,256
N. Mexico	2,015	49,363	1,510	5,326	3,636	2,374	40,891	1,324	3,549	2,838	2,351	429	115,607
New York	3,836	95,883	5,084	17,929	1,464	569	9,909	594	1,600	975	1,376	1,089	140,309
N. Car.	293	7,814	287	1,012	2,822	1,962	34,163	1,011	2,724	999	842	167	54,095
N. Dakota	100	2,106	78	275	4,757	4,707	82,253	2,378	6,419	5,820	5,624	1,835	116,351
Ohio	1,672	35,095	1,625	5,732	2,378	1,485	25,946	704	1,899	5,279	1,520	7,204	90,538

Oklahoma	249	5,602	368	1,299	13,624	10,160	176,931	6,065	16,345	24,151	11,382	11,367	277,542
Oregon	780	17,222	824	2,905	4,155	3,063	52,746	1,713	4,593	4,930	3,527	3,558	100,016
Penn.	3,306	77,283	4,431	15,624	2,440	813	14,156	797	2,147	4,038	1,721	4,036	130,789
R. Island	6	121	7	26	10	8	142	7	20	14	6	2	368
S. Car.	94	2,249	80	281	1,362	919	15,999	433	1,167	250	374	57	23,265
S. Dakota	617	13,582	845	2,980	9,513	8,482	148,221	5,698	15,384	18,408	14,896	16,426	255,053
Tenn.	293	6,850	398	1,405	5,839	4,718	82,160	2,022	5,448	3,331	2,027	410	114,901
Texas	2,932	73,299	3,683	12,987	31,140	22,319	388,683	10,830	29,187	69,955	43,346	107,136	795,495
Utah	599	14,257	659	2,324	2,285	1,890	32,552	1,215	3,257	2,330	2,150	1,047	64,566
Vermont	823	19,144	813	2,869	293	65	1,132	58	156	111	156	24	25,645
Virginia	580	14,817	685	2,416	3,892	3,442	59,949	1,588	4,281	4,303	1,310	858	98,123
Wash.	1,728	41,902	1,867	6,585	1,870	1,155	19,893	841	2,255	5,229	4,535	8,876	96,736
W. Virg.	56	1,136	58	205	1,269	1,003	17,459	478	1,288	1,225	626	180	24,983
Wisconsin	7,953	177,016	9,492	33,473	3,330	1,448	25,301	1,055	2,849	10,151	1,368	11,152	284,588
Wyoming	37	830	65	229	4,155	4,048	69,725	3,006	8,059	4,033	4,770	3,217	102,177

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Table A-178: CH_4 Emissions from Enteric Fermentation from Other Livestock (metric tons), by State, for 2015

State	Swine	Horses	Sheep	Goats	American Bison	Mules and Asses	Total
Alabama	150	894	97	181	15	117	1,454
Alaska	2	21	97	3	149	1	273
Arizona	198	1,919	1,200	447	-	37	3,800
Arkansas	249	907	97	181	7	85	1,525
California	143	2,154	4,800	728	72	64	7,961
Colorado	1,076	1,893	3,360	131	648	65	7,173
Connecticut	4	378	57	21	11	10	481
Delaware	5	135	97	5	8	1	250
Florida	24	2,183	97	243	-	101	2,648
Georgia	240	1,184	97	322	13	88	1,943
Hawaii	14	77	97	76	4	4	271
Idaho	38	970	2,080	92	373	39	3,592
Illinois	7,238	948	456	151	28	34	8,855
Indiana	5,644	1,928	400	168	79	55	8,274
Iowa	31,575	1,014	1,400	282	99	44	34,414
Kansas	2,861	1,185	528	190	377	36	5,178
Kentucky	623	2,190	384	218	102	131	3,648
Louisiana	12	1,068	97	86	2	77	1,341
Maine	7	214	57	34	15	4	331
Maryland	32	493	97	35	19	12	688
Massachusetts	17	363	57	44	6	5	492
Michigan	1,676	1,442	608	133	71	41	3,971
Minnesota	12,075	938	1,040	159	97	29	14,339
Mississippi	773	985	97	104	-	91	2,049
Missouri	4,481	1,767	680	540	84	93	7,645
Montana	263	1,684	1,720	46	1,211	48	4,971
Nebraska	4,838	1,144	648	103	2,164	40	8,936
Nevada	2	448	552	135	3	6	1,147
New Hampshire	6	155	57	27	27	2	274
New Jersey	18	471	97	34	17	9	646
New Mexico	2	882	720	141	441	18	2,204
New York	114	1,679	640	172	40	38	2,682
North Carolina	12,863	1,079	240	236	9	94	14,521
North Dakota	207	821	512	25	474	13	2,052
Ohio	3,611	2,000	968	204	45	71	6,899
Oklahoma	3,289	2,789	424	337	764	136	7,738
Oregon	15	1,063	1,560	151	125	31	2,945
Pennsylvania	1,748	2,197	688	224	39	94	4,989
Rhode Island	2	32	57	5	-	1	98
South Carolina	353	1,042	97	179	10	59	1,739
South Dakota	1,999	1,227	2,040	100	2,515	15	7,896
Tennessee	330	1,247	352	341	0	137	2,407
Texas	1,324	6,660	5,760	3,611	285	636	18,276
Utah	1,058	1,053	2,320	66	80	33	4,610
Vermont	6	193	57	65	6	13	340
Virginia	405	1,525	600	217	80	70	2,898
Washington	38	892	416	118	51	35	1,550
West Virginia	8	355	264	67	-	29	722
Wisconsin	480	1,684	616	321	256	58	3,415
Wyoming	158	1,218	2,760	49	638	28	4,850

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3.11. Methodology for Estimating CH_4 and N_2O 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.[80]

Step 1: Livestock Population Characterization Data

Annual animal population data for 1990 through 2015 for all livestock types, except American bison, goats, horses, mules and asses 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 Quick Stats Database (USDA 2016a). Poultry population data were obtained from USDA NASS reports (USDA 1995a, 1995b, 1998, 1999, 2004a, 2004b, 2009a, 2009b, 2009c, 2009d, 2010a, 2010b, 2011a, 2011b, 2012a, 2012b, 2013a, 2013b, 2014b, 2014c, 2015a 2015b, 2016b, and 2016c). Goat population data for 1992, 1997, 2002, 2007, and 2012 were obtained from the Census of Agriculture (USDA 2014a), as were horse, mule and ass population data for 1987, 1992, 1997, 2002, 2007, and 2012, and American bison population for 2002, 2007, and 2012. American bison population data for 1990-1999 were obtained from the National Bison Association (1999). 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—see section 5.1 Enteric Fermentation). 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 fluctuating 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 emission calculations. For states where only December inventory is reported, the December data were used directly.

Sheep: The USDA provides total state-level data annually for lambs and sheep. Population distribution 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 2015 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, 2007, and 2012 (USDA 2014a). The data for 1992 were used for 1990 through 1992. Data for 1993 through 1996, 1998 through 2001, 2003 through 2006, 2008 through 2011, and 2013 through 2015 were interpolated and extrapolated based on the 1992, 1997, 2002, 2007, and 2012 Census data.

Horses: Annual horse population data by state were available for 1987, 1992, 1997, 2002, 2007, and 2012 (USDA 2014a). Data for 1990 through 1991, 1993 through 1996, 1998 through 2001, 2003 through 2006, 2008 through 2011, and 2013 through 2015 were interpolated and extrapolated based on the 1987, 1992, 1997, 2002, 2007, and 2012 Census data.

[80] Note that direct N_2O emissions from dung and urine spread onto fields either directly as daily spread or after it is removed from manure management systems (e.g., lagoon, pit, etc.) and from livestock dung and urine deposited on pasture, range, or paddock lands are accounted for and discussed in the Agricultural Soil Management source category within the Agriculture sector. Indirect N_2O emissions dung and urine spread onto fields after it is removed from manure management systems (e.g., lagoon, pit, etc.) and from livestock dung and urine deposited on pasture, range, or paddock lands are also included in the Agricultural Soil Management source category.

Mules and Asses: Annual mule and ass (burro and donkey) population data by state were available for 1987, 1992, 1997, 2002, 2007, and 2012 (USDA 2014a). Data for 1990 through 1991, 1993 through 1996, 1998 through 2001, 2003 through 2006, 2008 through 2011, and 2013 through 2015 were interpolated and extrapolated based on the 1987, 1992, 1997, 2002, 2007, and 2012 Census data.

American Bison: Annual American bison population data by state were available for 2002, 2007, and 2012 (USDA 2014a). Data for 1990 through 1999 were obtained from the Bison Association (1999). Data for 2000, 2001, 2003 through 2006, 2008 through 2011, and 2013 through 2015 were interpolated and extrapolated based on the Bison Association and 2002, 2007, and 2012 Census data.

Poultry: The USDA provides population data for hens (one year old or older), pullets (hens younger than one year old), other chickens, and production (slaughter) data for broilers and turkeys (USDA 1995a, 1995b, 1998, 1999, 2004a, 2004b, 2009b, 2009c, 2009d, 2009e, 2010a, 2010b, 2011a, 2011b, 2012a, 2012b, 2013a, 2013b, 2014b, 2014c, 2015a, 2015b, 2016b, and 2016c). 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.

Because only production data are available for boilers and turkeys, population data are calculated by dividing the number of animals produced by the number of production cycles per year, or the turnover rate. Based on personal communications with John Lange, an agricultural statistician with USDA NASS, the broiler turnover rate ranges from 3.4 to 5.5 over the course of the inventory (Lange 2000). For turkeys, the turnover rate ranges from 2.4 to 3.0. A summary of the livestock population characterization data used to calculate CH_4 and N_2O emissions is presented in Table A-179.

Step 2: Waste Characteristics Data

Methane and N_2O 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-180 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 1996, 2008) is one of the primary sources of waste characteristics for non-cattle animal groups. Data from the 1996 and 2008 USDA AWMFH were used to estimate VS and Nex for most non-cattle animal groups across the time series of the inventory, as shown in Table A-181 (ERG 2010b and 2010c). The 1996 AWMFH data were based on measured values from U.S. farms; the 2008 AWMFH data were developed using the calculation method created by the American Society of Agricultural and Biological Engineers (ASABE), which is based on U.S. animal dietary intake and performance measures. Since the values from each of the two AWMFHs result from different estimation methods and reflect changes in animal genetics and nutrition over time, both data sources were used to create a time series across the Inventory as neither value would be appropriate to use across the entire span of Inventory years. Expert sources agreed interpolating the two data sources across the time series would be appropriate as each methodology reflect the best available for that time period and the more recent data may not appropriately reflect the historic time series (ERG 2010b). Although the AWMFH values are lower than the IPCC values, these values are more appropriate for U.S. systems because they have been calculated using U.S.-specific data. Animal-specific notes about VS and Nex are presented below:

- *Swine:* 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). Differing trends in VS and Nex values are due to the updated Nex calculation method from 2008 AWMFH. VS calculations did not follow the same procedure and were updated based on a fixed ratio of VS to total solids and past ASABE standards (ERG 2010b).
- *Poultry:* Due to the change in USDA reporting of hens and pullets in 2005, 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.

- *Goats, Sheep, Horses, Mules and Asses:* In cases where data were not available in the USDA documents, data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) or the *2006 IPCC Guidelines* were used as a supplement.

The method for calculating VS excretion and Nex for cattle (including American bison, beef and dairy cows, bulls, 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 *2006 IPCC Guidelines* Tier II methodology, and is modeled using the CEFM as described in the enteric fermentation portion of the inventory (documented in Moffroid and Pape 2013) in order to take advantage of the detailed diet and animal performance data assembled as part of the Tier II analysis for cattle. For American bison, VS and Nex were assumed to be the same as beef NOF bulls.

The VS 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 CEFM uses the input of digestible energy (DE) and the energy requirements of cattle to estimate gross energy (GE) intake and enteric CH_4 emissions. GE and DE are used to calculate the indigestible energy per animal as gross energy minus digestible energy plus the amount of gross energy for urinary energy excretion per animal (2 or 4 percent). This value is then converted to VS production per animal 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:

$$\text{VS production (kg)} = \left[(\text{GE} - \text{DE}) + (\text{UE} \times \text{GE})\right] \times \frac{1 - ASH}{18.45}$$

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.

Total nitrogen ingestion in cattle is determined by dietary protein intake. 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 CEFM utilizes the energy balance calculations recommended by the *2006 IPCC Guidelines* 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.

$$\text{N}_{\text{excreted}} = \text{N}_{\text{consumed}} - \left(\text{N}_{\text{growth}} + \text{N}_{\text{milk}}\right)$$

where,

$\text{N}_{\text{excreted}}$	=	Daily N excreted per animal, kg per animal per day.
$\text{N}_{\text{consumed}}$	=	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 N 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 N 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:

$$N_{growth} = \frac{\left\{WG * \left[268 - \frac{(7.03 * NEg)}{WG}\right]\right\}}{\frac{1000}{6.25}}$$

where,

N_{growth} = Nitrogen retained by the animal for growth, kg per animal per day
WG = Daily weight gain of the animal, as input into the CEFM transition matrix, kg per day
268 = Constant from *2006 IPCC Guidelines*
7.03 = Constant from *2006 IPCC Guidelines*
NEg = Net energy required for growth, as calculated in the CEFM, 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*, and is calculated using milk production and percent protein, along with conversion factors. Milk N 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 (Fat assumed to be 4%)
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, animal type (heifers and steer on feed, heifers and steer not on feed, bulls and American bison), and year. Table A-182 presents the state-specific VS and Nex production rates used for cattle in 2015.

Step 3: Waste Management System Usage Data

Table A-183 summarizes 2015 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, American bison, goats, horses, mules and asses and sheep) is managed on pasture, range, or paddocks, on drylot, or with solids storage systems. Note that the Inventory WMS estimates are based on state or regional WMS usage data and not built upon farm-level WMS estimates. 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-184.

Beef Cattle, Dairy Heifers and American Bison: The beef feedlot and dairy heifer WMS data were developed using regional 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 personal communication 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. Using EPA and USDA data and expert opinions (documented in ERG 2000a), the runoff from feedlots was calculated by region in *Calculations: Percent Distribution of Manure for Waste Management Systems* 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 (ERG 2000a). 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. American bison WMS data were assumed to be the same as beef cattle NOF.

Dairy Cows: The WMS data for dairy cows were developed using state and regional data from the Census of Agriculture, EPA's Office of Water, USDA, and the expert sources noted below. Farm-size distribution data are reported in the 1992, 1997, 2002, and 2007 and 2012 Census of Agriculture (USDA 2016d). It was assumed that the Census data provided for 1992 were the same as that for 1990 and 1991, and data provided for 2012 were the same as that for 2013 through 2015. Data for 1993 through 1996, 1998 through 2001, and 2003 through 2006, and 2008 through 2011 were interpolated using the 1992, 1997, 2002, 2007, and 2012 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 the expert opinion of 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 at the regional level from USDA's Animal and Plant Health Inspection Service (APHIS)'s National Animal Health Monitoring System (Ott 2000). These data are based on a statistical sample of farms in the 20 U.S. states with the most dairy cows. Small 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, 2002, 2007, and 2012 (USDA 2016d) 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 2015, which were obtained from the USDA NASS (USDA 2016a).

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 APHIS collects 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).

Finally, the percentage of manure managed with anaerobic digestion (AD) systems with methane capture and combustion was added to the WMS distributions at the state-level. AD system data were obtained from EPA's AgSTAR Program's project database (EPA 2016). This database includes basic information for AD systems in the United States, based on publicly available data and data submitted by farm operators, project developers, financiers, and others involved in the development of farm AD projects.

Swine: The regional distribution of manure managed in each WMS was estimated using data from a USDA APHIS report and EPA's Office of Water site visits (Bush 1998, ERG 2000a). The USDA APHIS data are based on a statistical sample of farms in the 16 U.S. states with the most hogs. For operations with less than 200 head, manure management system data were obtained from USDA APHIS (Bush 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, 2002, 2007, and 2012 Census of Agriculture (USDA 2016d) 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 2012 were the same as that for 2013 through 2015. Data for 1993 through 1996, 1998 through 2001, 2003 through 2006, and 2008 through 2011 were interpolated using the 1992, 1997, 2002, 2007, and 2012 data. The manure management systems reported in the census 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. As with dairy, AD WMS were added to the state-level WMS distribution based on data from EPA's AgSTAR database (EPA 2016).

Sheep: WMS 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's national sheep report (USDA, APHIS 2003). The USDA APHIS data are based on a statistical sampled of farms in the 22 U.S. states with the most sheep. 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. Based on expert opinion, it was assumed that all sheep manure not deposited in feedlots was deposited on pasture, range, or paddock lands (Anderson 2000).

Goats, Horses, and Mules and Asses: WMS data for 1990 to 2015 were obtained from Appendix H of *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). This report presents state WMS usage in percentages for the major animal types in the United States, based on information obtained from extension service personnel in each state. It was assumed that all manure not deposited in pasture, range, or paddock lands was managed in dry systems. For mules and asses, the WMS was assumed to be the same as horses.

Poultry—Hens (one year old or older), Pullets (hens less than one year old), and Other Chickens: WMS 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, APHIS 2000). It was assumed that the change in system usage between 1990 and 1999 is proportionally distributed among those years of the inventory. It was also assumed that system usage in 2000 through 2015 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. As with dairy and swine, using information about AD WMS from EPA's AgSTAR database (EPA 2016), AD was added to the WMS distribution for poultry operations.

Poultry—Broilers and Turkeys: The percentage of turkeys and broilers on pasture was obtained from the Office of Air and Radiation's *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. As with dairy, swine, and other poultry, AD systems were used to update the WMS distributions based on information from EPA's AgSTAR database (EPA 2016).

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-185. 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. The average county and state temperature data were obtained from the National Climate Data Center (NOAA 2016) and each state and year in the inventory was assigned a climate classification of cool, temperate or warm. Although there are some specific locations in the United States that may be included in the warm climate category, no aggregated state-level annual average temperatures are included in this category. In addition, some counties in a particular state may be included in the cool climate category, although the aggregated state-level annual average temperature may be included in the temperate category. Although considering the temperatures at a state level instead of a county level may be causing some specific locations to be classified into an inappropriate climate category, using the state level annual average temperature provides an estimate that is appropriate for calculating the national average.

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 latest 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,

f = van't Hoff-Arrhenius f factor, the proportion of VS that are biologically available for conversion to CH_4 based on the temperature of the system
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)

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). County population data were calculated from state-level population data from NASS and county-state distribution data from the 1992, 1997, 2002, and 2007 Census data (USDA 2014a). 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 interpolated based on 1992 and 1997 data; county population data for 1998 through 2001 were interpolated based on 1997 and 2002 data; county population data for 2003 through 2006 were interpolated based on 2002 and 2007 data; county population data for 2008 through 2015 were assumed to be the same as 2007.

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 county 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 due to the biological activity in the lagoon which keeps the temperature above freezing.
- Monthly production of VS added to the system is estimated based on the animal type, number of animals present, and the volatile solids excretion rate of the animals.
- 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 management and design factors which cause a system to operate at a less than optimal level.

- For all systems other than anaerobic lagoons, the amount of VS available for conversion to CH_4 each month 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 in the month of October.
- 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
$VS\ produced_{annual}$ = 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-186 by state, WMS, and animal group for 2015.

Nitrous Oxide Emission Factors

Direct N_2O EFs 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-187.

Indirect N_2O EFs 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 EFs 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.

Country-specific estimates of N losses were developed for $Frac_{gas}$ and $Frac_{runoff/leach}$ for the United States. 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 $Frac_{runoff/leach}$, data from EPA's Office of Water were used 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 and there are a lack of data to quantify these losses. Therefore, leaching losses were assumed to be zero and $Frac_{runoff/leach}$ was set equal to the runoff loss factor. Nitrogen losses from volatilization and runoff/leaching are presented in Table A-188.

Step 5: CH_4 Emission Calculations

To calculate CH_4 emissions for animals other than cattle, first the amount of VS excreted in manure that is managed in each WMS was estimated:

$$\text{VS excreted}_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \frac{\text{TAM}}{1000} \times \text{VS} \times \text{WMS} \times 365.25$$

where,

$\text{VS excreted}_{\text{State, Animal, WMS}}$	= Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
$\text{Population}_{\text{State, Animal}}$	= 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 in manure that is managed in each WMS was estimated using the following equation:

$$\text{VS excreted}_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \text{ x VS x WMS}$$

where,

$\text{VS excreted}_{\text{State, Animal, WMS}}$	= Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
$\text{Population}_{\text{State, Animal}}$	= 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 excreted into a WMS was used to calculate CH_4 emissions using the following equation:

$$CH_4 = \sum_{\text{State, Animal, WMS}} \left(\text{VS excreted}_{\text{State, Animal, WMS}} \times B_o \times \text{MCF} \times 0.662\right)$$

where,

CH_4	= CH_4 emissions (kg CH_4/yr)
$\text{VS excreted}_{\text{WMS, State}}$	= 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)
$\text{MCF}_{\text{animal, state, WMS}}$	= MCF for the animal group, state and WMS (percent)
0.662	= Density of methane at 25° C (kg CH_4/m^3 CH_4)

A calculation was developed to estimate the amount of CH_4 emitted from AD systems utilizing CH_4 capture and combustion technology. First, AD systems were assumed to produce 90 percent of the maximum CH_4 producing capacity (B_0) of the manure. This value is applied for all climate regions and AD system types. However, this is a conservative assumption as 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:

$$CH_4\ ProductionAD_{ADSystem} = ProductionAD_{ADSystem} \times \frac{TAM}{1000} \times VS \times B_O \times 0.662 \times 365.25 \times 0.90$$

where,

CH_4 Production $AD_{AD\ system}$	=	CH_4 production from a particular AD system, (kg/yr)
Population AD_{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 (CH_4 m^3/kg VS)
0.662	=	Density of CH_4 at 25° C (kg CH_4/m^3 CH_4)
365.25	=	Days/year
0.90	=	CH_4 production factor for AD systems

The total amount of CH_4 produced by AD is calculated only as a means to estimate the emissions from AD; i.e., only the estimated amount of CH_4 actually entering the atmosphere from AD is reported in the inventory. The emissions to the atmosphere from AD are a result of leakage from the system (e.g. from the cover, piping, tank, etc.) and incomplete combustion and are calculated using the collection efficiency (CE) and destruction efficiency (DE) of the AD system. The three primary types of AD systems in the United States are covered lagoons, complete mix and plug flow systems. 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 AD was calculated with the following equation:

$$\text{CH}_4\ \text{Emissions AD} = \sum_{\text{State, Animal, AD Systems}} \left(\begin{array}{l} \left[\text{CH}_4\ \text{Production AD}_{\text{AD system}} \times \text{CE}_{\text{AD system}} \times (1 - \text{DE})\right] \\ + \left[\text{CH}_4\ \text{Production AD}_{\text{AD system}} \times (1 - \text{CE}_{\text{AD system}})\right] \end{array} \right)$$

where,

CH_4 Emissions AD	=	CH_4 emissions from AD systems, (kg/yr)
CH_4 Production $AD_{AD\ system}$	=	CH_4 production from a particular AD system, (kg/yr)
$CE_{AD\ system}$	=	Collection efficiency of the AD system, varies by AD system type
DE	=	Destruction efficiency of the AD system, 0.98 for all systems

Step 6: N_2O Emission Calculations

Total N_2O emissions from manure management systems 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 N excreted in manure and managed in each WMS. For calves and animals other than cattle the following equation was used:

$$\text{N excreted}_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \text{WMS} \times \frac{\text{TAM}}{1000} \times \text{Nex} \times 365.25$$

where,

N excreted $_{State,\ Animal,\ WMS}$	= Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
Population $_{state}$	= 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 other than calves, the amount of N excreted was calculated using the following equation:

$$\text{N excreted}_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \text{WMS} \times \text{Nex}$$

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 N excretion rate (kg N/animal/year)

For all animals, direct N_2O emissions were calculated as follows:

$$\text{Direct } N_2O = \sum_{\text{State, Animal, WMS}} \left(\text{N excreted}_{\text{State, Animal, WMS}} \times EF_{\text{WMS}} \times \frac{44}{28} \right)$$

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:

$$\text{Indirect } N_2O = \sum_{\text{State, Animal, WMS}} \left(\left[\text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{gas, WMS}}}{100} \times EF_{\text{volatilization}} \times \frac{44}{28} \right] + \left[\text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{runoff/leach, WMS}}}{100} \times EF_{\text{runnoff/leach}} \times \frac{44}{28} \right] \right)$$

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)
$EF_{\text{volatilization}}$ = Emission factor for volatilization (0.010 kg N_2O-N/kg N)
$EF_{\text{runoff/leach}}$ = 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-189 and Table A-190 respectively. Emission estimates for 2015 are presented by animal type and state in Table A-191 and Table A-192 respectively.

Table A-179: Livestock Population (1,000 Head)

Animal Type	1990	1995	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Dairy Cattle	19,512	18,681	18,142	17,927	17,833	17,919	17,642	17,793	18,078	18,190	18,422	18,560	18,297	18,442	18,587	18,505	18,527
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*	*9,087*	*9,156*	*9,236*	*9,221*	*9,208*
Dairy Heifer	*4,129*	*4,108*	*4,008*	*4,045*	*4,060*	*4,073*	*4,033*	*4,162*	*4,294*	*4,343*	*4,401*	*4,437*	*4,545*	*4,577*	*4,581*	*4,525*	*4,579*
Dairy Calves	*5,369*	*5,091*	*17,431*	*17,508*	*17,483*	*17,126*	*17,013*	*16,918*	*16,814*	*16,644*	*16,231*	*16,051*	*16,067*	*15,817*	*15,288*	*14,859*	*14,741*
Swine[a]	53,941	58,899	58,864	58,913	60,028	59,827	60,735	61,073	61,887	65,417	67,183	65,842	64,723	65,572	66,363	65,437	64,325
Market <50 lb.	*18,359*	*19,656*	*19,574*	*19,659*	*19,863*	*19,929*	*20,222*	*20,228*	*20,514*	*21,812*	*19,933*	*19,411*	*19,067*	*19,285*	*19,472*	*19,002*	*18,952*
Market 50-119 lb.	*11,734*	*12,836*	*12,926*	*12,900*	*13,284*	*13,138*	*13,400*	*13,519*	*13,727*	*14,557*	*17,163*	*16,942*	*16,645*	*16,904*	*17,140*	*16,834*	*16,576*
Market 120-179 lb.	*9,440*	*10,545*	*10,748*	*10,708*	*11,013*	*11,050*	*11,227*	*11,336*	*11,443*	*12,185*	*12,825*	*12,517*	*12,377*	*12,514*	*12,714*	*12,674*	*12,333*
Market >180 lb.	*7,510*	*8,937*	*9,385*	*9,465*	*9,738*	*9,701*	*9,922*	*9,997*	*10,113*	*10,673*	*11,161*	*11,067*	*10,856*	*11,078*	*11,199*	*11,116*	*10,572*
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*	*5,778*	*5,791*	*5,839*	*5,812*	*5,892*
Beef Cattle[b]	81,576	90,361	84,810	84,237	84,260	83,361	81,672	82,193	83,263	82,801	81,532	80,993	80,484	78,937	76,858	76,075	75,245
Feedlot Steers	*6,357*	*7,233*	*8,304*	*7,932*	*8,116*	*8,416*	*8,018*	*8,116*	*8,724*	*8,674*	*8,474*	*8,434*	*8,584*	*8,771*	*8,586*	*8,614*	*8,695*
Feedlot Heifers	*3,192*	*3,831*	*4,702*	*4,569*	*4,557*	*4,676*	*4,521*	*4,536*	*4,801*	*4,730*	*4,585*	*4,493*	*4,620*	*4,830*	*4,742*	*4,653*	*4,525*
NOF Bulls	*2,160*	*2,385*	*2,293*	*2,274*	*2,244*	*2,248*	*2,201*	*2,214*	*2,258*	*2,214*	*2,207*	*2,188*	*2,190*	*2,165*	*2,100*	*2,074*	*2,038*
Beef Calves	*16,909*	*18,177*	*4,951*	*4,710*	*4,668*	*4,704*	*4,621*	*4,628*	*4,680*	*4,703*	*4,765*	*4,791*	*4,666*	*4,709*	*4,770*	*4,758*	*4,740*
NOF Heifers	*10,182*	*11,829*	*9,781*	*9,832*	*9,843*	*9,564*	*9,321*	*9,550*	*9,716*	*9,592*	*9,356*	*9,473*	*9,349*	*8,874*	*8,687*	*8,787*	*8,787*
NOF Steers	*10,321*	*11,716*	*8,724*	*8,724*	*8,883*	*8,347*	*8,067*	*8,185*	*8,248*	*8,302*	*8,244*	*8,560*	*8,234*	*7,568*	*7,173*	*7,457*	*7,374*
NOF Cows	*32,455*	*35,190*	*33,575*	*33,398*	*33,134*	*32,983*	*32,531*	*32,674*	*32,703*	*32,644*	*32,435*	*31,794*	*31,440*	*30,913*	*30,282*	*29,631*	*29,085*
Sheep	11,358	8,989	7,036	6,908	6,623	6,321	6,065	6,135	6,200	6,120	5,950	5,747	5,620	5,470	5,375	5,360	5,245
Sheep On Feed	*1,180*	*1,771*	*2,963*	*3,256*	*3,143*	*3,049*	*2,923*	*2,971*	*3,026*	*3,000*	*2,911*	*2,806*	*2,778*	*2,687*	*2,666*	*2,655*	*2,593*
Sheep NOF	*10,178*	*7,218*	*4,073*	*3,652*	*3,480*	*3,272*	*3,142*	*3,164*	*3,174*	*3,120*	*3,039*	*2,941*	*2,842*	*2,783*	*2,709*	*2,705*	*2,652*
Goats	2,516	2,357	2,419	2,475	2,530	2,652	2,774	2,897	3,019	3,141	3,037	2,933	2,829	2,725	2,622	2,518	2,414
Poultry[c]	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	2,088,828	2,104,335	2,095,951	2,168,697	2,106,502	2,116,333
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*	*341,005*	*341,884*	*338,944*	*346,965*	*361,403*	*370,637*
Pullets	*73,167*	*81,369*	*95,159*	*95,656*	*95,289*	*100,346*	*101,429*	*96,809*	*96,596*	*103,816*	*99,458*	*102,301*	*105,738*	*102,233*	*104,460*	*106,646*	*106,490*
Chickens	*6,545*	*7,637*	*8,088*	*8,126*	*8,353*	*8,439*	*8,248*	*8,289*	*7,938*	*8,164*	*7,589*	*8,487*	*7,390*	*6,922*	*6,827*	*6,853*	*6,403*
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*	*1,554,582*	*1,567,927*	*1,565,018*	*1,625,945*	*1,551,600*	*1,553,636*
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*	*81,396*	*82,833*	*84,500*	*80,000*	*79,167*
Horses	2,212	2,632	3,395	3,519	3,644	3,721	3,798	3,875	3,952	4,029	3,947	3,866	3,784	3,703	3,621	3,540	3,458
Mules and Asses	63	101	112	109	105	141	177	212	248	284	286	287	289	291	293	294	296
American Bison	47	104	194	213	232	225	218	212	205	198	191	184	177	169	162	155	148

Source(s): See *Step 1: Livestock Population Characterization Data*

[a] 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.

[b] NOF - Not on Feed

[c] Pullets includes laying pullets, pullets younger than 3 months, and pullets older than 3 months.

Note: Totals may not sum due to independent rounding.

Table A-180: Waste Characteristics Data

	Typical Animal Mass, TAM		Total Kjeldahl Nitrogen Excreted, Nex[a]		Maximum Methane Generation Potential, B_0		Volatile Solids Excreted, VS[a]	
Animal Group	Value (kg)	Source	Value	Source	Value (m^3 CH_4/kg VS added)	Source	Value	Source
Dairy Cows	680	CEFM	Table A-182	CEFM	0.24	Morris 1976	Table A-182	CEFM
Dairy Heifers	406-408	CEFM	Table A-182	CEFM	0.17	Bryant et al. 1976	Table A-182	CEFM
Feedlot Steers	419-457	CEFM	Table A-182	CEFM	0.33	Hashimoto 1981	Table A-182	CEFM
Feedlot Heifers	384-430	CEFM	Table A-182	CEFM	0.33	Hashimoto 1981	Table A-182	CEFM
NOF Bulls	831-917	CEFM	Table A-182	CEFM	0.17	Hashimoto 1981	Table A-182	CEFM
NOF Calves	118	ERG 2003b	Table A-181	USDA 1996, 2008	0.17	Hashimoto 1981	Table A-181	USDA 1996, 2008
NOF Heifers	296-407	CEFM	Table A-182	CEFM	0.17	Hashimoto 1981	Table A-182	CEFM
NOF Steers	314-335	CEFM	Table A-182	CEFM	0.17	Hashimoto 1981	Table A-182	CEFM
NOF Cows	554-611	CEFM	Table A-182	CEFM	0.17	Hashimoto 1981	Table A-182	CEFM
American Bison	578.5	Meagher 1986	Table A-182	CEFM	0.17	Hashimoto 1981	Table A-182	CEFM
Market Swine <50 lbs.	13	ERG 2010a	Table A-181	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-181	USDA 1996, 2008
Market Swine <60 lbs.	16	Safley 2000	Table A-181	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-181	USDA 1996, 2008
Market Swine 50-119 lbs.	39	ERG 2010a	Table A-181	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-181	USDA 1996, 2008
Market Swine 60-119 lbs.	41	Safley 2000	Table A-181	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-181	USDA 1996, 2008
Market Swine 120-179 lbs.	68	Safley 2000	Table A-181	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-181	USDA 1996, 2008
Market Swine >180 lbs.	91	Safley 2000	Table A-181	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-181	USDA 1996, 2008
Breeding Swine	198	Safley 2000	Table A-181	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-181	USDA 1996, 2008
Feedlot Sheep	25	EPA 1992	Table A-181	ASAE 1998, USDA 2008	0.36	EPA 1992	Table A-181	ASAE 1998, USDA 2008
NOF Sheep	80	EPA 1992	Table A-181	ASAE 1998, USDA 2008	0.19	EPA 1992	Table A-181	ASAE 1998, USDA 2008
Goats	64	ASAE 1998	Table A-181	ASAE 1998	0.17	EPA 1992	Table A-181	ASAE 1998
Horses	450	ASAE 1998	Table A-181	ASAE 1998, USDA 2008	0.33	EPA 1992	Table A-181	ASAE 1998, USDA 2008
Mules and Asses	130	IPCC 2006	Table A-181	IPCC 2006	0.33	EPA 1992	Table A-181	IPCC 2006
Hens >/= 1 yr	1.8	ASAE 1998	Table A-181	USDA 1996, 2008	0.39	Hill 1982	Table A-181	USDA 1996, 2008
Pullets	1.8	ASAE 1998	Table A-181	USDA 1996, 2008	0.39	Hill 1982	Table A-181	USDA 1996, 2008
Other Chickens	1.8	ASAE 1998	Table A-181	USDA 1996, 2008	0.39	Hill 1982	Table A-181	USDA 1996, 2008
Broilers	0.9	ASAE 1998	Table A-181	USDA 1996, 2008	0.36	Hill 1984	Table A-181	USDA 1996, 2008
Turkeys	6.8	ASAE 1998	Table A-181	USDA 1996, 2008	0.36	Hill 1984	Table A-181	USDA 1996, 2008

[a] Nex and VS values vary by year; Table A-182 shows state-level values for 2015 only.

Table A-181: Estimated Volatile Solids (VS) and Total Kjeldahl Nitrogen Excreted (Nex) Production Rates by year for Swine, Poultry, Sheep, Goats, Horses, Mules and Asses, and Cattle Calves (kg/day/1000 kg animal mass)

Animal Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
VS																		
Swine, Market <50 lbs.	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
Swine, Market 50-119 lbs.	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
Swine, Market 120-179 lbs.	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
Swine, Market >180 lbs.	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
Swine, Breeding	2.6	2.6	2.6	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
NOF Cattle Calves	6.4	6.4	6.8	6.9	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
Sheep	9.2	9.2	9.0	8.9	8.8	8.8	8.7	8.6	8.5	8.4	8.3	8.3	8.3	8.3	8.3	8.3	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
Hens >1yr.	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Pullets	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Chickens	10.8	10.8	10.9	10.9	10.9	10.9	10.9	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
Broilers	15.0	15.0	15.7	15.8	16.0	16.2	16.3	16.5	16.7	16.8	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
Turkeys	9.7	9.7	9.3	9.2	9.1	9.0	8.9	8.8	8.7	8.6	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Horses	10.0	10.0	9.2	8.8	8.4	8.1	7.7	7.3	6.9	6.5	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Mules and Asses	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Nex																		
Swine, Market <50 lbs.	0.60	0.60	0.71	0.73	0.76	0.79	0.81	0.84	0.87	0.89	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Swine, Market 50-119 lbs.	0.42	0.42	0.46	0.47	0.48	0.49	0.50	0.51	0.52	0.53	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Market 120-179 lbs.	0.42	0.42	0.46	0.47	0.48	0.49	0.50	0.51	0.52	0.53	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Market >180 lbs.	0.42	0.42	0.46	0.47	0.48	0.49	0.50	0.51	0.52	0.53	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Breeding	0.24	0.24	0.22	0.22	0.22	0.22	0.21	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
NOF Cattle Calves	0.30	0.30	0.35	0.36	0.38	0.39	0.40	0.41	0.43	0.44	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sheep	0.42	0.42	0.43	0.43	0.43	0.44	0.44	0.44	0.44	0.45	0.45	0.45	0.45	0.45	0.45	0.45	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
Hens >1yr.	0.70	0.70	0.73	0.73	0.74	0.75	0.76	0.77	0.77	0.78	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
Pullets	0.70	0.70	0.73	0.73	0.74	0.75	0.76	0.77	0.77	0.78	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
Chickens	0.83	0.83	0.92	0.94	0.97	0.99	1.01	1.03	1.06	1.08	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Broilers	1.10	1.10	1.05	1.04	1.03	1.02	1.01	1.00	0.98	0.97	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Turkeys	0.74	0.74	0.70	0.69	0.68	0.67	0.66	0.65	0.64	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Horses	0.30	0.30	0.29	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Mules and Asses	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30

Source: USDA AWMFH

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Table A-182: Estimated Volatile Solids (VS) and Total Kjeldahl Nitrogen Excreted (Nex) Production Rates by State for Cattle (other than Calves) and American Bison[a] for 2015 (kg/animal/year)

	Volatile Solids									Nitrogen Excreted								
State	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison
Alabama	2,097	1,251	1,664	1,101	972	690	669	1,721	1,721	128	69	73	51	42	56	57	83	83
Alaska	1,971	1,251	1,891	1,273	1,116	690	670	1,956	1,956	121	69	59	42	33	56	57	69	69
Arizona	2,928	1,251	1,891	1,247	1,116	691	669	1,956	1,956	162	69	59	40	33	56	57	69	69
Arkansas	2,075	1,251	1,664	1,097	972	690	669	1,721	1,721	126	69	73	50	42	56	57	83	83
California	2,799	1,251	1,891	1,232	1,116	690	669	1,956	1,956	156	69	59	40	33	56	57	69	69
Colorado	3,018	1,251	1,891	1,204	1,116	691	669	1,956	1,956	166	69	59	38	33	56	57	69	69
Connecticut	2,656	1,251	1,674	1,111	977	691	669	1,731	1,731	151	69	74	52	42	56	57	84	84
Delaware	2,571	1,251	1,674	1,081	977	691	668	1,731	1,731	147	69	74	50	42	56	57	84	84
Florida	2,697	1,251	1,664	1,103	972	691	669	1,721	1,721	154	69	73	51	42	56	57	83	83
Georgia	2,771	1,251	1,664	1,098	972	691	668	1,721	1,721	157	69	73	50	42	56	57	83	83
Hawaii	2,288	1,251	1,891	1,254	1,116	691	668	1,956	1,956	135	69	59	41	33	56	57	69	69
Idaho	2,902	1,251	1,891	1,224	1,116	691	669	1,956	1,956	161	69	59	39	33	56	57	69	69
Illinois	2,603	1,251	1,589	1,011	924	691	669	1,643	1,643	148	69	75	49	43	56	57	85	85
Indiana	2,753	1,251	1,589	1,025	924	691	669	1,643	1,643	155	69	75	50	43	56	57	85	85
Iowa	2,813	1,251	1,589	991	924	691	669	1,643	1,643	157	69	75	48	43	56	57	85	85
Kansas	2,760	1,251	1,589	985	924	691	669	1,643	1,643	155	69	75	48	43	56	57	85	85
Kentucky	2,469	1,251	1,664	1,082	972	690	669	1,721	1,721	144	69	73	49	42	56	57	83	83
Louisiana	2,107	1,251	1,664	1,099	972	691	669	1,721	1,721	127	69	73	50	42	56	57	83	83
Maine	2,578	1,251	1,674	1,095	977	691	669	1,731	1,731	147	69	74	51	42	56	57	84	84
Maryland	2,598	1,251	1,674	1,081	977	691	669	1,731	1,731	148	69	74	50	42	56	57	84	84
Massachusetts	2,450	1,251	1,674	1,097	977	691	668	1,731	1,731	142	69	74	51	42	56	57	84	84
Michigan	2,977	1,251	1,589	1,011	924	691	669	1,643	1,643	164	69	75	49	43	56	57	85	85
Minnesota	2,636	1,251	1,589	1,007	924	691	669	1,643	1,643	150	69	75	49	43	56	57	85	85
Mississippi	2,274	1,251	1,664	1,097	972	690	669	1,721	1,721	136	69	73	50	42	56	57	83	83
Missouri	2,258	1,251	1,589	1,032	924	691	669	1,643	1,643	134	69	75	51	43	56	57	85	85
Montana	2,695	1,251	1,891	1,254	1,116	690	670	1,956	1,956	152	69	59	41	33	56	58	69	69
Nebraska	2,812	1,251	1,589	994	924	691	669	1,643	1,643	157	69	75	48	43	56	57	85	85
Nevada	2,823	1,251	1,891	1,241	1,116	691	669	1,956	1,956	158	69	59	40	33	56	57	69	69
New Hampshire	2,604	1,251	1,674	1,097	977	691	669	1,731	1,731	148	69	74	51	42	56	57	84	84
New Jersey	2,454	1,251	1,674	1,090	977	691	669	1,731	1,731	142	69	74	50	42	56	57	84	84
New Mexico	2,910	1,251	1,891	1,239	1,116	691	669	1,956	1,956	162	69	59	40	33	56	57	69	69
New York	2,804	1,251	1,674	1,079	977	691	668	1,731	1,731	157	69	74	50	42	56	57	84	84
North Carolina	2,721	1,251	1,664	1,095	972	691	669	1,721	1,721	155	69	73	50	42	56	57	83	83
North Dakota	2,649	1,251	1,589	1,020	924	691	668	1,643	1,643	150	69	75	50	43	56	57	85	85
Ohio	2,636	1,251	1,589	1,022	924	691	669	1,643	1,643	150	69	75	50	43	56	57	85	85
Oklahoma	2,483	1,251	1,664	1,078	972	691	669	1,721	1,721	143	69	73	49	42	56	57	83	83
Oregon	2,624	1,251	1,891	1,235	1,116	691	668	1,956	1,956	149	69	59	40	33	56	57	69	69
Pennsylvania	2,622	1,251	1,674	1,081	977	690	669	1,731	1,731	149	69	74	50	42	56	57	84	84
Rhode Island	2,419	1,251	1,674	1,101	977	691	669	1,731	1,731	140	69	74	51	42	56	57	84	84

	Volatile Solids									Nitrogen Excreted								
State	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison
South Carolina	2,454	1,251	1,664	1,095	972	690	669	1,721	1,721	144	69	73	50	42	56	57	83	83
South Dakota	2,762	1,251	1,589	1,017	924	691	669	1,643	1,643	155	69	75	50	43	56	57	85	85
Tennessee	2,385	1,251	1,664	1,092	972	692	666	1,721	1,721	141	69	73	50	42	55	56	83	83
Texas	2,765	1,251	1,664	1,058	972	691	669	1,721	1,721	155	69	73	48	42	56	57	83	83
Utah	2,828	1,251	1,891	1,240	1,116	691	669	1,956	1,956	158	69	59	40	33	56	57	69	69
Vermont	2,608	1,251	1,674	1,075	977	691	669	1,731	1,731	149	69	74	49	42	56	57	84	84
Virginia	2,608	1,251	1,664	1,095	972	691	669	1,721	1,721	150	69	73	50	42	56	57	83	83
Washington	2,881	1,251	1,891	1,207	1,116	691	668	1,956	1,956	160	69	59	38	33	56	57	69	69
West Virginia	2,269	1,251	1,674	1,093	977	690	669	1,731	1,731	134	69	74	51	42	56	57	84	84
Wisconsin	2,795	1,251	1,589	1,034	924	691	669	1,643	1,643	157	69	75	51	43	56	57	85	85
Wyoming	2,785	1,251	1,891	1,242	1,116	691	669	1,956	1,956	156	69	59	40	33	56	57	69	69

1 Source: CEFM. NA: Not available; no population exists in this state.
2 [a] Beef NOF Bull values were used for American bison Nex and VS.
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Table A-183: 2015 Manure Distribution Among Waste Management Systems by Operation (Percent)

	Beef Feedlots		Beef Not on Feed Operations	Dairy Cow Farms[a]						Dairy Heifer Facilities				Swine Operations[a]					Layer Operations		Broiler and Turkey Operations	
State	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock	Pasture, Range, Paddock	Daily Spread	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[b]	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock[b]	Pasture, Range, Paddock	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Anaerobic Lagoon	Poultry without Litter	Pasture, Range, Paddock	Poultry with Litter
Alabama	100	1	100	51	16	9	9	14	0	17	38	0	45	6	4	7	54	30	42	58	1	99
Alaska	100	1	100	4	7	34	19	25	10	6	90	1	4	66	1	9	7	16	25	75	1	99
Arizona	100	0	100	0	10	9	19	61	0	10	90	0	0	5	4	7	54	31	60	40	1	99
Arkansas	100	1	100	63	14	8	6	8	0	15	28	0	57	5	4	17	36	38	0	100	1	99
California	100	1	100	0	10	9	20	60	0	11	88	1	1	20	3	7	43	27	12	88	1	99
Colorado	100	0	100	0	1	11	22	66	0	1	98	0	1	1	6	26	17	50	60	40	1	99
Connecticut	100	1	100	6	43	15	22	13	2	43	51	0	6	83	1	5	4	8	5	95	1	99
Delaware	100	1	100	6	44	18	19	11	2	44	50	0	6	17	4	22	16	41	5	95	1	99
Florida	100	1	100	12	22	7	15	43	0	22	61	1	17	73	1	7	6	13	42	58	1	99
Georgia	100	1	100	28	20	10	13	29	0	18	42	0	40	8	3	6	53	30	42	58	1	99
Hawaii	100	1	100	1	0	11	21	67	0	0	99	1	1	47	2	15	11	25	25	75	1	99
Idaho	100	0	100	0	0	11	22	66	0	1	99	0	0	9	5	24	16	46	60	40	1	99
Illinois	100	1	100	3	6	35	33	19	4	8	87	0	5	1	5	29	13	53	2	98	1	99
Indiana	100	1	100	6	10	26	30	26	2	13	79	0	8	1	5	29	13	52	0	100	1	99
Iowa	100	1	100	3	5	30	34	25	3	10	83	0	6	0	4	8	56	32	0	100	1	99
Kansas	100	1	100	2	3	15	38	40	1	5	92	0	3	1	5	29	13	53	2	98	1	99
Kentucky	100	1	100	57	15	15	8	4	1	14	24	0	61	5	4	8	52	31	5	95	1	99
Louisiana	100	1	100	51	16	9	9	14	0	14	26	0	60	89	0	3	2	5	60	40	1	99
Maine	100	1	100	6	44	18	19	12	2	45	48	0	7	75	1	7	5	12	5	95	1	99
Maryland	100	1	100	6	44	20	17	10	3	44	49	0	7	19	4	22	15	40	5	95	1	99
Massachusetts	100	1	100	7	45	22	17	7	2	45	47	0	7	67	1	9	7	15	5	95	1	99
Michigan	100	1	100	2	3	20	39	33	2	6	91	0	3	2	5	26	17	49	2	98	1	99
Minnesota	100	1	100	4	7	35	30	20	4	10	84	0	6	0	5	26	17	50	0	100	1	99
Mississippi	100	1	100	55	15	10	8	11	1	15	28	0	57	1	4	6	59	31	60	40	1	99
Missouri	100	1	100	7	12	39	24	14	4	14	77	0	8	1	5	29	13	53	0	100	1	99
Montana	100	0	100	3	4	19	27	43	4	4	93	0	3	3	5	26	17	50	60	40	1	99
Nebraska	100	1	100	3	5	21	36	33	2	6	90	0	4	1	5	29	14	52	2	98	1	99
Nevada	100	0	100	0	0	10	23	66	0	0	99	0	0	100	0	0	0	0	0	100	1	99
New Hampshire	100	1	100	6	44	18	19	10	2	44	49	0	7	100	0	0	0	0	5	95	1	99
New Jersey	100	1	100	8	46	25	13	6	3	45	47	0	8	70	1	8	6	14	5	95	1	99
New Mexico	100	0	100	0	10	9	19	61	0	10	90	0	0	74	1	7	6	12	60	40	1	99
New York	100	1	100	6	44	16	18	14	2	45	48	0	7	30	4	19	13	35	5	95	1	99
North Carolina	100	1	100	41	18	10	17	13	1	15	31	0	54	0	4	6	59	31	42	58	1	99
North Dakota	100	1	100	5	9	27	31	25	2	11	83	0	6	2	5	26	17	50	2	98	1	99

	Beef Feedlots		Beef Not on Feed Operations	Dairy Cow Farms[a]						Dairy Heifer Facilities				Swine Operations[a]					Layer Operations		Broiler and Turkey Operations	
State	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock	Pasture, Range, Paddock	Daily Spread	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[b]	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock[b]	Pasture, Range, Paddock	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Anaerobic Lagoon	Poultry without Litter	Pasture, Range, Paddock	Poultry with Litter
Ohio	100	1	100	7	11	33	27	19	3	14	78	0	8	2	5	28	13	52	0	100	1	99
Oklahoma	100	0	100	0	8	17	22	50	3	6	94	0	0	1	4	6	59	31	60	40	1	99
Oregon	100	1	100	12	0	10	22	54	1	0	80	1	20	78	1	6	5	11	25	75	1	99
Pennsylvania	100	1	100	8	46	24	13	7	2	47	44	0	9	3	5	26	18	48	0	100	1	99
Rhode Island	100	1	100	7	45	24	15	6	3	47	44	0	9	77	1	6	5	11	5	95	1	99
South Carolina	100	1	100	44	17	7	12	20	0	15	31	0	54	5	4	7	54	31	60	40	1	99
South Dakota	100	1	100	2	4	17	39	38	1	8	87	0	5	1	5	26	17	50	2	98	1	99
Tennessee	100	1	100	55	15	12	10	5	2	15	26	0	59	11	3	7	50	29	5	95	1	99
Texas	100	0	100	0	9	11	21	59	1	8	92	0	0	6	4	6	56	30	12	88	1	99
Utah	100	0	100	1	1	13	24	60	1	1	98	0	1	1	6	26	17	51	60	40	1	99
Vermont	100	1	100	5	43	15	20	15	2	44	49	0	7	81	1	5	4	9	5	95	1	99
Virginia	100	1	100	52	16	12	12	7	2	15	28	0	57	7	3	7	53	30	5	95	1	99
Washington	100	1	100	8	0	10	22	59	1	0	83	1	17	33	3	18	13	33	12	88	1	99
West Virginia	100	1	100	8	46	24	14	5	3	45	48	0	7	93	0	2	1	3	5	95	1	99
Wisconsin	100	1	100	4	6	32	32	22	3	12	82	0	7	12	4	24	17	43	2	98	1	99
Wyoming	100	0	100	4	7	19	21	44	4	12	81	0	7	1	6	26	17	51	60	40	1	99

Source(s): *See Step 3: Waste Management System Usage Data*

[a] In the methane inventory for manure management, the percent of dairy cows and swine with AD systems is estimated using data from EPA's AgSTAR Program.

[b] 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-184: Manure Management System Descriptions

Manure Management System	Description[a]
Pasture, Range, Paddock	The manure from pasture and range grazing animals is allowed to lie as is, and is not managed. Methane emissions are accounted for under Manure Management, but the N_2O emissions from manure deposited on PRP are included under the Agricultural Soil Management category.
Daily Spread	Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion. Methane and indirect N_2O emissions are accounted for under Manure Management. Direct N_2O emissions from land application are covered under the Agricultural Soil Management 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 VS 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 (complete mix or plug flow digester) or covered lagoon. Digesters are designed and operated for waste stabilization by the microbial reduction of complex organic compounds to CO_2 and CH_4, 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.

[a] Manure management system descriptions are based on 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-185: Methane Conversion Factors (percent) for Dry Systems

Waste Management System	Cool Climate MCF	Temperate Climate MCF	Warm Climate MCF
Aerobic Treatment	0	0	0
Anaerobic Digester	0	0	0
Cattle Deep Litter (<1 month)	3	3	30
Cattle Deep Litter (>1 month)	21	44	76
Composting - In Vessel	0.5	0.5	0.5
Composting - Static Pile	0.5	0.5	0.5
Composting-Extensive/ Passive	0.5	1	1.5
Composting-Intensive	0.5	1	1.5
Daily Spread	0.1	0.5	1
Dry Lot	1	1.5	5
Fuel	10	10	10
Pasture	1	1.5	2

Waste Management System	Cool Climate MCF	Temperate Climate MCF	Warm Climate MCF
Poultry with bedding	1.5	1.5	1.5
Poultry without bedding	1.5	1.5	1.5
Solid Storage	2	4	5

Source: IPCC 2006

Table A-186: Methane Conversion Factors by State for Liquid Systems for 2015 (percent)

	Dairy		Swine		Beef	Poultry
State	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Liquid/Slurry	Anaerobic Lagoon
Alabama	78	42	78	41	43	78
Alaska	49	15	49	15	15	49
Arizona	79	58	78	49	54	75
Arkansas	77	37	78	40	37	77
California	73	34	73	33	43	74
Colorado	66	22	68	24	24	65
Connecticut	71	26	71	26	26	71
Delaware	76	33	76	33	33	76
Florida	82	60	81	58	58	81
Georgia	78	44	78	42	42	77
Hawaii	77	58	77	58	58	77
Idaho	68	25	65	22	22	67
Illinois	73	30	73	29	28	73
Indiana	71	27	72	28	28	72
Iowa	70	26	70	26	26	70
Kansas	76	34	76	33	34	76
Kentucky	75	33	75	33	32	76
Louisiana	80	50	80	50	50	79
Maine	65	21	65	21	21	65
Maryland	75	31	75	32	32	75
Massachusetts	69	24	70	25	25	70
Michigan	68	24	69	24	24	68
Minnesota	68	24	69	24	24	68
Mississippi	79	45	78	43	46	79
Missouri	75	32	74	32	32	75
Montana	60	19	63	21	21	63
Nebraska	72	27	72	28	27	72
Nevada	70	26	71	28	26	70
New Hampshire	66	22	66	23	22	66
New Jersey	74	30	75	31	29	74
New Mexico	74	32	72	29	30	71
New York	67	23	68	24	24	68
North Carolina	76	35	78	41	33	76
North Dakota	67	23	67	23	23	67
Ohio	71	27	72	28	28	72
Oklahoma	78	40	77	37	37	77
Oregon	65	23	65	23	23	65
Pennsylvania	71	27	72	28	28	72
Rhode Island	71	26	71	26	26	71
South Carolina	78	43	79	44	42	78
South Dakota	69	25	70	25	25	70
Tennessee	76	34	76	36	35	76
Texas	78	42	78	45	39	79
Utah	66	22	69	25	24	65
Vermont	64	21	64	21	21	65
Virginia	73	30	76	33	31	74
Washington	65	23	67	24	25	66
West Virginia	72	28	72	28	27	71
Wisconsin	67	23	68	24	24	68
Wyoming	62	20	63	21	22	62

Note: MCFs developed using Tier 2 methods described in *2006 IPCC Guidelines*, Section 10.4.2.

Table A-187: Direct Nitrous Oxide Emission Factors for 2015 (kg N_2O-N/kg Kjdl 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

Source: *2006 IPCC Guidelines*

Table A-188: Indirect Nitrous Oxide Loss Factors (percent)

Animal Type	Waste Management System	Volatilization Nitrogen Loss	Runoff/Leaching Nitrogen Loss[a]				
			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
American Bison	Pasture	0	0	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
Mules and Asses	Dry Lot	23	0	0	0	0	0
Mules and Asses	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

Animal Type	Waste Management System	Volatilization Nitrogen Loss	Runoff/Leaching Nitrogen Loss[a]				
			Central	Pacific	Mid-Atlantic	Midwest	South
Swine	Pasture	0	0	0	0	0	0
Swine	Solid Storage	45	0	0	0	0	0

[a] Data for nitrogen losses due to leaching were not available, so the values represent only nitrogen losses due to runoff.
Source: EPA 2002b, 2005.

Table A-189: Total Methane Emissions from Livestock Manure Management (kt)[a]

Animal Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Dairy Cattle	**590**	**685**	**889**	**951**	**985**	**1,036**	**988**	**1,057**	**1,091**	**1,212**	**1,243**	**1,243**	**1,256**	**1,297**	**1,373**	**1,338**	**1,361**	**1,391**
Dairy Cows	*581*	*676*	*880*	*942*	*977*	*1,027*	*980*	*1,049*	*1,083*	*1,202*	*1,233*	*1,233*	*1,247*	*1,288*	*1,363*	*1,328*	*1,350*	*1,380*
Dairy Heifer	*7*	*7*	*7*	*7*	*7*	*7*	*6*	*7*	*7*	*8*	*8*	*8*	*8*	*8*	*9*	*8*	*8*	*9*
Dairy Calves	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*
Swine	**622**	**763**	**835**	**854**	**877**	**859**	**858**	**916**	**902**	**984**	**938**	**899**	**950**	**949**	**982**	**930**	**890**	**985**
Market Swine	483	608	681	697	719	705	707	755	742	816	780	751	794	795	823	779	739	826
Market <50 lbs.	*102*	*121*	*131*	*134*	*137*	*135*	*135*	*142*	*141*	*155*	*110*	*104*	*110*	*110*	*114*	*106*	*104*	*113*
Market 50-119 lbs.	*101*	*123*	*136*	*138*	*144*	*140*	*141*	*150*	*148*	*163*	*174*	*168*	*177*	*0*	*0*	*0*	*0*	*0*
Market 120-179 lbs.	*136*	*170*	*189*	*192*	*199*	*196*	*196*	*210*	*206*	*228*	*228*	*219*	*233*	*232*	*241*	*231*	*219*	*244*
Market >180 lbs.	*144*	*193*	*225*	*232*	*240*	*234*	*235*	*252*	*247*	*270*	*268*	*260*	*274*	*276*	*283*	*268*	*249*	*284*
Breeding Swine	139	155	155	158	158	154	151	161	160	168	158	149	156	155	159	151	151	160
Beef Cattle	**126**	**139**	**131**	**134**	**131**	**131**	**129**	**133**	**137**	**134**	**130**	**130**	**132**	**131**	**128**	**121**	**120**	**126**
Feedlot Steers	*14*	*14*	*15*	*15*	*15*	*16*	*15*	*15*	*16*	*16*	*16*	*16*	*16*	*17*	*16*	*16*	*16*	*16*
Feedlot Heifers	*7*	*8*	*9*	*9*	*9*	*9*	*9*	*9*	*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*
Beef Calves	*6*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*6*	*6*	*7*
NOF Heifers	*12*	*15*	*13*	*13*	*13*	*13*	*12*	*13*	*13*	*13*	*13*	*13*	*13*	*12*	*12*	*12*	*12*	*13*
NOF Steers	*12*	*14*	*11*	*11*	*11*	*10*	*10*	*10*	*11*	*10*	*10*	*11*	*10*	*10*	*9*	*9*	*9*	*9*
NOF Cows	*69*	*76*	*71*	*73*	*71*	*71*	*71*	*73*	*75*	*73*	*70*	*70*	*71*	*71*	*69*	*64*	*63*	*67*
Sheep	**7**	**5**	**4**	**4**	**4**	**4**	**3**	**3**	**3**	**3**	**3**	**3**	**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**
Poultry	**131**	**128**	**127**	**131**	**129**	**130**	**129**	**129**	**131**	**134**	**129**	**128**	**129**	**127**	**128**	**128**	**131**	**135**
Hens >1 yr.	*73*	*69*	*66*	*70*	*67*	*68*	*66*	*66*	*66*	*67*	*64*	*64*	*64*	*63*	*63*	*65*	*67*	*68*
Total Pullets	*25*	*22*	*22*	*22*	*22*	*22*	*23*	*22*	*23*	*25*	*23*	*23*	*24*	*23*	*23*	*24*	*24*	*26*
Chickens	*4*	*4*	*3*	*3*	*4*	*4*	*3*	*3*	*3*	*3*	*3*	*4*	*3*	*3*	*3*	*3*	*3*	*3*
Broilers	*19*	*23*	*28*	*28*	*29*	*29*	*30*	*31*	*32*	*32*	*33*	*31*	*31*	*31*	*32*	*31*	*31*	*32*
Turkeys	*10*	*9*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*6*	*6*	*6*	*6*	*6*	*6*	*6*
Horses	**9**	**11**	**13**	**13**	**13**	**13**	**12**	**12**	**12**	**11**	**10**	**10**	**10**	**10**	**10**	**9**	**9**	**9**
Mules and Asses	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
American Bison	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.5 kt.

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

Table A-190: Total (Direct and Indirect) Nitrous Oxide Emissions from Livestock Manure Management (kt)

Animal Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Dairy Cattle	**17.7**	**18.2**	**18.4**	**18.7**	**18.9**	**19.1**	**18.2**	**18.7**	**19.3**	**19.3**	**19.0**	**19.2**	**19.3**	**19.5**	**19.8**	**19.7**	**19.8**	**20.3**
Dairy Cows	*10.6*	*10.7*	*10.8*	*10.9*	*11.0*	*11.1*	*10.6*	*10.8*	*11.1*	*11.1*	*10.9*	*11.1*	*11.0*	*11.1*	*11.3*	*11.3*	*11.4*	*11.6*
Dairy Heifer	*7.1*	*7.5*	*7.6*	*7.8*	*7.9*	*8.0*	*7.6*	*7.8*	*8.2*	*8.2*	*8.0*	*8.1*	*8.3*	*8.4*	*8.5*	*8.3*	*8.4*	*8.7*
Dairy Calves	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Swine	**4.0**	**4.5**	**5.0**	**5.1**	**5.3**	**5.4**	**5.6**	**5.7**	**5.9**	**6.3**	**6.4**	**6.3**	**6.2**	**6.3**	**6.4**	**6.3**	**6.2**	**6.6**
Market Swine	*3.0*	*3.5*	*4.1*	*4.2*	*4.4*	*4.5*	*4.7*	*4.9*	*5.0*	*5.5*	*5.6*	*5.5*	*5.4*	*5.5*	*5.6*	*5.5*	*5.4*	*5.8*
Market <50 lbs.	*0.6*	*0.6*	*0.8*	*0.8*	*0.8*	*0.9*	*0.9*	*0.9*	*1.0*	*1.1*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*
Market 50-119 lbs.	*0.6*	*0.7*	*0.8*	*0.8*	*0.9*	*0.9*	*0.9*	*1.0*	*1.0*	*1.1*	*1.3*	*1.2*	*1.2*	*1.2*	*1.3*	*1.2*	*1.2*	*1.3*
Market 120-179 lbs.	*0.9*	*1.0*	*1.1*	*1.2*	*1.2*	*1.3*	*1.3*	*1.4*	*1.4*	*1.5*	*1.6*	*1.6*	*1.6*	*1.6*	*1.6*	*1.6*	*1.6*	*1.7*
Market >180 lbs.	*0.9*	*1.1*	*1.3*	*1.4*	*1.5*	*1.5*	*1.6*	*1.6*	*1.6*	*1.8*	*1.9*	*1.9*	*1.8*	*1.9*	*1.9*	*1.9*	*1.8*	*2.0*
Breeding Swine	*1.0*	*1.1*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*
Beef Cattle	**19.8**	**21.8**	**25.0**	**24.1**	**24.8**	**25.0**	**23.6**	**24.0**	**25.7**	**25.6**	**25.1**	**25.1**	**25.3**	**25.9**	**25.8**	**26.0**	**26.0**	**25.8**
Feedlot Steers	*13.4*	*14.4*	*16.1*	*15.4*	*16.0*	*16.3*	*15.3*	*15.5*	*16.7*	*16.7*	*16.5*	*16.5*	*16.6*	*16.9*	*16.7*	*17.0*	*17.3*	*17.3*
Feedlot Heifers	*6.4*	*7.4*	*8.9*	*8.6*	*8.7*	*8.8*	*8.4*	*8.5*	*9.0*	*8.9*	*8.7*	*8.6*	*8.7*	*9.1*	*9.0*	*9.0*	*8.8*	*8.5*
Sheep	**0.4**	**0.7**	**1.1**	**1.2**	**1.2**	**1.2**	**1.1**	**1.2**	**1.2**	**1.2**	**1.2**	**1.1**	**1.1**	**1.1**	**1.1**	**1.1**	**1.0**	**1.0**
Goats	**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**	**0.1**	**0.1**
Poultry	**4.7**	**5.1**	**5.3**	**5.3**	**5.4**	**5.3**	**5.4**	**5.4**	**5.4**	**5.4**	**5.4**	**5.2**	**5.2**	**5.2**	**5.3**	**5.2**	**5.2**	**5.2**
Hens >1 yr.	*1.0*	*1.0*	*1.1*	*1.2*	*1.2*	*1.2*	*1.2*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.4*	*1.3*
Total Pullets	*0.3*	*0.3*	*0.3*	*0.3*	*0.3*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*
Chickens	*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*	*0.0*	*0.0*
Broilers	*2.2*	*2.7*	*2.9*	*2.9*	*3.0*	*2.9*	*2.9*	*3.0*	*2.9*	*2.9*	*2.9*	*2.7*	*2.8*	*2.8*	*2.9*	*2.7*	*2.7*	*2.8*
Turkeys	*1.2*	*1.1*	*0.9*	*0.9*	*0.9*	*0.9*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*
Horses	**0.3**	**0.4**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Mules and Asses	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
American Bison	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**

+ Does not exceed 0.5 kt.

NA (Not Applicable)

Note: American bison are maintained entirely on unmanaged WMS; there are no American bison N_2O emissions from managed systems.

Table A-191: Methane Emissions by State from Livestock Manure Management for 2015 (kt)[a]

State	Beef on Feedlots	Beef Not on Feed[b]	Dairy Cow	Dairy Heifer	Swine—Market	Swine—Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses	Mules and Asses	American Bison
Alabama	0.0151	2.3891	0.4306	0.0081	1.6671	0.4671	9.3023	3.9333	0.0208	0.0085	0.0135	0.1632	0.0132	0.0005
Alaska	+	0.0166	0.0161	0.0002	0.0023	0.0015	0.2705	+	0.0207	0.0057	0.0002	0.0026	+	0.0040
Arizona	0.6429	1.0611	54.2481	0.1537	2.0060	0.6661	0.9310	+	0.0208	0.1057	0.0335	0.3502	0.0041	+
Arkansas	0.0336	3.2110	0.2329	0.0106	0.9678	1.8692	0.6232	3.4942	0.6877	0.0085	0.0136	0.1655	0.0095	0.0002
California	1.3318	3.6631	399.7726	1.9988	1.3906	0.1080	2.8400	0.2036	0.2876	0.4229	0.0546	0.3931	0.0072	0.0029
Colorado	1.5020	2.8195	33.5230	0.1506	4.5934	2.6309	3.9822	+	0.0207	0.1973	0.0066	0.2303	0.0049	0.0174
Connecticut	0.0003	0.0189	1.1524	0.0137	0.0044	0.0021	0.1012	+	0.0207	0.0034	0.0011	0.0459	0.0008	0.0002
Delaware	0.0003	0.0092	0.3293	0.0045	0.0194	0.0124	0.1061	0.8844	0.0207	0.0057	0.0003	0.0164	0.0001	0.0002
Florida	0.0111	3.2606	23.4736	0.1038	0.0609	0.0435	7.0412	0.2365	0.0208	0.0085	0.0182	0.3985	0.0113	+
Georgia	0.0133	1.7873	10.2297	0.0740	2.2700	0.8846	16.1855	4.8657	0.0208	0.0085	0.0241	0.2160	0.0099	0.0005
Hawaii	0.0027	0.2858	0.5184	0.0029	0.0615	0.0411	0.4163	+	0.0208	0.0085	0.0057	0.0140	0.0005	0.0002
Idaho	0.3871	1.6927	122.1684	0.4856	0.1477	0.0870	0.8315	+	0.0207	0.1222	0.0046	0.1180	0.0030	0.0100
Illinois	0.4035	1.0113	9.3806	0.0844	44.8221	10.5079	0.2696	0.2029	0.0207	0.0268	0.0076	0.1153	0.0026	0.0006
Indiana	0.1744	0.5910	15.9269	0.1285	36.1877	5.5922	1.0429	0.2029	0.4811	0.0235	0.0084	0.2346	0.0041	0.0018
Iowa	2.0667	3.1056	26.2279	0.2073	315.5249	31.8828	1.3261	0.2029	0.2268	0.0822	0.0141	0.1234	0.0033	0.0022
Kansas	3.8121	5.0002	27.4863	0.1485	21.7869	4.1020	0.0607	+	0.0207	0.0310	0.0095	0.1442	0.0027	0.0085
Kentucky	0.0302	2.5062	1.6651	0.0802	6.5611	1.4136	0.6808	1.1139	0.0207	0.0226	0.0109	0.2664	0.0099	0.0024
Louisiana	0.0089	1.6866	0.8189	0.0141	0.0125	0.0090	2.4196	0.2036	0.0208	0.0085	0.0064	0.1950	0.0086	0.0001
Maine	0.0008	0.0399	1.3959	0.0265	0.0092	0.0050	0.0951	+	0.0207	0.0034	0.0017	0.0260	0.0003	0.0004
Maryland	0.0193	0.1268	2.6337	0.0442	0.1577	0.0992	0.3375	1.0987	0.0207	0.0057	0.0018	0.0600	0.0009	0.0005
Massachusetts	0.0003	0.0194	0.3615	0.0118	0.0355	0.0145	0.0135	+	0.0207	0.0034	0.0022	0.0442	0.0004	0.0001
Michigan	0.2642	0.4435	60.3755	0.2640	10.0486	2.0626	0.8292	0.2029	0.1296	0.0357	0.0066	0.1755	0.0031	0.0016
Minnesota	0.6416	1.2525	37.3493	0.4428	67.6863	10.8214	0.3365	0.1680	1.0219	0.0611	0.0080	0.1142	0.0021	0.0022
Mississippi	0.0173	1.7844	0.4742	0.0166	8.6468	1.8000	8.2770	2.6243	0.0208	0.0085	0.0078	0.1798	0.0102	+
Missouri	0.1236	4.5447	6.6046	0.0985	23.2820	8.4510	0.4077	1.0665	0.4736	0.0399	0.0270	0.2150	0.0070	0.0019
Montana	0.0679	4.4400	1.7480	0.0105	1.1951	0.3948	0.3877	+	0.0207	0.1010	0.0023	0.2049	0.0036	0.0324
Nebraska	4.2658	5.9518	8.3449	0.0321	27.8275	8.3543	0.4730	0.2029	0.0207	0.0381	0.0051	0.1392	0.0030	0.0487
Nevada	0.0064	0.6131	6.6164	0.0137	0.0002	0.0002	0.0305	+	0.0207	0.0324	0.0068	0.0545	0.0005	0.0001
New Hampshire	0.0002	0.0117	0.6768	0.0092	0.0011	0.0005	0.0961	+	0.0207	0.0034	0.0014	0.0189	0.0001	0.0006
New Jersey	0.0003	0.0218	0.2701	0.0067	0.0477	0.0117	0.1047	+	0.0207	0.0057	0.0017	0.0573	0.0006	0.0004
New Mexico	0.0164	1.2871	77.4625	0.1702	0.0033	0.0033	0.8774	+	0.0207	0.0423	0.0070	0.1073	0.0014	0.0118
New York	0.0459	0.4512	34.6877	0.5859	0.4460	0.1100	0.6165	0.2029	0.0207	0.0376	0.0086	0.2043	0.0029	0.0009
North Carolina	0.0076	0.9251	3.4750	0.0453	138.7190	33.7077	13.0670	2.9882	0.7753	0.0211	0.0177	0.1970	0.0106	0.0002
North Dakota	0.0711	2.2401	1.6826	0.0094	0.8179	0.5490	0.0571	+	0.0207	0.0301	0.0013	0.0998	0.0010	0.0107
Ohio	0.2862	0.8297	22.4935	0.2006	22.0331	3.6934	1.0647	0.2911	0.1296	0.0569	0.0102	0.2433	0.0053	0.0010
Oklahoma	0.6394	7.8899	7.8296	0.0572	29.2451	16.8565	3.3746	0.7882	0.0208	0.0374	0.0252	0.5090	0.0153	0.0270
Oregon	0.1582	1.6292	20.1686	0.1044	0.0176	0.0096	0.8733	0.2029	0.0207	0.0916	0.0076	0.1293	0.0023	0.0033
Pennsylvania	0.1757	0.6268	18.5185	0.5243	11.1041	2.0637	0.8124	0.6893	0.1620	0.0404	0.0112	0.2673	0.0071	0.0009
Rhode Island	0.0001	0.0044	0.0325	0.0009	0.0028	0.0022	0.1017	+	0.0207	0.0034	0.0002	0.0039	0.0001	+
South Carolina	0.0039	0.6349	1.2822	0.0136	4.4947	0.4184	5.0005	0.8812	0.0208	0.0085	0.0134	0.1901	0.0067	0.0003

State	Beef on Feedlots	Beef Not on Feed[b]	Dairy Cow	Dairy Heifer	Swine—Market	Swine—Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses	Mules and Asses	American Bison
South Dakota	0.6453	4.3993	15.3640	0.1034	11.0760	3.3747	0.1014	+	0.1072	0.1198	0.0050	0.1493	0.0011	0.0566
Tennessee	0.0259	3.2529	1.5998	0.0449	3.6006	0.6394	0.2260	0.6727	0.0208	0.0310	0.0256	0.2276	0.0155	+
Texas	6.0470	18.2179	113.7558	0.5747	13.4191	3.4142	4.9055	2.2109	0.0208	0.5075	0.2708	1.2156	0.0715	0.0101
Utah	0.0391	0.9999	19.2656	0.0724	5.7015	1.2942	4.0254	+	0.0897	0.1363	0.0033	0.1281	0.0025	0.0021
Vermont	0.0010	0.0651	6.6809	0.0927	0.0063	0.0041	0.0102	+	0.0207	0.0034	0.0032	0.0234	0.0010	0.0001
Virginia	0.0383	1.6286	3.5346	0.0753	4.8657	0.1645	0.3717	0.9514	0.4237	0.0352	0.0109	0.1856	0.0053	0.0019
Washington	0.4006	0.8123	52.7571	0.2355	0.1193	0.0689	1.4902	0.2029	0.0207	0.0244	0.0059	0.1085	0.0026	0.0014
West Virginia	0.0078	0.4799	0.2976	0.0069	0.0038	0.0031	0.1820	0.3392	0.0748	0.0155	0.0033	0.0432	0.0022	+
Wisconsin	0.4347	1.1380	123.7352	1.1506	2.4610	0.7450	0.3117	0.1951	0.0207	0.0362	0.0160	0.2049	0.0043	0.0058
Wyoming	0.1192	2.1020	0.8642	0.0075	0.3552	0.4711	0.7751	+	0.0207	0.1621	0.0024	0.1482	0.0021	0.0171

+ Does not exceed 0.00005 kt.

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Beef Not on Feed includes calves.

Table A-192: Nitrous Oxide Emissions by State from Livestock Manure Management for 2015 (kt)

	Beef Feedlot-Heifer	Beef Feedlot-Steers	Dairy Cow	Dairy Heifer	Swine-Market	Swine-Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses	Mules and Asses
Alabama	0.0033	0.0067	0.0036	0.0027	0.0081	0.0017	0.0650	0.3480	0.0024	0.0046	0.0011	0.0056	0.0005
Alaska	+	+	0.0003	0.0002	+	+	0.0045	+	0.0024	0.0015	+	0.0001	+
Arizona	0.1684	0.3396	0.2457	0.1379	0.0094	0.0023	0.0048	+	0.0024	0.0165	0.0026	0.0120	0.0001
Arkansas	0.0077	0.0155	0.0023	0.0027	0.0059	0.0082	0.0882	0.3091	0.0797	0.0040	0.0011	0.0057	0.0003
California	0.2950	0.5935	2.1651	1.6122	0.0078	0.0004	0.0596	0.0180	0.0333	0.0747	0.0043	0.0135	0.0003
Colorado	0.6137	1.2390	0.2039	0.2301	0.0485	0.0205	0.0239	+	0.0024	0.0463	0.0008	0.0119	0.0003
Connecticut	0.0001	0.0002	0.0174	0.0100	+	+	0.0043	+	0.0024	0.0027	0.0001	0.0024	+
Delaware	0.0001	0.0002	0.0045	0.0031	0.0002	0.0001	0.0043	0.0785	0.0024	0.0046	+	0.0008	+
Florida	0.0022	0.0045	0.1143	0.0514	0.0003	0.0002	0.0463	0.0209	0.0024	0.0046	0.0015	0.0137	0.0004
Georgia	0.0029	0.0060	0.0648	0.0273	0.0110	0.0032	0.1128	0.4305	0.0024	0.0046	0.0019	0.0074	0.0004
Hawaii	0.0005	0.0011	0.0025	0.0023	0.0003	0.0002	0.0045	+	0.0024	0.0015	0.0005	0.0005	+
Idaho	0.1589	0.3214	0.7943	0.7418	0.0016	0.0007	0.0048	+	0.0024	0.0287	0.0005	0.0061	0.0002
Illinois	0.1558	0.3138	0.1370	0.1066	0.4147	0.0709	0.0192	0.0180	0.0024	0.0187	0.0009	0.0059	0.0001
Indiana	0.0673	0.1356	0.2458	0.1488	0.3485	0.0395	0.1449	0.0180	0.0559	0.0164	0.0010	0.0121	0.0002
Iowa	0.8033	1.6226	0.3207	0.2555	1.8775	0.1390	0.1842	0.0180	0.0264	0.0574	0.0017	0.0064	0.0002
Kansas	1.4249	2.8802	0.2062	0.1944	0.1831	0.0255	0.0043	+	0.0024	0.0217	0.0011	0.0074	0.0001
Kentucky	0.0104	0.0209	0.0301	0.0266	0.0353	0.0056	0.0277	0.0989	0.0024	0.0183	0.0013	0.0137	0.0005
Louisiana	0.0019	0.0038	0.0062	0.0031	0.0001	+	0.0121	0.0180	0.0024	0.0040	0.0005	0.0067	0.0003
Maine	0.0003	0.0006	0.0265	0.0189	0.0001	+	0.0043	+	0.0024	0.0027	0.0002	0.0013	+
Maryland	0.0066	0.0134	0.0444	0.0301	0.0013	0.0006	0.0137	0.0975	0.0024	0.0046	0.0002	0.0031	+
Massachusetts	0.0001	0.0002	0.0106	0.0082	0.0003	0.0001	0.0006	+	0.0024	0.0027	0.0003	0.0023	+
Michigan	0.1036	0.2096	0.6380	0.3560	0.1016	0.0155	0.0612	0.0180	0.0151	0.0249	0.0008	0.0090	0.0002
Minnesota	0.2515	0.5083	0.6572	0.5547	0.6848	0.0807	0.0468	0.0149	0.1188	0.0426	0.0009	0.0059	0.0001
Mississippi	0.0038	0.0076	0.0053	0.0041	0.0415	0.0062	0.0423	0.2322	0.0024	0.0046	0.0006	0.0062	0.0004
Missouri	0.0468	0.0943	0.1073	0.1095	0.2157	0.0569	0.0568	0.0947	0.0551	0.0279	0.0032	0.0111	0.0004
Montana	0.0283	0.0569	0.0188	0.0153	0.0140	0.0034	0.0024	+	0.0024	0.0237	0.0003	0.0106	0.0002
Nebraska	1.6457	3.3280	0.0799	0.0425	0.2698	0.0596	0.0341	0.0180	0.0024	0.0266	0.0006	0.0072	0.0002
Nevada	0.0026	0.0053	0.0376	0.0209	+	+	0.0042	+	0.0024	0.0076	0.0008	0.0028	+
New Hampshire	0.0001	0.0001	0.0125	0.0066	+	+	0.0043	+	0.0024	0.0027	0.0002	0.0010	+
New Jersey	0.0001	0.0002	0.0058	0.0044	0.0004	0.0001	0.0043	+	0.0024	0.0046	0.0002	0.0030	+
New Mexico	0.0065	0.0132	0.4053	0.2332	+	+	0.0048	+	0.0024	0.0099	0.0008	0.0055	0.0001
New York	0.0167	0.0339	0.5709	0.4138	0.0045	0.0008	0.0269	0.0180	0.0024	0.0305	0.0010	0.0105	0.0002
North Carolina	0.0026	0.0052	0.0331	0.0132	0.6712	0.1203	0.0923	0.2644	0.0898	0.0114	0.0014	0.0068	0.0004
North Dakota	0.0280	0.0567	0.0218	0.0117	0.0088	0.0044	0.0043	+	0.0024	0.0210	0.0001	0.0051	0.0001
Ohio	0.1102	0.2229	0.3582	0.2316	0.2128	0.0262	0.1466	0.0258	0.0151	0.0459	0.0012	0.0125	0.0003
Oklahoma	0.1736	0.3507	0.0481	0.0549	0.1469	0.0616	0.0172	0.0697	0.0024	0.0173	0.0020	0.0175	0.0005
Oregon	0.0548	0.1110	0.1444	0.1130	0.0002	0.0001	0.0111	0.0180	0.0024	0.0243	0.0009	0.0067	0.0001
Pennsylvania	0.0627	0.1260	0.4561	0.3336	0.1024	0.0142	0.1130	0.0612	0.0188	0.0328	0.0013	0.0138	0.0004
Rhode Island	+	0.0001	0.0008	0.0005	+	+	0.0043	+	0.0024	0.0027	+	0.0002	+

South Carolina	0.0009	0.0018	0.0084	0.0037	0.0227	0.0016	0.0252	0.0780	0.0024	0.0046	0.0011	0.0065	0.0002
South Dakota	0.2515	0.5083	0.1437	0.1336	0.1087	0.0244	0.0074	+	0.0125	0.0837	0.0006	0.0077	0.0001
Tennessee	0.0062	0.0127	0.0226	0.0159	0.0187	0.0025	0.0093	0.0595	0.0024	0.0168	0.0020	0.0078	0.0005
Texas	1.6347	3.3045	0.5806	0.5408	0.0713	0.0133	0.0977	0.1956	0.0024	0.0794	0.0214	0.0418	0.0025
Utah	0.0160	0.0323	0.1305	0.1100	0.0573	0.0107	0.0240	+	0.0104	0.0320	0.0004	0.0066	0.0001
Vermont	0.0004	0.0007	0.1181	0.0673	0.0001	+	0.0005	+	0.0024	0.0027	0.0004	0.0012	0.0001
Virginia	0.0132	0.0267	0.0512	0.0288	0.0256	0.0006	0.0154	0.0844	0.0493	0.0286	0.0013	0.0096	0.0003
Washington	0.1369	0.2771	0.3563	0.2674	0.0012	0.0005	0.0347	0.0180	0.0024	0.0065	0.0007	0.0056	0.0001
West Virginia	0.0028	0.0056	0.0071	0.0047	+	+	0.0078	0.0301	0.0087	0.0126	0.0004	0.0022	0.0001
Wisconsin	0.1709	0.3452	1.9134	1.4068	0.0245	0.0055	0.0230	0.0173	0.0024	0.0253	0.0019	0.0106	0.0002
Wyoming	0.0491	0.0992	0.0077	0.0095	0.0049	0.0047	0.0048	+	0.0024	0.0380	0.0003	0.0076	0.0001

+ Does not exceed 0.00005 kt.

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3.12. Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Lands (Cropland and Grassland)

Nitrous oxide (N_2O) is produced in soils through the microbial processes of nitrification and denitrification[81] Management influences these processes by modifying the availability of mineral nitrogen (N), which is a key control on the N_2O emissions rates (Mosier et al. 1998). 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_2O. Management practices influence soil organic C stocks in agricultural soils by modifying the natural processes of photosynthesis (i.e., crop and forage production) and microbial decomposition. CH_4 emissions from rice cultivation occur under flooded conditions through the process of methanogenesis. This sub-annex describes the methodologies used to calculate N_2O emissions from agricultural soil management and annual carbon (C) stock changes from mineral and organic soils classified as *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*[82], and CH_4 emissions from *Rice Cultivation.* This annex provides the underlying methodologies for these three emission sources because there is considerable overlap in the methods with the majority of emissions estimated using the DAYCENT biogeochemical[83] simulation model.

A combination of Tier 1, 2 and 3 approaches are used to estimate direct and indirect N_2O emissions and C stock changes in agricultural soils.

More specifically, the methodologies used to estimate soil N_2O emissions include:

1) A Tier 3 method using the DAYCENT biogeochemical simulation model to estimate direct emissions from mineral soils that have less than 35 percent coarse fragments by volume and are used to produce alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat, as well as non-federal grasslands and land use change between grassland and cropland (with the crops listed above and less than 35 percent coarse fragments);
2) A combination of the Tier 3 and 1 methods to estimate indirect N_2O emissions associated with management of cropland and grassland simulated with DAYCENT in Item 1;
3) A Tier 1 method to estimate direct and indirect N_2O emissions from mineral soils that are not simulated with DAYCENT, including very gravelly, cobbly, or shaley soils (greater than 35 percent coarse fragments by volume); mineral soils with less than 35 percent coarse fragments that are used to produce crops that are not simulated by DAYCENT; and crops that are rotated with the crops that are not simulated with DAYCENT Pasture/Range/Paddock (PRP) manure N deposited on federal grasslands; and
4) A Tier 1 method to estimate direct N_2O emissions due to partial or complete drainage of organic soils in croplands and grasslands.

The methodologies used to estimate soil CH_4 emissions from rice cultivation include:

1) A Tier 3 method using the DAYCENT biogeochemical simulation model to estimate CH_4 emissions from mineral soils that have less than 35 percent coarse fragments by volume and rice grown continuously or in rotation with a crop listed in (1) for soil N_2O emissions; and
2) A Tier 1 method to estimate CH_4 emissions from all other soils used to produce rice that are not estimated with the Tier 3 method, including rice grown on organic soils (i.e., *Histosols*), mineral soils with very gravelly, cobbly, or shaley soils (greater than 35 percent coarse fragments by volume), and rice grown in rotation with crops that are not simulated by DAYCENT.

The methodologies used to estimate soil organic C stock changes include:

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[81] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product in the reaction sequence of denitrification, which leaks from microbial cells into the soil and then into the atmosphere. Nitrous oxide is also produced during nitrification, although by a less well-understood mechanism (Nevison 2000).

[82] Soil C stock change methods for forestland are described in the *Forestland Remaining Forestland* section.

[83] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

1) A Tier 3 method using the DAYCENT biogeochemical simulation model to estimate soil organic C stock changes in mineral soils as described in Item 1 for N_2O emissions;
2) Tier 2 methods with country-specific stock change factors for estimating mineral soil organic C stock changes for mineral soils that are very gravelly, cobbly, or shaley (greater than 35 percent coarse fragments by volume), are used to produce crops or have land use changes to cropland and grassland (other than the conversions between cropland and grassland that are included in Item 1) that are not simulated with DAYCENT;
3) Tier 2 methods with country-specific stock change factors for estimating mineral soil organic C stock changes on federal lands;
4) Tier 2 methods with country-specific emission factors for estimating losses of C from organic soils that are partly or completely drained for agricultural production; and
5) 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 2010.

As described above, the Inventory uses a Tier 3 approach to estimate direct soil N_2O emissions, CH_4 emissions from rice cultivation, and C stock changes for the majority of agricultural lands. This approach has the following advantages over the IPCC Tier 1 or 2 approaches:

1) It utilizes actual weather data at sub-county scales enabling quantification of inter-annual variability in N_2O emissions and C stock changes at finer spatial scales, as opposed to a single emission factor for the entire country for soil N_2O or broad climate region classification for soil C stock changes;
2) The model uses a more detailed characterization of spatially-mapped soil properties that influence soil C and N dynamics, as opposed to the broad soil taxonomic classifications of the IPCC methodology;
3) 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
4) Soil N_2O and CH_4 emissions, and C stock changes are estimated on a more continuous, daily basis as a function of the interaction of climate, soil, and land management, compared with the linear rate changes that are estimated with the Tier 1 and 2 methods.

The DAYCENT process-based simulation model (daily time-step version of the Century model) has been selected for the Tier 3 approach based on the following criteria:

1) The model has been developed in the U.S. and extensively tested and verified for U.S. conditions (e.g., Parton et al. 1987, 1993). 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), soil N_2O emissions (e.g., Canada, China, Ireland, New Zealand) (Abdalla et al. 2010; Li et al. 2005; Smith et al. 2008; Stehfest and Muller 2004; Cheng et al. 2014), and CH_4 emissions (Cheng et al. 2013).
2) 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.
3) The model is designed to simulate management practices that influence soil C dynamics, CH_4 emissions and direct N_2O emissions, with the exception of cultivated organic soils; cobbly, gravelly, or shaley soils; and crops that have not been parameterized for DAYCENT simulations (e.g., some vegetables, tobacco, perennial/horticultural crops, and crops that are rotated with these crops). For these latter cases, an IPCC Tier 2 method has been used for soil C stock changes and IPCC Tier 1 method for CH_4 and N_2O emissions. The model can also be used estimate the amount of N leaching and runoff, as well as volatilization of N, which is subject to indirect N_2O emissions.
4) Much of the data needed for the model is available from existing national databases. The exceptions are CRP enrollment after 2010, management of federal grasslands, and sewage sludge amendments to soils, which are not known at a sufficient resolution to use the Tier 3 model. Soil N_2O emissions and C stock changes associated with these practices are addressed with a Tier 1 and 2 method, respectively.

Overall, the Tier 3 approach is used to estimate approximately 89 percent of direct soil N_2O emissions 94 percent of the rice cultivation, and 88 percent of the land area associated with estimation of soil organic C stock changes under agricultural management in the United States.

Tier 3 Method Description and Model Evaluation

The DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011) simulates biogeochemical C and N fluxes between the atmosphere, vegetation, and soil; and provides a more complete estimation of soil C stock changes and N_2O emissions than IPCC Tier 1 or 2 methods by more thoroughly accounting for the influence of environmental conditions. These conditions include soil characteristics, weather patterns, crop and forage characteristics, and management practices. The DAYCENT model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Carbon and N dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the three source categories (i.e., agricultural soil C, rice CH_4 and soil N_2O) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions between C and N cycling in soils. For example, plant growth is controlled by nutrient availability, water, and temperature stress. Plant growth, along with residue management, determines C inputs to soils, which influence C stock changes, and removal of mineral N from the soil where plant growth influences the amount of N that can be converted into N_2O. 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 a reduction in soil organic C stocks due to microbial respiration, and greater N_2O emissions by enhancing mineral N availability in soils.

Key processes simulated by DAYCENT include (1) plant growth; (2) organic matter formation and decomposition; (3) soil water and temperature regimes by layer; (4) nitrification and denitrification processes; and (5) methanogenesis (Figure A-7). Each of these submodels will be described separately below.

1) 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). Maximum daily net primary production (NPP) is estimated using the NASA-CASA production algorithm (Potter et al.1993, 2007) and MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, or an approximation of EVI data derived from the MODIS products (Gurung et al. 2009). The NASA-CASA production algorithm is only used for the following major crops: corn, soybeans, sorghum, cotton and wheat.[84] Other regions and crops are simulated with a single value for the maximum daily NPP, instead of the more dynamic NASA-CASA algorithm. The maximum daily NPP rate is modified by air temperature and available water (to capture temperature and moisture stress). If the NASA-CASA algorithm is not used in the simulation, then production is further subject to nutrient limitations (i.e., nitrogen). Model evaluation has shown that the NASA-CASA algorithm improves the precision of NPP estimates using the EVI products to inform the production model. The r^2 is 83 percent for the NASA-CASA algorithm and 64 percent for the single parameter value approach. See Figure A-8.

2) Dynamics of soil organic C and N (Figure A-7) are simulated for the surface and belowground litter pools and soil organic matter in 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 (metabolic and structural) and three soil organic matter (SOM) pools (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 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 decomposition, leading to enhanced SOM stabilization in finely textured soils. Soil temperature and moisture, tillage disturbance, aeration, and other factors influence decomposition and loss of C from the soil organic matter pools.

[84] It is a planned improvement to estimate NPP for additional crops and grass forage with the NASA-CASA method in the future.

3) 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.

Figure A-7: DAYCENT Model Flow Diagram

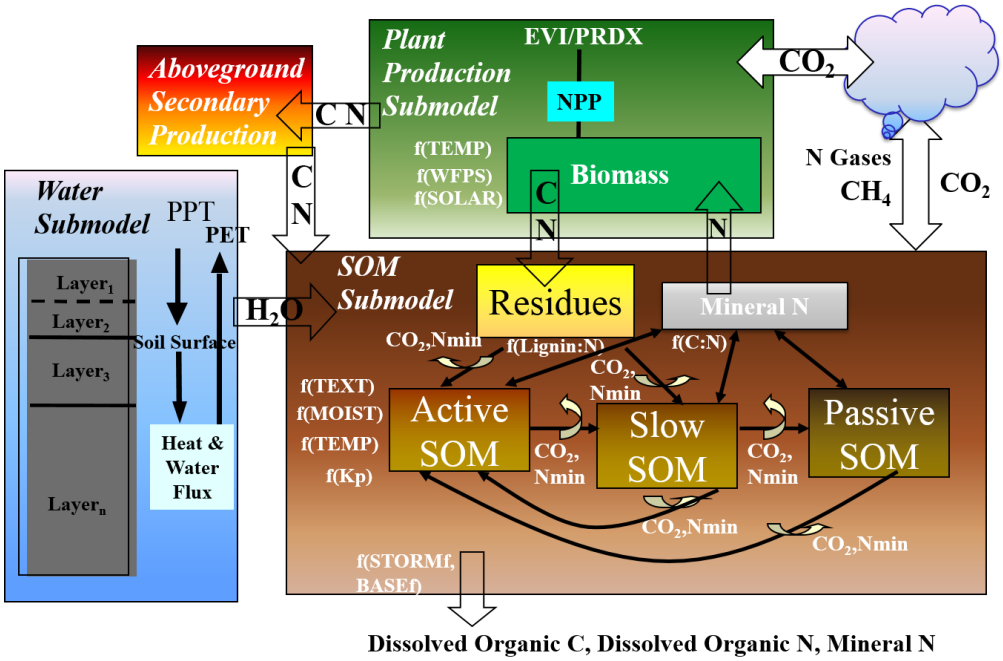
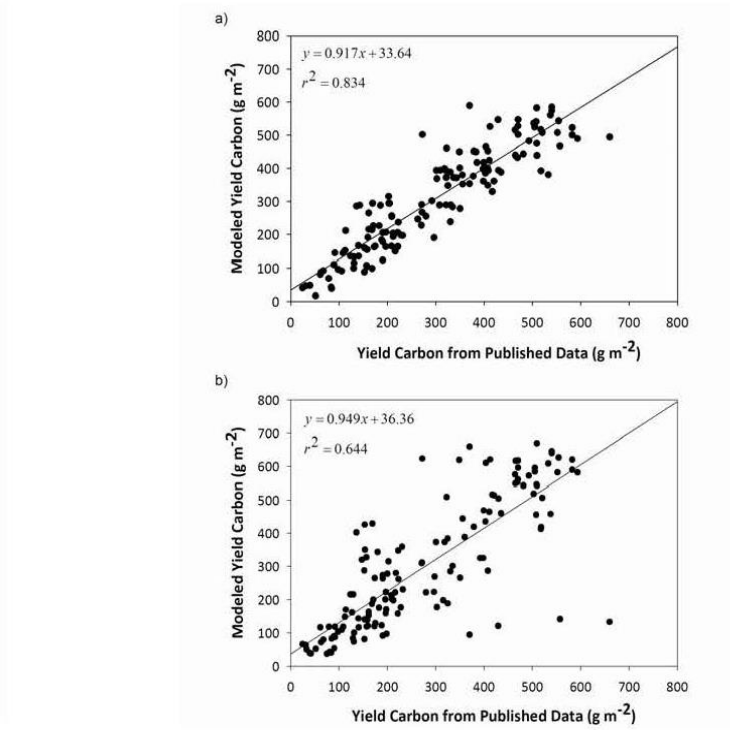


Figure A-8: Modeled versus measured net primary production (g C m^{-2})



Part a) presents results of the NASA-CASA algorithm (r^2 = 83%) and part b) presents the results of a single parameter value for maximum net primary production (r^2 = 64%).

4) Soil mineral N dynamics are modeled based on N inputs from fertilizer inputs (synthetic and organic), residue N inputs, soil organic matter mineralization in addition to symbiotic and asymbiotic N fixation. Mineral N is available for plant and microbial uptake, and is largely controlled by the specified stoichiometric limits for these organisms (i.e., C:N ratios). Mineral and organic N losses are simulated with leaching and runoff, and nitrogen can be volatilized and lost from the soil through ammonia volatilization, nitrification and denitrification. N_2O emissions occur through nitrification and denitrification. Denitrification is a function of soil NO_3^- concentration, water filled pore space (WFPS), heterotrophic (i.e., microbial) respiration, and texture. Nitrification is controlled by soil ammonium (NH_4^+) concentration, water filled pore space, temperature, and pH (See Box 2 for more information).

5) Methanogenesis is modeled under anaerobic conditions and is controlled by carbon substrate availability, temperature, and redox potential (Cheng et al. 2013). Carbon substrate supply is determined by decomposition of residues and soil organic matter, in addition to root exudation. The transport of CH_4 to the atmosphere occurs through the rice plant and via ebullition (i.e., bubbles). CH_4 can be oxidized (methanotrophy) as it moves through a flooded soil and the oxidation rates are higher as the plants mature and in soils with more clay (Sass et al. 1994).

The model allows for a variety of management options to be simulated, including specifying different crop types, crop sequences (e.g., rotation), tillage practices, fertilization, organic matter addition (e.g., manure amendments), harvest events (with variable residue removal), drainage, flooding, 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 day 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 with the model 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, 1998), Del Grosso et al. (2001, 2011), Cheng et al. (2013) and Metherell et al. (1993), and archived copies of the model source code are available.

[BEGIN TEXT BOX]

Box 2. DAYCENT Model Simulation of Nitrification and Denitrification

The DAYCENT model simulates the two biogeochemical processes, nitrification and denitrification, that result in N_2O emissions from soils (Del Grosso et al. 2000, Parton et al. 2001). Nitrification is calculated for the top 15 cm of soil (where nitrification mostly occurs) while denitrification is calculated for the entire soil profile (accounting for denitrification near the surface and subsurface as nitrate leaches through the profile). The equations and key parameters controlling N_2O emissions from nitrification and denitrification are described below.

Nitrification is controlled by soil ammonium (NH_4^+) concentration, temperature (t), Water Filled Pore Space (WFPS) 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-9a)

F(WFPS) = the effect of soil water content and soil texture on nitrification (Figure A-9b)

F(pH) = the effect of soil pH on nitrification (Figure A-9c)

The current parameterization used in the model assumes that 1.2 percent of nitrified N is converted to N_2O.

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. These rates vary for particular levels of electron acceptor and C substrate, and account 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)

$F(NO_3)$ = a function relating N gas flux to nitrate levels (Figure A-10a)

$F(CO_2)$ = a function relating N gas flux to soil respiration (Figure A-10b)

F(WFPS) = a dimensionless multiplier (Figure A-10c).

The x inflection point of F(WFPS) is a function of respiration and soil gas diffusivity at field capacity (D_{FC}):

$$x\ inflection = 0.90 - M(CO_2)$$

where,

M = a multiplier that is a function of D_{FC}. In technical terms, the inflection point is the domain where either F(WFPS) is not differentiable or its derivative is 0. In this case, the inflection point can be interpreted as the WFPS value at which denitrification reaches half of its maximum rate.

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-9b). 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-9: Effect of Soil Temperature (a) , Water-Filled Pore Space (b) , and pH (c) on Nitrification Rates

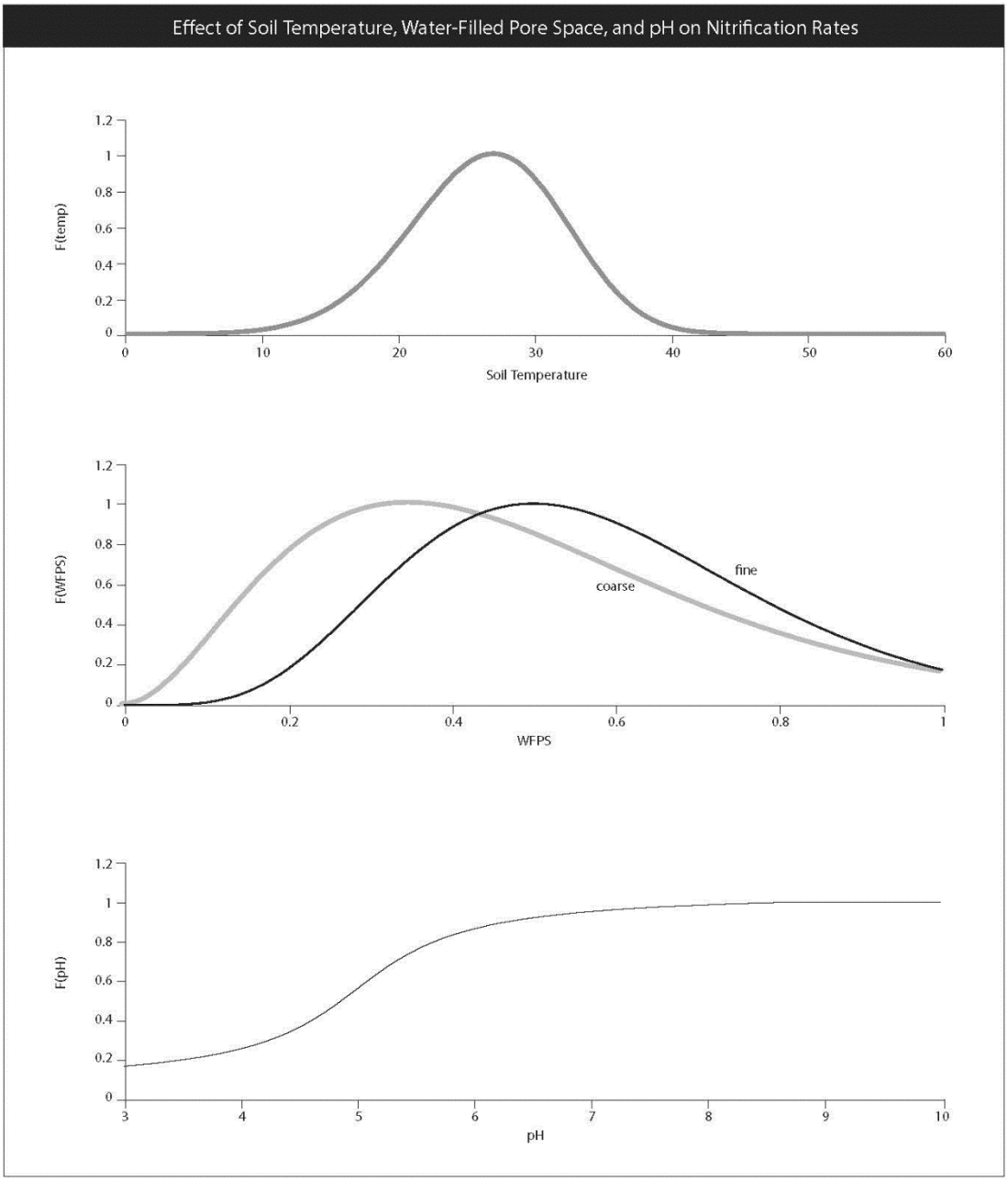
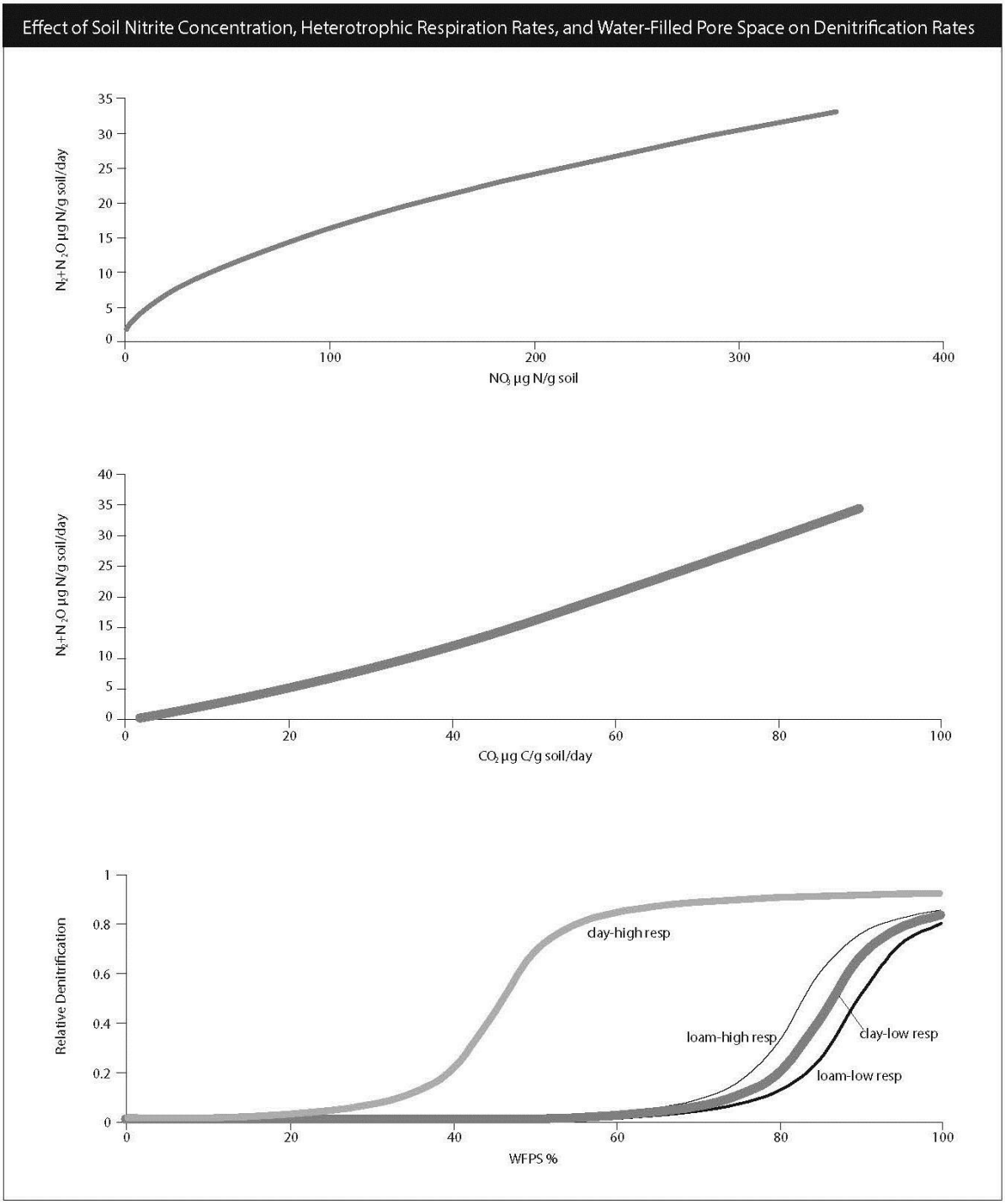


Figure A-10: Effect of Soil Nitrite Concentration (a), Heterotrophic Respiration Rates (b), and Water-Filled Pore Space (c) on Denitrification Rates



Comparison of model results and plot level data show that DAYCENT reliably simulates soil organic matter levels (Ogle et al. 2007). The model was tested and shown to capture the general trends in C storage across 908 treatment observations from 92 experimental sites (Figure A-11). Some bias and imprecision occur in predictions of soil organic C,

which is reflected in the uncertainty associated with DAYCENT model results. Regardless, the Tier 3 approach has considerably less uncertainty than Tier 1 and 2 methods (Del Grosso et al. 2010; Figure A-12).

Similarly, DAYCENT model results have been compared to trace gas N_2O fluxes for a number of native and managed systems (Del Grosso et al. 2001, 2005, 2010) (Figure A-13). In general, the model simulates accurate emissions, but some bias and imprecision does occur in predictions, which is reflected in the uncertainty associated with DAYCENT model results. Comparisons with measured data showed that DAYCENT estimated N_2O emissions more accurately and precisely than the IPCC Tier 1 methodology (IPCC 2006) (See Agricultural Soil Management, QA/QC and Verification Section). The linear regression of simulated vs. measured emissions for DAYCENT had higher r^2 values and a fitted line closer to a perfect 1:1 relationship between measured and modeled N_2O emissions compared to the IPCC Tier 1 approach (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_2O 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). Volatilization of N gases that contribute to indirect soil N_2O emissions is the only component that has not been thoroughly tested, which is due to a lack of measurement data. Overall, the Tier 3 approach has reduced uncertainties in the agricultural soil C stock changes and N_2O emissions compared to using lower Tier methods.

DAYCENT predictions of soil CH_4 emissions have also been compared to experimental measurements from sites in California, Texas, Arkansas and Louisiana (Figure A-14). There are 10 experiments and 126 treatment observations. In general, the model estimates CH_4 emissions in most states with no apparent bias, but there is a lack of precision, which is addressed in the uncertainty analysis. The exception is California where the model tends to over-estimate low emission rates, and this additional uncertainty is captured in the error propagation associated with the inventory analysis for California.

Figure A-11: Comparisons of Results from DAYCENT Model and Measurements of Soil Organic C Stocks

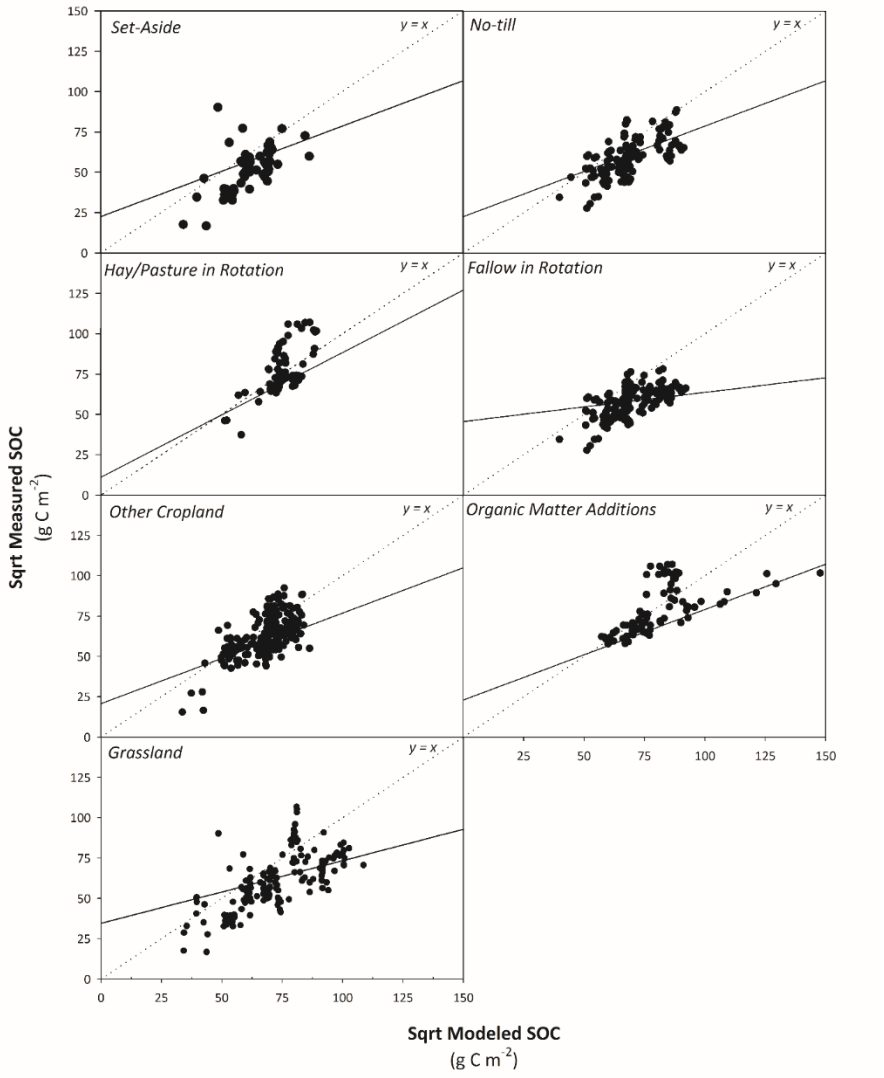


Figure A-12: Comparison of Estimated Soil Organic C Stock Changes and Uncertainties using Tier 1 (IPCC 2006), Tier 2 (Ogle et al. 2003, 2006) and Tier 3 Methods

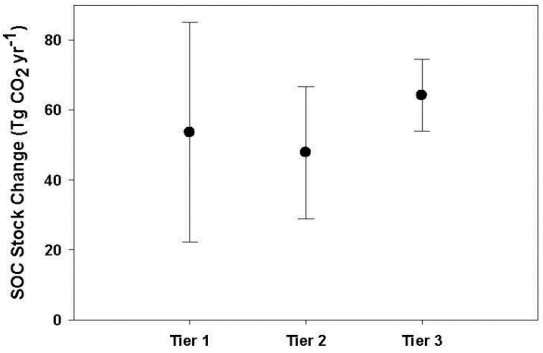


Figure A-13: Comparisons of Results from DAYCENT Model and Measurements of Soil Nitrous Oxide Emissions

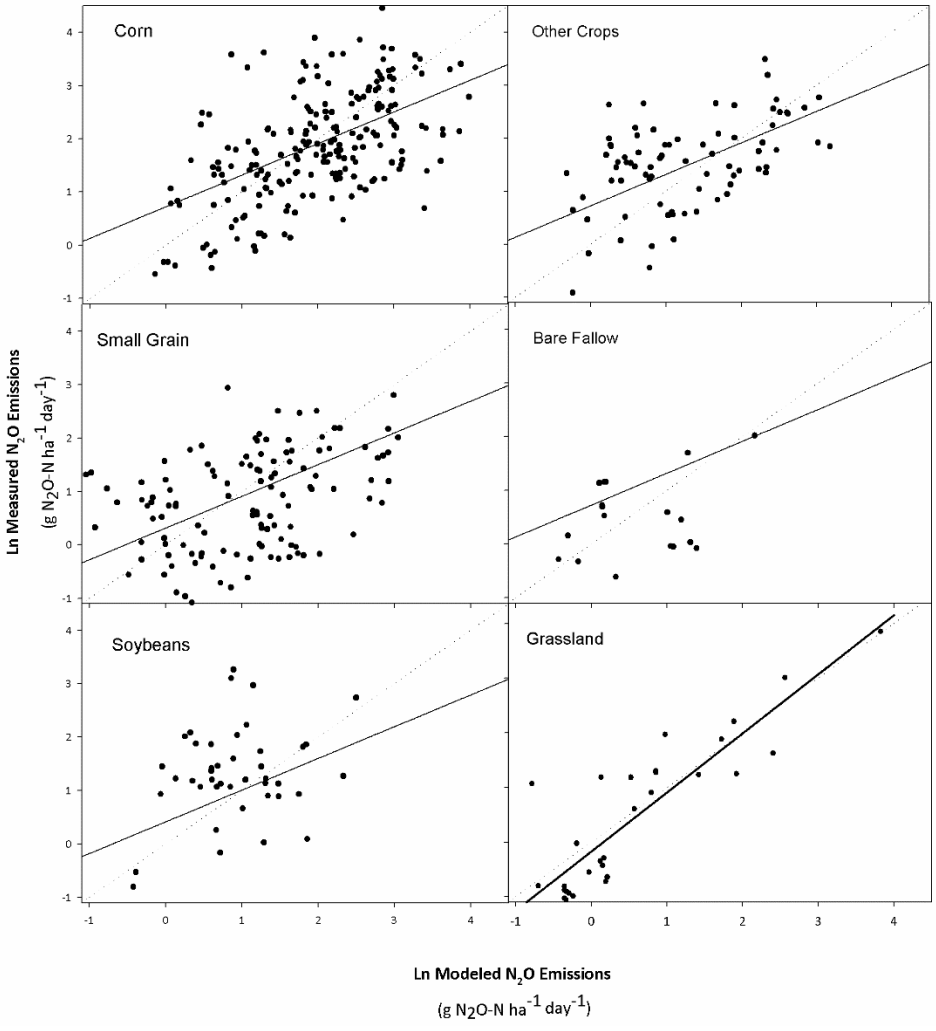
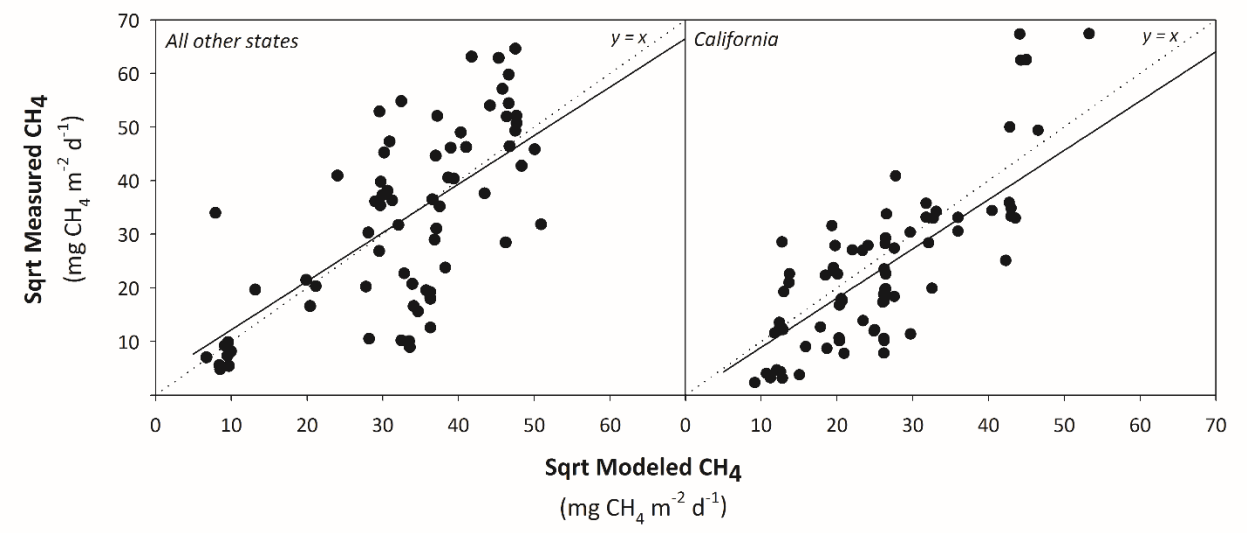


Figure A-14: Comparisons of Results from DAYCENT Model and Measurements of Soil Methane Emissions



Inventory Compilation Steps

There are five steps involved in estimating soil organic C stock changes for *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland* and *Land Converted to Grassland;* direct N_2O emissions from cropland and grassland soils; indirect N_2O emissions from volatilization, leaching, and runoff from croplands and grasslands; and CH_4 emissions from rice cultivation. 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, soil organic C stock changes, direct and indirect N_2O emissions are estimated using DAYCENT and/or the Tier 1 and 2 methods. In the fifth step, total emissions are computed by summing all components separately for soil organic C stock changes and N_2O emissions. The remainder of this annex describes the methods underlying each step.

Step 1: Derive Activity Data

The following describes how the activity data are derived to estimate soil organic C stock changes and direct and indirect N_2O emissions. The activity data requirements include: (1) land base and history data, (2) crop-specific mineral N fertilizer rates,[85] (3) crop-specific manure amendment N rates and timing, (4) other N inputs, (5) tillage practices, (6) irrigation data, (7) Enhanced Vegetation Index (EVI), (8) daily weather data, and (9) edaphic characteristics.[86]

Step 1a: Activity Data for the Agricultural Land Base and Histories

The U.S. Department of Agriculture's 2012 National Resources Inventory (NRI) (USDA-NRCS 2015) provides 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*. In 1998, the NRI program began collecting annual data, and data are currently available through 2012 (USDA-NRCS, 2015). The time series will be extended as new data are released by the USDA NRI program. Note that the Inventory does not include estimates of N_2O emissions for federal grasslands (with the exception of soil N_2O from PRP manure N, i.e., manure deposited directly onto pasture, range or paddock by grazing livestock) and a minor amount of croplands on federal lands.

The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the U.S. Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit, typically a 160-acre (64.75 ha) square quarter-section, three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land-use information (Nusser and Goebel 1997). In principle, the expansion factors represent the amount of area

[85] No data are currently available at the national scale to distinguish the type of fertilizer applied or timing of applications rates. It is a planned improvement to address variation in these practices in future inventories.

[86] Edaphic characteristics include such factors as water content, acidity, aeration, and the availability of nutrients.

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 uses a sampling approach, 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 (Nusser et al. 1998).[87] 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 2012, with the exception of 1983, 1988, and 1993. These years are gap-filled using an automated set of rules so that cropping sequences are filled with the most likely crop type given the historical cropping pattern at each NRI point location. Grassland data are reported on 5-year increments prior to 1998, but it is assumed that the land use is also grassland between the years of data collection (see Easter et al. 2008 for more information).

NRI points are included in the land base for the agricultural soil C and N_2O emissions inventories if they are identified as cropland or grassland[88] between 1990 and 2012 (Table A-193).[89] NRI does not provide land use data on federal lands, therefore land use on federal lands are derived from the National Land Cover Database (NLCD) (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). Federal NRI points classified as cropland or grassland according to the NLCD are included in the agricultural land base. The NRI data are reconciled with the Forest Inventory and Analysis Dataset, and in this process, the time series for *Grassland Remaining Grassland* and *Land Converted to Grassland* is modified to account for differences in forest land area between the two national surveys (See Section 6.1 for more information on the U.S. land representation). Overall, 674,613 NRI survey points are included in the inventory (USDA-NRCS 2013).

For each year, land parcels are 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 are classified as *Cropland Remaining Cropland* if the parcel has been used as cropland for at least 20 years[90]. Similarly land parcels under grassland management in a specific year of the inventory are classified as *Grassland Remaining Grassland* if they have been designated as grassland for at least 20 years. Otherwise, land parcels are 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 *2006 IPCC Guidelines*. Lands converted into Cropland and Grassland are further subdivided into the specific land use conversions (e.g., *Forest Land Converted to Cropland)*.

[87] In the current Inventory, NRI data only provide land-use and management statistics through 2010. More recent data will be incorporated in the future to extend the time series of land use and management data.

[88] Includes only non-federal lands because federal lands are not classified into land uses as part of the NRI survey (i.e., they are only designated as federal lands).

[89] Land use for 2011 to 2014 is assumed to be the same as 2010, but will be updated with newer NRI (i.e., USDA-NRCS 2015).

[90] NRI points are classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifications are based on less than 20 years from 1990 to 1998.

Table A-193: Total Land Areas for the Agricultural Soil C and N_2O Inventory, Subdivided by Land Use Categories (Million Hectares)

	Land Areas (million ha)														
Category	**1990**	**1995**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Mineral Soils	**421.74**	**418.34**	**414.32**	**410.79**	**410.09**	**409.44**	**408.83**	**408.29**	**407.70**	**407.18**	**406.59**	**406.36**	**406.13**	**405.89**
Croplands	**172.92**	**171.34**	**167.42**	**164.42**	**164.02**	**163.70**	**163.22**	**162.81**	**162.37**	**162.08**	**161.86**	**161.86**	**161.86**	**161.86**
Cropland Remaining Cropland	160.44	155.62	149.71	149.40	149.09	149.32	149.46	149.68	149.28	148.86	148.59	148.59	148.59	148.59
Grassland Converted to Cropland	11.79	14.95	16.92	14.43	14.33	13.82	13.25	12.66	12.63	12.75	12.80	12.80	12.80	12.80
Forest Converted to Cropland	0.28	0.23	0.17	0.10	0.09	0.09	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Other Lands Converted to Cropland	0.20	0.26	0.32	0.25	0.25	0.24	0.23	0.22	0.22	0.21	0.21	0.21	0.21	0.21
Settlements Converted to Croplands	0.08	0.09	0.10	0.09	0.09	0.09	0.08	0.07	0.08	0.08	0.09	0.09	0.09	0.09
Wetlands Converted to Croplands	0.14	0.19	0.20	0.17	0.17	0.15	0.13	0.11	0.11	0.12	0.12	0.12	0.12	0.12
Grasslands	**248.82**	**247.00**	**246.90**	**246.37**	**246.08**	**245.74**	**245.61**	**245.48**	**245.33**	**245.10**	**244.74**	**244.50**	**244.27**	**244.03**
Grasslands Remaining Grasslands	238.89	233.70	228.31	226.83	226.48	226.44	226.74	226.93	226.62	226.26	226.03	225.80	225.56	225.33
Croplands Converted to Grasslands	8.65	11.58	16.29	17.14	17.21	16.92	16.61	16.36	16.57	16.76	16.72	16.72	16.72	16.72
Forest Converted to Grasslands	0.57	0.58	0.81	0.76	0.72	0.68	0.63	0.62	0.60	0.59	0.57	0.57	0.57	0.57
Other Lands Converted to Grasslands	0.41	0.66	0.95	1.07	1.09	1.12	1.14	1.13	1.14	1.14	1.12	1.12	1.12	1.12
Settlements Converted to Grasslands	0.06	0.09	0.11	0.12	0.13	0.13	0.13	0.12	0.12	0.12	0.13	0.13	0.13	0.13
Wetlands Converted to Grasslands	0.24	0.40	0.43	0.44	0.44	0.44	0.37	0.31	0.27	0.23	0.17	0.17	0.17	0.17
Organic Soils	**1.43**	**1.43**	**1.32**	**1.40**	**1.38**	**1.37**	**1.36**	**1.37**	**1.36**	**1.33**	**1.33**	**1.32**	**1.33**	**1.33**
Croplands	**0.73**	**0.73**	**0.63**	**0.73**	**0.73**	**0.72**	**0.71**	**0.72**	**0.71**	**0.68**	**0.69**	**0.69**	**0.69**	**0.69**
Cropland Remaining Cropland	0.66	0.64	0.54	0.64	0.64	0.64	0.63	0.64	0.64	0.61	0.61	0.61	0.61	0.61
Grassland Converted to Cropland	0.06	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.07	0.07	0.07	0.07
Forest Converted to Cropland	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Lands Converted to Cropland	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Settlements Converted to Croplands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wetlands Converted to Croplands	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Grasslands	**0.70**	**0.70**	**0.69**	**0.67**	**0.65**	**0.65**	**0.65**	**0.65**	**0.65**	**0.65**	**0.64**	**0.64**	**0.64**	**0.64**
Grasslands Remaining Grasslands	0.64	0.61	0.58	0.53	0.52	0.51	0.51	0.51	0.50	0.50	0.49	0.49	0.49	0.49
Croplands Converted to Grasslands	0.05	0.06	0.08	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Forest Converted to Grasslands	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Other Lands Converted to Grasslands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Settlements Converted to Grasslands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wetlands Converted to Grasslands	0.01	0.02	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Total	**423.18**	**419.77**	**415.64**	**412.19**	**411.48**	**410.81**	**410.19**	**409.66**	**409.06**	**408.51**	**407.92**	**407.69**	**407.45**	**407.22**

Note: The area estimates are not consistent with the land area values shown in the Representation of the U.S. Land Base chapter because the current Inventory does not estimate emissions and removals for all managed lands. Specifically, grassland and cropland in Alaska are not included in the current Inventory.

The Tier 3 method using the DAYCENT model is applied to estimate soil C stock changes and N_2O emissions for most of the NRI points that occur on mineral soils. For the Tier 3 inventory, the actual crop and grassland histories are simulated with the DAYCENT model. Parcels of land that are not simulated with DAYCENT are allocated to the Tier 2 approach for estimating soil organic C stock change, and a Tier 1 method (IPCC 2006) to estimate soil N_2O emissions (Table A-194) (Note: the Tier 1 method for soil N_2O does not require land area data with the exception of emissions from drainage and cultivation of organic soils, so in practice it is only the amount of N input to mineral soils that is addressed by the Tier 1 method and not the actual land area).

The land base for the Tier 1 and 2 methods includes (1) land parcels occurring on organic soils; (2) land parcels that include non-agricultural uses such as forest and federal lands in one or more years of the inventory; (3) land parcels on mineral soils that are 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 are used to produce some of the vegetable crops, perennial/horticultural crops, and tobacco, which are either grown continuously or in rotation with other crops. DAYCENT has not been fully tested or developed to simulate biogeochemical processes in soils used to produce some annual (e.g., tobacco), horticultural (e.g., flowers), or perennial (e.g., vineyards, orchards) crops and agricultural use of organic soils. In addition, DAYCENT has not been adequately tested for soils with a high gravel, cobble, or shale content.

Table A-194: Total Land Area Estimated with Tier 2 and 3 Inventory Approaches (Million Hectares)

	Land Areas (million ha)				
	Mineral			Organic	
Year	Tier 1/2	Tier 3	Total	Tier 1/2	Total
1990	106.49	315.25	421.74	1.43	423.18
1991	105.49	315.54	421.03	1.42	422.45
1992	104.55	315.86	420.41	1.41	421.82
1993	103.40	316.34	419.74	1.42	421.16
1994	102.30	316.81	419.11	1.43	420.54
1995	101.02	317.33	418.34	1.43	419.77
1996	99.68	317.78	417.45	1.42	418.88
1997	98.34	318.26	416.61	1.42	418.02
1998	96.96	318.77	415.72	1.42	417.15
1999	95.63	319.30	414.93	1.33	416.26
2000	94.65	319.66	414.32	1.32	415.64
2001	93.80	320.00	413.79	1.41	415.20
2002	92.97	320.32	413.29	1.42	414.71
2003	92.14	320.30	412.44	1.41	413.85
2004	91.47	320.31	411.78	1.41	413.18
2005	90.53	320.27	410.79	1.40	412.19
2006	89.87	320.23	410.09	1.38	411.48
2007	89.24	320.20	409.44	1.37	410.81
2008	88.83	320.00	408.83	1.36	410.19
2009	88.45	319.84	408.29	1.37	409.66
2010	88.05	319.65	407.70	1.36	409.06
2011	87.60	319.57	407.18	1.33	408.51
2012	87.26	319.34	406.59	1.33	407.92
2013	87.14	319.22	406.36	1.32	407.69
2014	87.03	319.09	406.13	1.33	407.45
2015	86.92	318.97	405.89	1.33	407.22

NRI points on mineral soils are classified into specific crop categories, continuous pasture/rangeland, and other non-agricultural uses for the Tier 2 inventory analysis (Table A-195). NRI points are assigned to IPCC input categories (low, medium, high, and high with organic amendments) according to the classification provided in IPCC (2006). For croplands on federal lands, information on specific cropping systems is not available, so all croplands are assumed to be medium input. In addition, NRI differentiates between improved and unimproved grassland, where improvements include irrigation and interseeding of legumes. Grasslands on federal lands (as identified with the NLCD) are classified according to rangeland condition (nominal, moderately degraded and severely degraded) in areas where information is available. For lands managed for livestock grazing by the Bureau of Land Management (BLM), IPCC rangeland condition classes are interpreted at the state-level from the Rangeland Inventory, Monitoring and Evaluation Report (BLM 2014). In order to estimate uncertainties, probability distribution functions (PDFs) for the NRI land-use data are 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 are taken into account resulting from the likelihood that current use is correlated with past use. These dependencies occur because as some land use/management categories increase in area, the area of other land use/management categories will decline. The covariance matrix addresses these relationships.

Table A-195: Total Land Areas by Land-Use and Management System for the Tier 2 Mineral Soil Organic C Approach (Million Hectares)

	Land Areas (million hectares)													
Land-Use/Management System	**1990**	**1995**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Cropland Systems	**22.42**	**20.48**	**17.93**	**16.57**	**16.40**	**16.22**	**16.13**	**16.00**	**15.90**	**15.78**	**15.73**	**15.73**	**15.73**	**15.73**
Conservation Reserve Program	1.98	1.90	1.14	0.76	0.75	0.73	0.69	0.68	0.66	0.61	0.55	0.55	0.55	0.55
High Input Cropping Systems, Full Tillage	1.42	0.88	0.69	0.57	0.55	0.53	0.54	0.55	0.53	0.53	0.51	0.51	0.51	0.51
High Input Cropping Systems, Reduced Tillage	1.00	1.27	1.12	0.93	0.91	0.88	0.90	0.91	0.88	0.88	0.86	0.86	0.86	0.86
High Input Cropping Systems, No Tillage	0.10	0.10	0.18	0.21	0.20	0.19	0.19	0.19	0.19	0.19	0.18	0.18	0.18	0.18
High Input Cropping Systems with Manure, Full Tillage	0.10	0.07	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
High Input Cropping Systems with Manure, Reduced Tillage	0.08	0.10	0.09	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06
High Input Cropping Systems with Manure, No Tillage	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Medium Input Cropping Systems, Full Tillage	5.31	3.47	2.01	2.00	1.98	1.98	1.98	1.98	1.97	1.97	1.97	1.97	1.97	1.97
Medium Input Cropping Systems, Reduced Tillage	4.32	4.83	4.97	4.42	4.38	4.39	4.39	4.39	4.38	4.38	4.39	4.39	4.39	4.39
Medium Input Cropping Systems, No Tillage	0.34	0.43	0.79	0.96	0.95	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Low Input Cropping Systems, Full Tillage	2.91	2.63	2.18	1.74	1.74	1.69	1.66	1.56	1.55	1.51	1.55	1.55	1.55	1.55
Low Input Cropping Systems, Reduced Tillage	0.07	0.27	0.38	0.44	0.43	0.42	0.41	0.38	0.38	0.37	0.39	0.39	0.39	0.39
Low Input Cropping Systems, No Tillage	0.02	0.04	0.08	0.25	0.25	0.24	0.24	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Hay with Legumes or Irrigation	1.23	1.07	0.76	0.75	0.73	0.73	0.72	0.68	0.70	0.66	0.66	0.66	0.66	0.66
Hay with Legumes or Irrigation and Manure	0.06	0.06	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Hay, Unimproved	0.71	0.62	0.53	0.50	0.49	0.50	0.48	0.47	0.46	0.46	0.46	0.46	0.46	0.46
Pasture with Legumes or Irrigation in Rotation	2.42	2.43	2.55	2.56	2.56	2.52	2.51	2.57	2.56	2.58	2.57	2.57	2.57	2.57
Pasture with Legumes or Irrigation and Manure, in Rotation	0.14	0.15	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Rice	0.17	0.16	0.19	0.16	0.14	0.13	0.14	0.12	0.14	0.14	0.13	0.13	0.13	0.13
Grassland Systems	**84.07**	**80.54**	**76.72**	**73.96**	**73.47**	**73.02**	**72.70**	**72.45**	**72.16**	**71.82**	**71.53**	**71.41**	**71.30**	**71.19**
Pasture with Legumes or Irrigation	5.59	4.82	3.64	3.17	3.09	2.98	2.90	2.90	2.81	2.76	2.73	2.72	2.72	2.72

Pasture with Legumes or Irrigation and Manure	0.17	0.15	0.10	0.08	0.08	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06
Rangelands and Unimproved Pasture	47.71	45.56	43.10	42.19	41.96	41.66	41.52	41.32	41.29	41.07	40.87	40.83	40.78	40.74
Rangelands and Unimproved Pasture, Moderately Degraded	22.07	22.16	22.29	20.76	20.64	20.69	20.63	20.62	20.52	20.48	20.43	20.39	20.34	20.30
Rangelands and Unimproved Pasture, Severely Degraded	8.52	7.85	7.60	7.77	7.70	7.62	7.58	7.54	7.47	7.45	7.43	7.41	7.39	7.37
Total	**106.49**	**101.02**	**94.65**	**90.53**	**89.87**	**89.24**	**88.83**	**88.45**	**88.05**	**87.60**	**87.26**	**87.14**	**87.03**	**86.92**

Organic soils are categorized into land-use systems based on drainage (IPCC 2006). Undrained soils are treated as having no loss of organic C or soil N_2O emissions. Drained soils are subdivided into those used for cultivated cropland, which are assumed to have high drainage and relatively large losses of C, and those used for managed pasture, which are assumed to have less drainage with smaller losses of C. Nitrous oxide emissions are assumed to be similar for both drained croplands and grasslands. Overall, the area of organic soils drained for cropland and grassland has remained relatively stable since 1990 (see Table A-196).

Table A-196: Total Land Areas for Drained Organic Soils by Land Management Category and Climate Region (Million Hectares)

IPCC Land-Use Category for Organic Soils	Land Areas (million ha)													
	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cold Temperate														
Cultivated Cropland (high drainage)	0.43	0.42	0.41	0.41	0.40	0.41	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41
Managed Pasture (low drainage)	0.47	0.48	0.46	0.47	0.47	0.46	0.46	0.46	0.46	0.45	0.44	0.44	0.44	0.45
Undrained	0.05	0.04	0.04	0.02	0.03	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02
Total	**0.95**	**0.94**	**0.92**	**0.90**	**0.90**	**0.89**	**0.89**	**0.88**	**0.88**	**0.88**	**0.87**	**0.87**	**0.87**	**0.87**
Warm Temperate														
Cultivated Cropland (high drainage)	0.10	0.10	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Managed Pasture (low drainage)	0.09	0.09	0.10	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Undrained	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	**0.21**	**0.20**	**0.20**	**0.21**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**	**0.19**
Sub-Tropical														
Cultivated Cropland (high drainage)	0.20	0.21	0.13	0.22	0.22	0.21	0.21	0.22	0.22	0.18	0.18	0.18	0.18	0.18
Managed Pasture (low drainage)	0.14	0.13	0.13	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Undrained	0.00	0.00	0.09	0.01	0.01	0.01	0.02	0.00	0.00	0.03	0.03	0.03	0.03	0.03
Total	**0.34**	**0.34**	**0.34**	**0.33**	**0.33**	**0.33**	**0.32**	**0.32**	**0.32**	**0.32**	**0.32**	**0.32**	**0.32**	**0.32**

The harvested rice cultivation area is estimated based on the NRI points classified as flooded rice (Table A-197). Ratoon crops occurs in the Southeast with a second season of rice during the year. Ratoon cropping occurs in Louisiana (LSU 2015 for years 2000 through 2013, 2015) and Texas (TAMU 2015 for years 1993 through 2014), averaging 32 percent and 48 percent of rice acres planted, respectively. Florida also has a large fraction of area with a ratoon crop (45 percent), and ratoon cropping occurs in Arkansas on relatively small fraction of fields estimated at about 1 percent. No data are available about ratoon crops in Missouri or Mississippi, and so amount of ratooning is assumed to be similar to Arkansas. Ratoon rice crops are not grown in California.

Table A-197: Total Rice Harvested Area Estimated with Tier 1 and 3 Inventory Approaches (Million Hectares)

	Land Areas (Million Hectares)[9]		
Year	Tier 1	Tier 3	Total
1990	0.16	1.54	1.70
1991	0.16	1.60	1.76
1992	0.17	1.67	1.84
1993	0.17	1.63	1.80
1994	0.17	1.53	1.70
1995	0.15	1.56	1.71
1996	0.15	1.56	1.72
1997	0.15	1.52	1.67
1998	0.17	1.43	1.60
1999	0.31	1.49	1.80
2000	0.33	1.51	1.84
2001	0.18	1.44	1.62
2002	0.18	1.60	1.79
2003	0.15	1.47	1.62
2004	0.17	1.53	1.69
2005	0.18	1.65	1.83
2006	0.14	1.33	1.48
2007	0.12	1.45	1.57
2008	0.14	1.27	1.41
2009	0.14	1.57	1.71
2010	0.15	1.61	1.76
2011	0.13	1.32	1.45
2012	0.11	1.18	1.29
2013	0.11	1.18	1.29
2014	0.11	1.18	1.29
2015	0.11	1.18	1.29

Note: Land use data for 2013 through 2015 are based on the 2012 NRI data product.

Step 1b: Obtain Management Activity Data for the Tier 3 Method to estimate Soil C Stock Changes, CH_4 and N_2O Emissions from Mineral Soils

Synthetic N Fertilizer Application: Data on N fertilizer rates are based primarily on the USDA–Economic Research Service Cropping Practices Survey through 1995 (USDA-ERS 1997), which became the Agricultural Resource Management Surveys (ARMS) in 1996 (USDA-ERS 2015)[91]. In these surveys, data on inorganic N fertilization rates are collected for crops simulated by DAYCENT (barley, corn, cotton, dry beans, hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat) in the high production states and for a subset of low production states. These data are used to build a time series of fertilizer application rates for specific crops and states for the 1990 through 1999 time period and 2000 through 2015 time period. If only a single survey is available for a crop, as is the case with sorghum, the rates for the one survey are used for both time periods.

Mean fertilizer rates and standard deviations for irrigated and rainfed crops are produced for each state. If a state is not surveyed for a particular crop or if there are not enough data to produce a state-level estimate, then data are aggregated to USDA 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 are not available, crop data are aggregated to the entire United States (all major states surveyed) to estimate a

[91] Available online at <http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/arms-data.aspx>

mean and standard deviation. Standard deviations for fertilizer rates are used to construct PDFs with log-normal densities in order to address uncertainties in application rates (see Step 2a for discussion of uncertainty methods). The survey summaries also present estimates for fraction of crop acres receiving fertilizer, and these fractions are used to determine if a crop is receiving fertilizer. Alfalfa hay and grass-clover hay are assumed to not be fertilized, but grass hay is fertilized according to rates from published farm enterprise budgets (NRIAI 2003). Total fertilizer application data are found in Table A-198.

Simulations are conducted for the period prior to 1990 in order to initialize the DAYCENT model (see Step 2a), and crop-specific regional fertilizer rates prior to 1990 are based largely on extrapolation/interpolation of fertilizer rates from the years with available data. For crops in some states, little or no data are available, and, therefore, a geographic regional mean is used to simulate N fertilization rates (e.g., no data are available for the State of Alabama during the 1970s and 1980s for corn fertilization rates; therefore, mean values from the southeastern United States are used to simulate fertilization to corn fields in this state).

Managed Livestock Manure Amendments:[92] County-level manure addition estimates have been derived from manure N addition rates developed by the USDA Natural Resources Conservation Service (NRCS) (Edmonds et al. 2003). Working with the farm-level crop and animal data from the 1997 Census of Agriculture, USDA-NRCS has coupled estimates of manure N produced with estimates of manure N recoverability by animal waste management system to produce county-level rates of manure N application to cropland and pasture. Edmonds et al. (2003) defined a hierarchy that included 24 crops, permanent pasture, and cropland used as 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 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. The estimates were based on 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. In order to address uncertainty in these data, uniform probability distributions are 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 is 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 is 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 is divided by the manure N available in 1997. If the ratio is greater than 1, there is more manure N available in that county relative to the amount in 1997, and so it is assumed a larger area is amended with manure. In contrast, ratios less than one imply less area is amended with manure because there is a lower amount available in the year compared to 1997. The amendment area in each county for 1997 is 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 is calculated by determining the populations of livestock on feedlots or otherwise housed, requiring collection and management of the manure. The methods are described in the Manure Management section (Section 5.2) and annex (Annex 3.11). The total managed manure N applied to soils is found in Table A-199.

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 are 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 are 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 is used to determine the associated C input for crop amendments derived from Edmonds et al. (2003).

[92] 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 drylots, 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.

To account for the common practice of reducing inorganic N fertilizer inputs when manure is added to a cropland soil, crop-specific reduction factors are derived from mineral fertilization data for land amended with manure versus land not amended with manure in the ERS 1995 Cropping Practices Survey (USDA-ERS 1997). Mineral N fertilization rates are reduced for crops receiving manure N based on a fraction of the amount of manure N applied, depending on the crop and whether it is irrigated or rainfed. The reduction factors are randomly selected from PDFs with normal densities in order to address uncertainties in the dependence between manure amendments and mineral fertilizer application.

PRP Manure N: Another key source of N for grasslands is PRP manure N deposition (i.e., manure deposited by grazing livestock). The total amount of PRP manure N is estimated using methods described in the Manure Management section (Section 5.2) and annex (Annex 3.11). Nitrogen from PRP animal waste deposited on non-federal grasslands in a county is generated by multiplying the total PRP N (based on animal type and population data in a county) by the fraction of non-federal grassland area in the county. PRP manure N input rates for the Tier 3 DAYCENT simulations are estimated by dividing the total PRP manure N amount by the land area associated with non-federal grasslands in the county from the NRI survey data. The total PRP manure N added to soils is found in Table A-199.

Residue N Inputs: Crop residue N, fixation by legumes, and N residue inputs from senesced grass litter are included as sources of N to the soil, and are estimated in the DAYCENT simulations as a function of vegetation type, weather, and soil properties. 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" as it is not a model input. The simulated total N inputs of above- and below-ground residue N and fixed N that is not harvested and not burned (the DAYCENT simulations assumed that 3 percent of non-harvested above ground residues for crops are burned[93]) are provided in Table A-200.

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. Mineralization of soil organic matter will also include the effect of land use change on this process as recommended by the IPCC (2006). 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 the IPCC (2006). The simulated N input from residues, soil organic matter mineralization and asymbiotic N fixation are provided in Table A-200.

Tillage Practices: Tillage practices are estimated for each cropping system based on data from the Conservation Technology Information Center[94] (CTIC 2004). 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 are provided by experts at CTIC to account for intermittent tillage activity and its impact on soil C (Towery 2001).

Tillage practices are grouped into three categories: full, reduced, and no-tillage. Full tillage is 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 (2004). No-till is 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 are derived from the 1995 Cropping Practices Survey by the Economic Research Service (USDA-ERS 1997).

Tillage data are further processed to construct PDFs. Transitions between tillage systems are 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 are modeled and applied to NRI points occurring within a county are full tillage to reduced and no-till, and reduced tillage to no-till. The remaining amount of cropland is assumed to have no change in tillage (e.g., full tillage remained in full tillage). Transition matrices are constructed from CTIC data to represent tillage changes for three time periods, 1980 through 1989, 1990 through 1999, and 2000 through 2015. Areas in each of the three tillage

[93] Another improvement is to reconcile the amount of crop residues burned with the *Field Burning of Agricultural Residues* source category (Section 5.5).

[94] National scale tillage data are no longer collected by CTIC, and a new data source will be needed, which is a planned improvement.

classes—full till (FT), reduced till (RT), no-till (NT)—in 1989 (the first year the CTIC data are available) are used for the first time period, data from 1997 are used for the second time period, and data from 2004 are used for the last time period. Percentage areas of cropland in each county are 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. It is assumed that there are no transitions for NT→FT or NT→NT after accounting for NT systems that have intermittent tillage. Uniform probability distributions are 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 is 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 is greater than or equal to 0 and less than 80, a transition from full to reduced till if the random draw is equal to or greater than 80 and less than 95, or a transition from full to no-till if the draw is greater than or equal to 95. See step 2b for additional discussion of the uncertainty analysis.

Irrigation: NRI (USDA-NRCS 2015) differentiates between irrigated and non-irrigated land, but does not provide more detailed information on the type and intensity of irrigation. Hence, irrigation is modeled by assuming that applied water to field capacity with intervals between irrigation events where the soils drain to about 60 percent of field capacity.

Daily Weather Data: Daily maximum/minimum temperature and precipitation data are based on gridded weather data from the PRISM Climate Group (2015). It is necessary to use computer-generated weather data because weather station data do not exist near all NRI points, and moreover weather station data are for a point in space. The PRISM product uses this information with interpolation algorithms to derive weather patterns for areas between these stations (Daly et al. 1998). PRISM weather data are available for the U.S. from 1981 through 2012 at a 4 km resolution. Each NRI point is assigned the PRISM weather data for the grid cell containing the point.

Enhanced Vegetation Index: The Enhanced Vegetation Index (EVI) from the MODIS vegetation products, (MOD13Q1 and MYD13Q1) is an input to DAYCENT for estimating net primary production using the NASA-CASA production algorithm (Potter et al. 1993, 2007). MODIS imagery is collected on a nominal 8 day-time frequency when combining the two products. A best approximation of the daily time series of EVI data is derived using a smoothing process based on the Savitzky-Golay Filter (Savitzky and Golay 1964) after pre-screening for outliers and for cloud-free, high quality data as identified in the MODIS data product quality layer. The NASA-CASA production algorithm is only used for the following crops: corn, soybeans, sorghum, cotton, wheat and other close-grown crops such as barley and oats.[95]

The MODIS EVI products have a 250 m spatial resolution, and some pixels in images have mixed land uses and crop types at this resolution, which is problematic for estimating NPP associated with a specific crop at a NRI point. Therefore, a threshold of 90 percent purity in an individual pixel is the cutoff for estimating NPP using the EVI data derived from the imagery (i.e., pixels with less than 90 percent purity for a crop are assumed to generate bias in the resulting NPP estimates). The USDA-NASS Crop Data Layer (CDL) (Johnson and Mueller 2010) is used to determine the purity levels of the EVI data. CDL data have a 30 to 58 m spatial resolution, depending on the year. The level of purity for individual pixels in the MODIS EVI products is determined by aggregating the crop cover data in CDL to the 250m resolution of the EVI data. In this step, the percent cover of individual crops is determined for the 250m EVI pixels. Pixels that did not meet a 90 percent purity level for any crop are eliminated from the dataset. CDL did not provide full coverage of crop maps for the conterminous United States until 2009 so it is not possible to evaluate purity for the entire cropland area prior to 2009. The nearest pixel with at least 90 percent purity for a crop is assigned to the NRI point based on a 10 km buffer surrounding the survey location. EVI data are not assigned to a point if there are no pixels with at least 90 percent purity within the 10 km buffer. In these cases, production is simulated with a single value for the maximum daily NPP, which is reduced if there is water, temperature or nutrient stress affecting the plants growth.

Water Management for Rice Cultivation: While rice crop production in the U.S. includes a minor amount of land with mid-season drainage or alternate wet-dry periods, the majority of rice growers use continuously flooded water management systems (Hardke 2015; UCCE 2015; Hollier 1999; Way et al. 2014). Therefore, continuous flooding is applied to all rice cultivation areas in the Inventory. Winter flooding is another key practice associated with water management in rice fields. Winter flooding occurs on 34 percent of rice fields in California (Miller et al. 2010; Fleskes et al. 2005), and approximately 21 percent of the fields in Arkansas (Wilson and Branson 2005 and 2006; Wilson and Runsick 2007 and 2008; Wilson et al. 2009 and 2010; Hardke and Wilson 2013 and 2014; Hardke 2015). No data are available on winter flooding for Texas, Louisiana, Florida, Missouri, or Mississippi. For these states, the average amount of flooding is assumed

[95] Additional crops and grassland will be used with the NASA-CASA method in the future, as a planned improvement.

to be similar to Arkansas. In addition, the amount of winter flooding is assumed to be relatively constant over the Inventory time period.

Organic Amendments for Rice Cultivation: Rice straw is not typically harvested from fields in the U.S. The C input from rice straw is simulated directly within the DAYCENT model for the Tier 3 method. For the Tier 1 method, residue inputs are assumed to be left on the field for more than 30 days prior to cultivation and flooding for the next crop, with the exception of ratoon crops, which are assumed to have residues on the field for less than 30 days prior to the next crop. To estimate the amount of rice straw, crop yield data (except rice in Florida) are compiled from USDA NASS QuickStats (USDA 2015). Rice yield data for Florida are estimated separately because yield data are not collected by USDA. Total rice production for Florida is determined using NRI crop areas, and total yields are based on average primary and ratoon rice yields from Deren (2002). Relative proportions of ratoon crops are derived from information in several publications (Schueneman 1997, 1999, 2000, 2001; Deren 2002; Kirstein 2003, 2004, 2006; Cantens 2004, 2005; Gonzalez 2007 through 2014). The yields are multiplied by residue: crop product ratios from Strehler and Stützle (1987), to estimate rice straw input amounts for the Tier 1 method.

Soil Properties: Soil texture and natural drainage capacity (i.e., hydric vs. non-hydric soil characterization) are the main soil variables used as input to the DAYCENT model. Texture is one of the main controls on soil C turnover and stabilization in the DAYCENT model, which uses particle size fractions of sand (50-2,000 μm), silt (2-50 μm), and clay (<2 μm) as inputs. Hydric condition are poorly-drained, and hence prone to have a high water table for part of the year in their native (pre-cultivation) condition , Non-hydric soils are moderately to well-drained .[96] 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 function that varies from 0.3 under completely anaerobic conditions to 1.0 under fully aerobic conditions (default parameters in DAYCENT).[97] Other soil characteristics needed in the simulation, such as field capacity and wilting-point water contents, are estimated from soil texture data using a standardized hydraulic properties calculator (Saxton et al. 1986). Soil input data are derived from Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2015). The data are based on field measurements collected as part of soil survey and mapping. Each NRI point is assigned the dominant soil component in the polygon containing the point from the SSURGO data product.

Step 1c: Obtain Additional Management Activity Data for the Tier 1 Method to estimate Soil N_2O Emissions from Mineral Soils

Synthetic N Fertilizer: A process-of-elimination approach is used to estimate synthetic N fertilizer additions to crops in the Tier 1 method. The total amount of fertilizer used on-farms has been estimated by the USGS from 1990 through 2001 on a county scale from fertilizer sales data (Ruddy et al. 2006). For 2002 through 2015, county-level fertilizer used on-farms is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 1995 through 2007; AAPFCO 2008 through 2016). The fertilizer consumption data are recorded in "fertilizer year" totals, (i.e., July to June), but are converted to calendar year totals. This is done by assuming that approximately 35 percent of fertilizer usage occurred from July to December and 65 percent from January to June (TVA 1992b). Values for July to December are not available for calendar years 2013 through 2015 so a "least squares line" statistical extrapolation using the previous 5 years of data is used to arrive at an approximate value for 2013 through 2015. Fertilizer application data are available for crops and grasslands simulated by DAYCENT (discussed in Step 1a section for Tier 3). Thus, the amount of N applied to crops in the Tier 1 method (i.e., not simulated by DAYCENT) is assumed to be the remainder of the fertilizer used on farms after subtracting the amount applied to crops and non-federal grasslands simulated by DAYCENT. The differences are aggregated to the state level, and PDFs are derived based on uncertainties in the amount of N applied to crops and non-federal grasslands for the Tier 3 method. Total fertilizer application to crops in the Tier 1 method is found in Table A-201.

Managed Livestock Manure and Other Organic Amendments: Manure N that is not applied to crops and grassland simulated by DAYCENT is assumed to be applied to other crops that are included in the Tier 1 method. Estimates of total national annual N additions from other commercial organic fertilizers are derived from organic fertilizer statistics (TVA 1991 through 1994; AAPFCO 1995 through 2016). Commercial organic fertilizers include dried blood, tankage, compost, and other; dried manure and sewage sludge that are used as commercial fertilizer are 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

[96] Artificial drainage (e.g., ditch- or tile-drainage) is simulated as a management variable.

[97] 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 DAYCENT model.

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 content of 0.5 percent (AAPFCO 2000). Similar to the data for synthetic fertilizers described above, the organic fertilizer consumption data are recorded in "fertilizer year" totals, (i.e., July to June), but are converted to calendar year totals. This is done by assuming that approximately 35 percent of fertilizer usage occurred from July to December and 65 percent from January to June (TVA 1992b). Values for July to December are not available for calendar year 2013 through 2015 so a "least squares line" statistical extrapolation using the previous 5 years of data is used to arrive at an approximate value for 2013 through 2015. PDFs are derived for the organic fertilizer applications assuming a default ±50 percent uncertainty. Annual consumption of other organic fertilizers is presented in Table A-10. The fate of manure N is summarized in Table A-199.

PRP Manure N: Soil N_2O emissions from PRP manure N deposited on federal grasslands are estimated with a Tier 1 method. PRP manure N data are derived using methods described in the Manure Management section (Section 5.2) and Annex 3.11. PRP N deposited on federal grasslands is calculated using a process of elimination approach. The amount of PRP N generated by DAYCENT model simulations of non-federal grasslands was subtracted from total PRP N and this difference was assumed to be applied to federal grasslands. The total PRP manure N added to soils is found in Table A-199.

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 are derived from national data on sewage sludge generation, disposition, and N content. Total sewage sludge generation data for 1990 through 2004, in dry mass units, are obtained from AAPFCO (1995 through 2004). Values for 2005 through 2015 were not available so a "least squares line" statistical extrapolation using the previous 16 years of data was used to arrive at an approximate value. The total sludge generation estimates are then converted to units of N by applying an average N content of 69 percent (AAPFCO 2000), and disaggregated into use and disposal practices using historical data in EPA (1993) and NEBRA (2007). The use and disposal practices are agricultural land application, other land application, surface disposal, incineration, landfilling, ocean dumping (ended in 1992), and other disposal methods. The resulting estimates of sewage sludge N applied to agricultural land are used to estimate N_2O emissions from agricultural soil management; the estimates of sewage sludge N applied to other land and surface-disposed are used in estimating N_2O fluxes from soils in Settlements Remaining Settlements (see section 6.9 of the Land Use, Land-Use Change, and Forestry chapter). Sewage sludge disposal data are provided in

Table A-203.

Residue N Inputs: Soil N_2O emissions for residue N inputs from croplands that are not simulated by DAYCENT are estimated with a Tier 1 method. Annual crop production statistics for all major commodity and specialty crops are taken from U.S. Department of Agriculture crop production reports (USDA-NASS 2015). Total production for each crop is converted to tons of dry matter product using the residue dry matter fractions shown in Table A-204. Dry matter yield is then converted to tons of above- and below-ground biomass N. Above-ground biomass is calculated by using linear equations to estimate above-ground biomass given dry matter crop yields, and below-ground biomass is calculated by multiplying above-ground biomass by the below-to-above-ground biomass ratio. N inputs are estimated by multiplying above- and below-ground biomass by respective N concentrations and by the portion of cropland that was not simulated by DAYCENT. All ratios and equations used to calculate residue N inputs are from IPCC (2006) and Williams (2006). PDFs are derived assuming a ±50 percent uncertainty in the yield estimates (USDA-NASS does not provide uncertainty), along with uncertainties provided by the IPCC (2006) for dry matter fractions, above-ground residue, ratio of below-ground to above-ground biomass, and residue N fractions. The resulting annual residue N inputs are presented in Table A-205.

Step 1d: Obtain Additional Management Activity Data for the Tier 2 Method to estimate Soil C Stock Changes in Mineral Soils

Tillage Practices: For the Tier 2 method that is used to estimate soil organic C stock changes, PDFs are constructed for the CTIC tillage data (CTIC 2004) as bivariate normal on a log-ratio scale to reflect negative dependence among tillage classes. This structure ensured that simulated tillage percentages are 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) are modified based on consultation with CTIC experts, as discussed in Step 1a (downward adjustment of total no-tillage area based on the amount of no-tillage that is rotated with more intensive tillage practices) (Towery 2001).

Managed Livestock Manure Amendments: 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 DAYCENT model discussion in Step1b, the amount of land receiving manure is 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 are used to re-classify a portion of crop and grassland into a new management category. Specifically, a portion of medium input cropping systems is re-classified as high input, and a portion of the high input systems is re-classified as high input with amendment. In grassland systems, the estimated proportions for land amended with manure are 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 2006). Uncertainties in the amount of land amended with manure are based on the sample variance at the climate region scale, assuming normal density PDFs (i.e., variance of the climate region estimates, which are derived from county-scale proportions).

Sewage Sludge Amendments: Sewage sludge is generated from the treatment of raw sewage in public or private wastewater treatment facilities and is typically used as a soil amendment or is sent for waste disposal to landfills. In this Inventory, all sewage sludge that is amended to agricultural soils is assumed to be applied to grasslands. See section on sewage sludge in Step 1c for more information about the methods used to derive sewage sludge N estimates. The total amount of sewage sludge N is given in

Table A-203. Sewage sludge N is 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 is divided by the assimilative capacity to estimate the total land area over which sewage sludge had been applied. The resulting estimates are used for the estimation of soil C stock change.

CRP Enrollment after 2012: The change in enrollment for the Conservation Reserve Program after 2012 is based on the amount of land under active contracts from 2013 through 2015 relative to 2012 (USDA-FSA 2015).

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 (USFWS 2010). The area of restored wetlands is 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 is used to construct the PDFs for the uncertainty analysis.

Table A-198: Synthetic Fertilizer N Added to Tier 3 Crops (kt N)

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Fertilizer N	9,681	9,435	9,697	9,689	9,465	10,263	9,850	9,755	9,912	9,935	10,101	10,101	10,101	10,101

Table A-199: Fate of Livestock Manure Nitrogen (kt N)

Activity	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Managed Manure N Applied to Tier 3 Cropland and Non-federal Grasslandsa,b	819	739	977	929	917	979	937	988	1,015	1,015	1,026	1,026	1,026	1,026
Managed Manure N Applied to Tier 1 CroplandC	1,311	1,484	1,330	1,359	1,449	1,420	1,421	1,338	1,298	1,319	1,320	1,320	1,319	1,360
Managed Manure N Applied to Grasslands	404	428	467	502	502	497	497	497	494	490	482	481	481	481
Pasture, Range, & Paddock Manure N	4,097	4,529	4,150	4,124	4,168	4,051	4,036	4,025	3,998	3,924	3,862	3,824	3,771	3,832
Total	**6,631**	**7,180**	**6,924**	**6,914**	**7,036**	**6,946**	**6,891**	**6,849**	**6,806**	**6,748**	**6,690**	**6,651**	**6,597**	**6,699**

[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-200: Crop Residue N and Other N Inputs to Tier 3 Crops as Simulated by DAYCENT (kt N)

Activity	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Residue Na	3,880	4,183	4,222	4,218	4,082	4,171	3,969	4,072	4,484	4,426	4,369	4,369	4,369	4,369
Mineralization & Asymbiotic Fixation	11,962	12,122	12,151	12,738	12,627	13,111	13,175	13,789	14,334	12,752	11,646	11,646	11,646	11,646

[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Table A-201: Synthetic Fertilizer N Added to Tier 1 Crops (kt N)

Activity	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2011	2012	2013	2014	2015
Fertilizer N	1,291	1,496	1,734	1,489	1,755	1,584	1,453	1,212	1,433	1,815	2,017	1,653	1,647	1,658	1,815	2,017	1,653	1,647	1,658

Table A-202: Other Organic Commercial Fertilizer Consumption on Agricultural Lands (kt N)

Activity	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Other Commercial Organic Fertilizer Na	4	10	9	10	12	15	12	10	10	12	13	12	12	12

[a] Includes dried blood, tankage, compost, other. Excludes dried manure and sewage sludge used as commercial fertilizer to avoid double counting.

Table A-203: Sewage Sludge Nitrogen by Disposal Practice (kt N)

Disposal Practice	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Applied to Agricultural Soils	52	68	84	98	101	104	107	110	113	116	119	122	124	127
Other Land Application	25	28	30	31	31	32	32	32	32	33	33	33	33	33
Surface Disposal	20	16	10	5	4	4	3	3	3	2	2	2	2	1
Total	**97**	**111**	**124**	**134**	**137**	**140**	**142**	**145**	**148**	**151**	**153**	**156**	**159**	**162**

Note: Totals may not sum due to independent rounding.

Table A-204: Key Assumptions for Crop Production in the Tier 1 Method

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
Alfalfa	0.9	0.29	0	0.4	0.027	0.019
Asparagus	0.07	0.5	0	0.2	0.006	0.009
Barley	0.89	0.98	0.59	0.22	0.007	0.014
Beans and Lentils	0.9	0.36	0.68	0.19	0.01	0.01
Broccoli	0.09	0.1	0	0.11	0.006	0.009
Cabbage	0.08	0.1	0	0.11	0.006	0.009
Carrots	0.13	0.46	0.02	0.15	0.019	0.014
Cauliflower	0.08	0.1	0	0.11	0.006	0.009
Celery	0.05	0.23	0	0.11	0.006	0.009
Corn	0.87	1.03	0.61	0.22	0.006	0.007
Corn for silage	0.3	0.3	0	0.22	0.006	0.007
Cotton	0.93	1.49	4.41	0.13	0.012	0.007
Cucumbers	0.04	1.77	0	0.03	0.006	0.009
Flaxseed	0.88	1.09	0.88	0.22	0.006	0.009
Garlic	0.11	0.23	0	0.15	0.019	0.014
Greens	0.08	0.1	0	0.11	0.006	0.009
Hay Grass	0.9	0.18	0	0.54	0.015	0.012
Hay legume	0.9	0.235	0	0.47	0.021	0.0155
Lettuce Head	0.04	0.1	0	0.11	0.006	0.009
Lettuce Leaf	0.04	0.1	0	0.11	0.006	0.009
Melons Cantaloup	0.06	1.77	0	0.04	0.006	0.009
Melons Honeydew	0.06	1.77	0	0.04	0.006	0.009
Melons Watermelon	0.085	1.77	0	0.04	0.006	0.009
Millet	0.88	1.09	0.88	0.22	0.006	0.009
Oats	0.89	0.91	0.89	0.25	0.007	0.008

Onions	0.12	0.23	0	0.14	0.019	0.014
Other Vegetables	0.05	0.59	0.57	0.19	0.006	0.009
Peanuts	0.94	1.07	1.54	0.2	0.016	0.014
Peas	0.91	1.13	0.85	0.05	0.011	0.008
Peppers	0.08	1.4	0	0.14	0.006	0.009
Potatoes	0.22	0.1	1.06	0.2	0.019	0.014
Pumpkins	0.1	1.77	0	0.04	0.006	0.009
Radishes	0.05	1.21	0.46	0.15	0.019	0.014
Rice	0.89	0.95	2.46	0.16	0.007	0.009
Sorghum Grain	0.89	0.88	1.33	0.22	0.007	0.006
Sorghum for silage	0.3	0.3	0	0.22	0.007	0.006
Soybeans	0.91	0.93	1.35	0.19	0.008	0.008
Squash	0.05	1.57	0	0.04	0.006	0.009
Sugar beets	0.22	0.1	1.06	0.2	0.019	0.014
Sugarcane	0.25	0.41	0	0.16	0.007	0.005
Sunflower	0.88	1.09	0.88	0.22	0.006	0.009
Sweet Potatoes	0.35	0.27	1.74	0.15	0.019	0.014
Tobacco	0.87	0.3	0	0.4	0.008	0.018
Tomatoes	0.05	0.59	0.57	0.19	0.006	0.009
Wheat	0.89	1.51	0.52	0.24	0.006	0.009

Table A-205: Nitrogen in Crop Residues Retained on Soils Producing Crops not simulated by DAYCENT (kt N)

Crop Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Alfalfa	83,273	72,238	62,386	52,225	53,611	53,721	49,848	49,151	48,496	45,641	40,879	44,003	45,225	45,089
Asparagus	7	6	11	18	13	20	9	6	7	12	6	6	6	6
Barley	7,202	7,046	3,745	1,634	1,928	1,814	2,353	3,387	3,464	3,183	3,932	4,158	4,230	4,045
Beans and Lentils	1,988	2,157	1,795	2,204	2,234	2,224	2,130	2,245	2,499	3,086	2,522	2,505	2,415	2,420
Broccoli	6	5	36	3	2	1	10	0	2	8	4	4	4	4
Cabbage	76	59	28	24	38	55	79	36	53	41	47	50	48	49
Carrots	1,653	1,767	1,376	654	1,330	450	1,145	919	1,207	2,530	1,375	1,429	1,522	1,442
Cauliflower	6	3	9	5	0	0	5	1	0	5	4	4	4	3
Celery	164	175	208	632	630	731	718	640	43	47	81	75	76	71
Corn	157,085	120,853	117,803	112,545	113,901	129,388	123,378	131,972	118,018	119,829	107,230	135,630	146,097	143,988
Corn for silage	6,044	5,169	5,241	4,016	3,862	4,874	4,136	3,148	3,369	3,682	2,642	3,164	3,383	4,039
Cotton	44,527	54,878	38,834	45,836	44,746	34,876	31,812	29,707	34,049	40,214	38,179	37,426	37,606	36,843
Cucumbers	108	104	17	30	29	17	15	0	0	23	92	85	79	76
Flaxseed	9,109	9,141	8,895	5,662	4,742	4,537	4,019	5,333	4,880	3,771	3,658	3,941	4,147	4,276
Garlic	260	226	475	407	497	331	351	338	66	101	92	90	90	90
Greens	0	0	9	0	0	0	0	0	0	0	0	0	0	13

Hay Grass	47,058	47,119	37,948	31,241	28,897	30,394	29,387	28,696	27,765	26,698	24,077	26,215	27,565	27,790
Hay legume	49,609	45,540	32,621	26,310	24,668	24,915	24,415	24,724	23,527	22,687	20,211	22,006	23,139	35,039
Lettuce Head	26	30	11	23	43	68	55	58	206	79	31	30	32	31
Lettuce Leaf	25	20	21	21	4	12	20	3	0	9	5	5	5	6
Melons Cantaloupe	498	518	333	406	263	419	322	281	1,006	616	591	596	530	584
Melons Honeydew	293	204	181	73	64	50	18	0	6	37	71	73	76	76
Melons Watermelon	2,100	2,009	2,768	3,676	3,733	4,176	4,835	4,479	2,593	4,891	4,332	4,415	4,068	4,207
Millet	159,271	157,691	101,557	109,375	95,290	124,607	122,910	126,667	121,519	108,278	74,845	111,564	118,168	124,772
Oats	3,804	2,431	2,022	2,019	1,540	1,584	1,732	2,073	1,868	1,305	1,286	1,330	1,387	1,421
Onions	607	735	608	771	808	860	985	1,013	1,046	1,579	1,513	1,510	1,625	1,575
Other Vegetables	3,450	2,637	2,926	2,993	2,574	3,052	2,453	2,512	952	1,022	833	794	825	839
Peanuts	13,828	12,005	9,060	13,977	10,533	12,173	12,259	10,775	12,284	11,419	16,557	15,914	15,675	15,437
Peas	3,066	4,523	3,168	5,336	4,253	4,981	4,137	5,594	4,779	3,523	4,009	4,315	4,230	3,875
Peppers	214	291	606	504	569	564	673	665	641	550	864	807	827	942
Potatoes	4,907	5,051	4,045	4,874	6,515	4,524	4,918	4,982	4,279	5,589	6,080	6,141	6,213	6,182
Pumpkins	238	290	168	219	196	200	291	188	974	877	898	842	1,004	694
Radishes	0	0	34	0	0	0	0	0	0	0	0	0	0	0
Rice	9,659	8,712	20,037	11,741	10,078	8,815	9,487	10,804	10,807	9,220	8,640	8,847	8,738	8,646
Sorghum Grain	5,348	2,936	2,272	1,324	946	2,017	1,508	688	1,019	1,032	824	938	1,028	1,124
Sorghum for silage	218	211	121	195	175	205	115	220	173	76	147	177	162	180
Soybeans	70,073	52,916	50,411	51,285	50,506	44,114	47,300	52,562	51,685	44,491	44,875	47,855	50,462	50,834
Squash	97	103	149	159	144	147	120	120	356	165	302	264	256	266
Sugar beets	6,277	6,084	4,749	2,560	3,373	1,630	1,887	1,796	3,799	2,223	2,658	2,596	2,528	2,768
Sugarcane	19,061	12,147	15,376	16,033	18,923	16,296	13,743	13,828	11,800	12,669	13,471	12,754	13,207	13,735
Sunflower	654	523	750	388	718	741	793	753	411	663	761	723	754	810
Sweet Potatoes	2,432	2,860	3,079	2,140	1,237	1,630	1,091	1,829	2,608	2,377	2,743	2,827	2,827	2,693
Tobacco	3,450	1,941	1,257	775	1,044	851	1,105	801	817	459	1,065	955	1,087	1,023
Tomatoes	2,567	3,016	2,982	2,812	3,513	3,795	3,297	3,445	5,366	3,795	4,305	4,138	4,315	4,289
Wheat	42,145	31,264	29,723	24,732	20,419	22,511	29,263	25,360	26,126	24,705	24,343	24,772	23,152	23,104
Total	**762,484**	**677,633**	**569,854**	**541,856**	**518,590**	**548,369**	**539,128**	**551,800**	**534,564**	**513,209**	**461,080**	**535,968**	**558,814**	**575,397**

1

Step 1e: Additional Activity Data for Indirect N_2O Emissions

A portion of the N that is applied as synthetic fertilizer, livestock manure, sewage sludge, and other organic amendments volatilizes as NH_3 and NO_x. In turn, this N is returned to soils through atmospheric deposition, thereby increasing mineral N availability and enhancing N_2O 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 N_2O. However, N leaching is assumed to be an insignificant source of indirect N_2O in cropland and grassland systems where the amount of precipitation plus irrigation does 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 N_2O 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-198 through

Table A-203, and Table A-205.

Using the DAYCENT model, volatilization and leaching/surface run-off of N from soils is computed internally for crops and non-federal grasslands in the Tier 3 method. 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 model 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 is also estimated by DAYCENT. Estimated leaching losses of N from DAYCENT are not used in the indirect N_2O calculation if the amount of precipitation plus irrigation did not exceed 80 percent of the potential evapotranspiration. Volatilized losses of N are 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 are summed for the annual cycle. Uncertainty in the estimates is 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 is used to estimate N losses from mineral soils due to volatilization and leaching/runoff for crops, sewage sludge applications, and PRP manure on federal grasslands, which is simulated by DAYCENT. To estimate volatilized losses, synthetic fertilizers, manure, sewage sludge, and other organic N inputs are 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 ranges from 0.03 to 0.3 kg NH_3-N+NO_x-N/kg N for synthetic fertilizer and 0.05 to 0.5 kg NH_3-N+NO_x-N/kg N for organic amendments (IPCC 2006). Leaching/runoff losses of N are 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 to 0.8 kg NO_3-N/kg N (IPCC 2006). However, N leaching is 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 are derived for each of the N inputs in the same manner as direct N_2O emissions, discussed in Steps 1a and 1c.

Volatilized N is summed for losses from croplands and grasslands. Similarly, the annual amounts of N lost from soil profiles through leaching and surface runoff are summed to obtain the total losses for this pathway.

Step 2: Estimate Soil Organic C Stock Changes, Direct N_2O Emissions from Mineral Soils, and CH_4 Emissions from Rice Cultivation

In this step, soil organic C stock changes, N_2O emissions, and CH_4 emissions from rice cultivation are estimated for cropland and non-federal grasslands. Three methods are used to estimate soil organic C stock changes, direct N_2O emissions from mineral soils, and CH_4 emissions from rice cultivation. The DAYCENT process-based model is used for the croplands and non-federal grasslands included in the Tier 3 method. A Tier 2 method is used to estimate soil organic C stock changes for crop histories that included crops that were not simulated by DAYCENT and land use change other than conversions between cropland and grassland. A Tier 1 methodology is used to estimate N_2O emissions from crops that are not simulated by DAYCENT, PRP manure N deposition on federal grasslands, and CH_4 emissions from rice cultivation. Soil organic C stock changes and N_2O emissions are not estimated for federal grasslands (other than the effect of PRP manure N), but are under evaluation as a planned improvement and may be estimated in future inventories.

Step 2a: Estimate Soil Organic C Stock Changes, N_2O Emissions, and CH_4 emissions for Crops and Non-Federal Grassland with the Tier 3 DAYCENT Model

Crops that are simulated with DAYCENT include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat, which combined represent approximately 87 to 90 percent of total cropland in the U.S. The DAYCENT simulations also included all non-federal grasslands in the U.S.

The methodology description is divided into two sub-steps. First, the model is used to establish the initial conditions and C stocks for 1979, which is the last year before the NRI survey is initiated. In the second sub-step, DAYCENT is used to estimate changes in soil organic C stocks, direct N_2O emissions, and CH_4 emissions from rice cultivation based on the land-use and management histories recorded in the NRI from 1990 through 2012 (USDA-NRCS 2015).

Simulate Initial Conditions (Pre-NRI Conditions): DAYCENT 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, and 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 soil organic C algorithms 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, historical climate data based on the PRISM product (1981 through 2010), 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 simulates 5,000 years in the pre-settlement era in order to achieve a steady-state condition.

The second step is to simulate the period of time from European settlement and expansion of agriculture 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 DAYCENT simulations has been 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).

NRI History Simulations: After model initialization, DAYCENT is used to simulate the NRI land use and management histories from 1979 through 2012.[98] The simulations address the influence of soil management on direct N_2O emissions, soil organic C stock changes and losses of N from the profile through leaching/runoff and volatilization. The NRI histories identify the land use and land use change histories for the NRI survey locations, as well as cropping patterns and irrigation history (see Step 1a for description of the NRI data). The input data for the model simulations also include the PRISM weather dataset and SSURGO soils data, synthetic N fertilizer rates, managed manure amendments to cropland and grassland, manure deposition on grasslands (i.e., PRP), tillage histories and EVI data (See Step 1b for description of the inputs). The total number of DAYCENT simulations is over 18 million with a 100 repeated simulations (i.e., iterations) for each NRI point location in a Monte Carlo Analysis. The simulation system incorporates a dedicated MySQL database server and a 30-node parallel processing computer cluster. Input/output operations are managed by a set of run executive programs written in PERL.

The simulations for the NRI history are integrated with the uncertainty analysis. Evaluating uncertainty is an integral part of the analysis and includes three components: (1) uncertainty in the main activity data inputs affecting soil C and N_2O emissions (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; Del Grosso et al. 2010). For component 1, input uncertainty is evaluated for fertilization management, manure applications, and tillage, which are primary management activity data that are supplemental to the NRI observations and have significant

[98] The estimated soil C stock change in 2012 is currently assumed to represent the changes between 2013 and 2015. More recent data will be incorporated in the future to extend the time series of land use and management data.

influence on soil organic C dynamics, soil N_2O and CH_4 emissions. As described in Step 1b, PDFs are derived from surveys at the county scale for the inputs in most cases. In addition, uncertainty is included for predictions of EVI data that are needed to fill-data gaps and extend the time series (see Enhanced Vegetation Index in Step 1b). To represent uncertainty in all of these inputs, a Monte-Carlo Analysis is used with 100 iterations for each NRI point; random draws are made from PDFs for fertilizer, manure application, tillage, and EVI predictions. As described above, an adjustment factor is also selected from PDFs with normal densities to represent the dependence between manure amendments and N fertilizer application rates.

The second component deals with uncertainty inherent in model formulation and parameterization. This component is the largest source of uncertainty in the Tier 3 model-based inventory analysis, accounting for more than 80 percent of the overall uncertainty in the final estimates (Ogle et al. 2010; Del Grosso et al. 2010). An empirically-based procedure is applied to develop a structural uncertainty estimator from the relationship between modeled results and field measurements from agricultural experiments (Ogle et al. 2007). For soil organic C, the DAYCENT model is evaluated with measurements from 92 long-term field experiments that have over 900 treatment observations, representing a variety of management conditions (e.g., variation in crop rotation, tillage, fertilization rates, and manure amendments). There are 41 experimental sites available with over200 treatment observations to evaluate structural uncertainty in the N_2O emission predictions from DAYCENT (Del Grosso et al. 2010). There are 10 experiments with 126 treatment observations for CH_4 emissions from rice cultivation. The inputs to the model are essentially known in the simulations for the long-term experiments, and, therefore, the analysis is designed to evaluate uncertainties associated with the model structure (i.e., model algorithms and parameterization). USDA is developing a national soil monitoring network to evaluate the Inventory in the future (Spencer et al. 2011).

The relationship between modeled soil organic C stocks and field measurements are statistically analyzed using linear-mixed effect modeling techniques. Additional fixed effects are 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 are 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 cropland model includes variables for modeled soil organic C inclusion of hay/pasture in cropping rotations, use of no-till, set-aside lands, organic matter amendments, and inclusion of bare fallow in the rotation, which are significant at an alpha level of 0.05. The final grassland model only included the model soil organic C. These fixed effects are used to make an adjustment to modeled values due to biases that are creating significant mismatches between the modeled and measured stocks. For soil N_2O, simulated DAYCENT emissions are a highly significant predictor of the measurements, with a p-value of <0.01. Several other variables are considered in the statistical model to evaluate if DAYCENT exhibits bias under certain conditions related to climate, soil types, and management practices. Random effects are included in the model to capture the dependence in time series and data collected from the same site, which are needed to estimate appropriate standard deviations for parameter coefficients. For rice CH_4 emissions, simulated DAYCENT emissions are a significant predictor of measured emission, similar to the results for soil N_2O emissions. Several other variables are tested including soil characteristics, geographic location (i.e., state), and management practices (e.g., with and without winter flooding). The only other significant variable is geographic location because the model does not predict emissions as accurately for California as other rice-producing states. Random effects are included to capture the dependence in time series and the data collected from the same site.

A Monte Carlo approach is used to apply the uncertainty estimator (Ogle et al. 2010). Parameter values for the statistical equation (i.e., fixed effects) are 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 estimate and associated management information is then used as input into the equation, and adjusted values are computed for each C stock, N_2O and CH_4 emissions estimate. The variance of the adjusted estimates is computed from the 100 simulated values from the Monte Carlo analysis.

The third element is the uncertainty associated with scaling the DAYCENT results for each NRI point to the entire land base, using the expansion factors provided with the NRI survey dataset. The expansion factors represent the number of hectares associated with the land-use and management history for a particular point. This uncertainty is determined by computing the variances from a set of replicated weights for the expansion factor. For the land base that is simulated with the DAYCENT model, soil organic C stock changes are provided in Table A-206, soil N_2O emissions are provided in Table A-207, and rice cultivation CH_4 emissions in Table A-208.

Table A-206: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Land Base Simulated with the Tier 3 DAYCENT Model-Based Approach (MMT CO_2 Eq.)

	Cropland Remaining Cropland		Land Converted to Cropland		Grassland Remaining Grassland		Land Converted to Grassland	
Year	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
1990	(65.75)	(98.30) to (33.20)	20.62	11.32 to 29.93	(10.20)	(47.18) to 26.77	(5.11)	(9.71) to (0.51)
1991	(71.64)	(103.66) to (39.63)	21.41	11.46 to 31.37	(12.53)	(50.86) to 25.80	(5.19)	(9.27) to (1.12)
1992	(63.04)	(91.32) to (34.76)	23.61	13.62 to 33.60	(6.81)	(37.06) to 23.44	(4.92)	(10.03) to 0.18
1993	(43.64)	(73.09) to (14.20)	17.95	7.22 to 28.69	1.66	(33.17) to 36.50	(5.53)	(10.31) to (0.74)
1994	(55.49)	(86.59) to (24.40)	14.40	3.88 to 24.92	(24.13)	(58.06) to 9.80	(7.36)	(12.99) to (1.73)
1995	(49.18)	(80.21) to (18.15)	20.04	8.90 to 31.17	(0.96)	(33.43) to 31.50	(6.37)	(12.27) to (0.48)
1996	(57.70)	(87.89) to (27.50)	16.93	7.08 to 26.79	(22.31)	(53.52) to 8.90	(7.59)	(14.10) to (1.08)
1997	(55.46)	(89.14) to (21.79)	18.98	8.58 to 29.37	(9.10)	(47.05) to 28.84	(7.46)	(13.49) to (1.43)
1998	(44.19)	(76.62) to (11.76)	12.57	1.18 to 23.95	(16.03)	(53.16) to 21.10	(8.12)	(15.15) to (1.10)
1999	(59.68)	(88.69) to (30.67)	12.78	2.58 to 22.98	(3.96)	(36.93) to 29.02	(8.55)	(15.40) to (1.69)
2000	(65.43)	(100.61) to (30.26)	12.95	1.93 to 23.98	(33.13)	(72.27) to 6.01	(10.51)	(17.58) to (3.44)
2001	(58.29)	(91.06) to (25.51)	11.21	0.34 to 22.09	(8.82)	(40.46) to 22.82	(9.81)	(17.37) to (2.26)
2002	(54.71)	(83.13) to (26.29)	11.21	0.07 to 22.34	(9.63)	(45.47) to 26.20	(10.51)	(17.31) to (3.70)
2003	(47.63)	(78.33) to (16.94)	13.08	2.53 to 23.63	(6.34)	(39.14) to 26.46	(10.52)	(17.46) to (3.59)
2004	(47.56)	(79.85) to (15.27)	12.63	3.60 to 21.66	0.42	(34.25) to 35.09	(9.91)	(17.96) to (1.86)
2005	(50.81)	(84.26) to (17.36)	12.40	1.10 to 23.71	1.97	(34.50) to 38.43	(10.22)	(17.93) to (2.52)
2006	(47.47)	(76.01) to (18.92)	13.21	3.03 to 23.39	(14.85)	(48.99) to 19.29	(12.24)	(20.62) to (3.86)
2007	(45.56)	(76.20) to (14.92)	11.83	1.45 to 22.21	1.80	(31.07) to 34.67	(10.92)	(19.03) to (2.81)
2008	(34.45)	(67.84) to (1.06)	12.68	2.46 to 22.89	(10.05)	(43.50) to 23.39	(10.84)	(18.52) to (3.17)
2009	(29.33)	(58.63) to (.04)	12.56	3.13 to 21.99	(5.66)	(43.85) to 32.53	(10.64)	(17.89) to (3.38)
2010	(29.43)	(62.67) to 3.80	14.53	5.38 to 23.68	1.34	(30.62) to 33.30	(10.76)	(19.24) to (2.29)
2011	(43.60)	(76.77) to (10.44)	14.27	4.15 to 24.40	(15.97)	(54.46) to 22.52	(10.97)	(18.96) to (2.98)
2012	(46.60)	(83.06) to (10.14)	13.38	2.10 to 24.66	(24.56)	(60.90) to 11.78	(11.21)	(19.48) to (2.94)
2013[a]	(42.67)	(73.46) to (11.88)	6.66	(3.47) to 16.79	3.73	(28.20) to 35.65	(10.17)	(18.87) to (1.47)
2014[a]	(42.67)	(73.46) to (11.88)	6.66	(3.47) to 16.79	3.80	(28.12) to 35.72	(10.17)	(18.87) to (1.47)
2015[a]	(42.67)	(73.46) to (11.88)	6.66	(3.47) to 16.79	3.88	(28.04) to 35.79	(10.17)	(18.87) to (1.47)

Note: Estimates after 2012 are based on NRI data from 2012 and therefore do not fully reflect changes occurring in the latter part of the time series.

[a] Quality control uncovered errors in the estimate and uncertainty for 2013, 2014, 2015, which will be updated following public review. Corrected estimates are provided in the footnotes of the emission summary tables for *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland* sections in the LULUCF chapter of this report.

Table A-207: Annual N_2O Emissions (95% Confidence Interval) for the Land Base Simulated with the Tier 3 DAYCENT Model-Based Approach (MMT CO_2 Eq.)

	Tier 3 Cropland		Non-Federal Grasslands	
Year	Estimate	95% CI	Estimate	95% CI
1990	128.5	121.74 to 137.33	51.2	48.03 to 55.26
1991	128.4	121.69 to 137.19	52.4	49.16 to 56.50
1992	128.5	121.81 to 137.26	51.4	48.61 to 55.10
1993	128.5	121.73 to 137.53	53.0	50.04 to 56.74
1994	127.8	121.29 to 136.23	49.4	46.52 to 53.03
1995	129.1	122.46 to 137.81	50.8	47.92 to 54.42
1996	129.6	122.94 to 138.48	53.9	50.62 to 58.21
1997	129.2	122.48 to 138.03	54.0	50.91 to 57.96
1998	136.2	128.94 to 145.71	58.6	55.19 to 62.99
1999	129.6	122.95 to 138.19	49.2	46.60 to 52.59
2000	132.2	125.41 to 141.24	49.7	46.63 to 53.68
2001	134.0	127.0 to 143.26	51.8	48.89 to 55.69
2002	132.5	125.60 to 141.66	53.8	50.52 to 58.06
2003	135.4	128.41 to 144.74	52.3	49.40 to 56.13
2004	142.0	134.79 to 151.32	62.7	58.77 to 67.99

2005	134.7	127.87 to 143.71	53.4	50.55 to 56.97
2006	135.7	128.82 to 144.66	55.9	52.77 to 60.04
2007	140.8	133.4 to 150.41	57.7	54.19 to 62.42
2008	137.3	130.17 to 146.68	54.7	51.81 to 58.49
2009	139.6	132.41 to 148.95	58.2	54.74 to 62.67
2010	144.2	136.70 to 154.10	57.4	54.31 to 61.52
2011	138.0	130.98 to 147.26	50.9	48.40 to 54.24
2012	135.7	128.72 to 144.87	47.7	44.84 to 51.4
2013	134.6	127.68 to 143.76	47.6	44.77 to 51.33
2014	134.6	127.68 to 143.76	47.6	44.73 to 51.28
2015	134.6	127.67 to 143.75	47.5	44.68 to 51.23

Table A-208: Annual CH_4 Emissions (95% Confidence Interval) for Rice Cultivation Simulated with the Tier 3 DAYCENT Model-Based Approach (MMT CO_2 Eq.)

Year	Estimate	95% CI
1990	14.39	10.22 to 18.57
1991	15.18	10.86 to 19.49
1992	15.17	10.58 to 19.76
1993	15.24	11.05 to 19.44
1994	13.10	9.20 to 16.99
1995	14.23	10.22 to 18.23
1996	14.40	10.32 to 18.48
1997	14.22	10.16 to 18.27
1998	14.35	9.96 to 18.73
1999	14.82	10.13 to 19.52
2000	14.98	10.45 to 19.51
2001	13.62	9.32 to 17.93
2002	14.62	10.23 to 19.01
2003	12.58	8.76 to 16.41
2004	12.26	8.40 to 16.12
2005	14.93	10.35 to 19.52
2006	11.38	7.96 to 14.80
2007	12.54	8.82 to 16.27
2008	9.92	6.85 to 12.99
2009	12.76	8.80 to 16.71
2010	14.09	9.85 to 18.33
2011	12.59	8.92 to 16.26
2012	9.96	6.70 to 13.22
2013	9.95	6.75 to 13.14
2014	9.90	6.76 to 13.04
2015	9.92	6.78 to 13.06

In DAYCENT, the model cannot distinguish among the original sources of N after the mineral N enters the soil pools, and therefore it is not possible 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 NRI point, the N inputs in a simulation are 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 is divided by the total N input, and this proportion is used to determine the amount of N_2O emissions assigned to each of the practices.[99] For example, if 70 percent of the mineral N made available in the soil

[99] 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 currently 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). Further research and model development may allow for other approaches in the future.

is due to mineral fertilization, then 70 percent of the N_2O emissions are 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 N fixation 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 cropland soils compared to application of synthetic fertilizers and manure amendments, along with symbiotic fixation. Mineralization of soil organic matter accounts for the majority of available N in grassland soils. Accounting for the influence of "other N inputs" is necessary in order to meet the recommendation for 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 results associated with subdividing the N_2O emissions based on N inputs are provided in Table A-209 and Table A-210.

Table A-209: Direct N_2O Emissions from Cropland Soils (MMT CO_2 Eq.)

Activity	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Mineral Soils	**144.1**	**146.2**	**149.2**	**150.6**	**153.1**	**157.4**	**153.3**	**154.1**	**159.5**	**155.1**	**153.5**	**151.0**	**151.1**	**151.4**
Tier 3	**128.5**	**129.1**	**132.2**	**134.7**	**135.7**	**140.8**	**137.3**	**139.6**	**144.2**	**138.0**	**135.7**	**134.6**	**134.6**	**134.6**
Synthetic Fertilizer	47.5	46.2	47.8	47.6	47.9	50.8	48.9	48.0	48.3	49.5	51.0	50.5	50.5	50.5
Managed Manure	3.9	3.5	4.7	4.4	4.5	4.7	4.5	4.8	4.9	4.9	5.0	5.0	5.0	5.0
Residue Na	18.6	20.2	20.5	20.5	20.3	20.4	19.3	19.6	21.5	21.5	21.4	21.3	21.3	21.2
Mineralization and Asymbiotic Fixation	58.4	59.2	59.2	62.2	63.0	64.9	64.7	67.2	69.6	62.1	58.2	57.8	57.8	57.8
Tier 1	**15.7**	**17.1**	**17.0**	**15.8**	**17.4**	**16.6**	**16.0**	**14.5**	**15.3**	**17.1**	**17.8**	**16.4**	**16.5**	**16.8**
Synthetic Fertilizer	6.0	7.0	8.1	7.0	8.2	7.4	6.8	5.7	6.7	8.5	9.4	7.7	7.7	7.8
Managed Manure and Other Organic														
Commercial Fertilizer	6.2	7.0	6.3	6.4	6.8	6.7	6.7	6.3	6.1	6.2	6.2	6.2	6.2	6.4
Residue Na	3.5	3.1	2.6	2.5	2.4	2.5	2.4	2.5	2.4	2.3	2.1	2.4	2.5	2.6
Organic Soils	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**	**3.2**	**3.2**	**3.2**	**3.2**	**3.2**	**3.2**	**3.2**
Totala	**147.5**	**149.5**	**152.5**	**153.9**	**156.4**	**160.7**	**156.5**	**157.3**	**162.7**	**158.3**	**156.7**	**154.2**	**154.3**	**154.6**

[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Table A-210: Direct N_2O Emissions from Grasslands (MMT CO_2 Eq.)

Activity	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Mineral Soils	**61.3**	**61.0**	**58.2**	**61.1**	**63.7**	**65.1**	**62.2**	**65.8**	**65.1**	**58.8**	**55.7**	**55.3**	**54.9**	**55.4**
Tier 3	**51.2**	**50.8**	**49.7**	**53.4**	**55.9**	**57.7**	**54.7**	**58.2**	**57.4**	**50.9**	**47.7**	**47.6**	**47.6**	**47.5**
Synthetic Fertilizer	0.9	0.8	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.7	0.7	0.7	0.7
PRP Manure	6.3	6.6	6.5	6.5	7.1	6.9	6.6	7.0	6.6	6.3	5.9	5.8	5.8	5.8
Managed Manure	0.9	0.9	1.0	1.1	1.1	1.1	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Residue Na	14.5	15.0	13.9	15.8	15.6	16.5	15.5	15.4	16.5	14.8	14.2	14.2	14.2	14.2
Mineralization and Asymbiotic Fixation	28.5	27.5	27.5	29.2	31.3	32.6	30.9	33.8	32.4	28.1	25.8	25.8	25.8	25.7
Tier 1	**10.1**	**10.2**	**8.5**	**7.8**	**7.8**	**7.4**	**7.5**	**7.6**	**7.7**	**7.8**	**8.0**	**7.7**	**7.3**	**7.9**
PRP Manure	9.9	9.9	8.1	7.3	7.3	6.9	7.0	7.1	7.1	7.3	7.4	7.1	6.7	7.3
Sewage Sludge	0.2	0.3	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6
Organic Soils	3.3	3.3	3.4	3.5	3.5	3.4	3.4	3.4	3.3	3.3	3.3	3.3	3.3	3.3
Total	**64.5**	**64.3**	**61.5**	**64.6**	**67.2**	**68.5**	**65.6**	**69.1**	**68.5**	**62.1**	**59.0**	**58.6**	**58.1**	**58.7**

[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Step 2b: Soil N_2O Emissions from Agricultural Lands on Mineral Soils Approximated with the Tier 1 Approach

To estimate direct N_2O emissions from N additions to crops in the Tier 1 method, the amount of N in applied synthetic fertilizer, manure and other commercial organic fertilizers (i.e., dried blood, tankage, compost, and other) is added to N inputs from crop residues, and the resulting annual totals are multiplied by the IPCC default emission factor of 0.01 kg N_2O-N/kg N (IPCC 2006) (see Table A-209). The uncertainty is determined based on simple error propagation methods (IPCC 2006). The uncertainty in the default emission factor ranges from 0.3 to 3.0 kg N_2O-N/kg N (IPCC 2006). For flooded rice soils, the IPCC default emission factor is 0.003 kg N_2O-N/kg N and the uncertainty range is 0.000 to 0.006 kg N_2O-N/kg N (IPCC 2006).[100] Uncertainties in the emission factor and fertilizer additions are 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.

The Tier 1 method is also used to estimate emissions from manure N deposited by livestock on federal lands (i.e., PRP manure N), and from sewage sludge application to grasslands. These two sources of N inputs to soils are multiplied by the IPCC (2006) default emission factors (0.01 kg N_2O-N/kg N for sludge and horse, sheep, and goat manure, and 0.02 kg N_2O-N/kg N for cattle, swine, and poultry manure) to estimate N_2O emissions (Table A-210). The uncertainty is 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 2c: Soil CH_4 Emissions from Agricultural Lands Approximated with the Tier 1 Approach

To estimate CH_4 emissions from rice cultivation for the Tier 1 method, an adjusted daily emission factor is calculated using the default baseline emission factor of 1.30 kg CH_4 ha^{-1} d^{-1} (ranging 0.8-2.2 kg CH_4 ha^{-1} d^{-1}) multiplied by a scaling factor for the cultivation water regime, pre-cultivation water regime and a scaling factor for organic amendments (IPCC 2006). The water regime during cultivation is continuously flooded for rice production in the United States and so the scaling factor is always 1 (ranging from 0.79 to 1.26). The pre-season water regime varies based on the proportion of land with winter flooding; land that does not have winter flooding is assigned a value of 0.68 (ranging from 0.58 to 0.80) and areas with winter flooding are assigned a value of 1 (ranging from 0.88 to 1.14). Organic amendments are estimated based on the amount of rice straw and multiplied by 1 (ranging 0.97 to 1.04) for straw incorporated greater than 30 days before cultivation, and by 0.29 (0.2 to 0.4) for straw incorporated greater than 30 days before cultivation. The adjusted daily emission factor is multiplied by the cultivation period and harvested area to estimate the total CH_4 emissions. The uncertainty is propagated through the calculation using an Approach 2 method with a Monte Carlo simulation (IPCC 2006), combining uncertainties associated with the calculation of the adjusted daily emission factor and the harvested areas derived from the USDA NRI survey data.

Step 2d: Soil Organic C Stock Changes in Agricultural Lands on Mineral Soils Approximated with the Tier 2 Approach

Mineral soil organic C stock values are derived for crop rotations that were not simulated by DAYCENT and land converted from non-agricultural land uses to cropland or grassland from 1990 to 2012, based on the land-use and management activity data in conjunction with appropriate reference C stocks, land-use change, management, input, and wetland restoration factors. Each input to the inventory calculations for the Tier 2 approach has some level of uncertainty that is quantified in PDFs, including the land-use and management activity data, reference C stocks, and management factors. A Monte Carlo Analysis is used to quantify uncertainty in soil organic C stock changes for the inventory period based on uncertainty in the inputs. Input values are 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.

Derive Mineral Soil Organic C Stock Change Factors: Stock change factors representative of U.S. conditions are 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). Studies from the United States and Canada are used in this analysis under the assumption that they would best represent management impacts for the Inventory.

[100] 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 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-211). Seven of these climate zones occur in the conterminous United States and Hawaii (Eve et al. 2001).

Table A-211: 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, Drya	> 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 precipitation and temperature (1950 to 2000) variables from the WorldClim data set (Hijmans et al. 2005) and potential evapotranspiration data from the Consortium for Spatial Information (CGIAR-CSI) (Zomer et al. 2008; Zomer et al. 2007) are used to classify climate zones (Figure A-15). IPCC climate zones are assigned to NRI point locations.

Soils are 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, are 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-212). These stocks are used in conjunction with management factors to estimate the change in SOC stocks that result from management and land-use activity. PDFs, which represent the variability in the stock estimates, are constructed as normal densities based on the mean and variance from the pedon data. Pedon locations are 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 are tested for spatial autocorrelation using the Moran's I test, and variance terms are inflated by 10 percent for all zones with significant p-values.

Figure A-15: IPCC Climate Zones

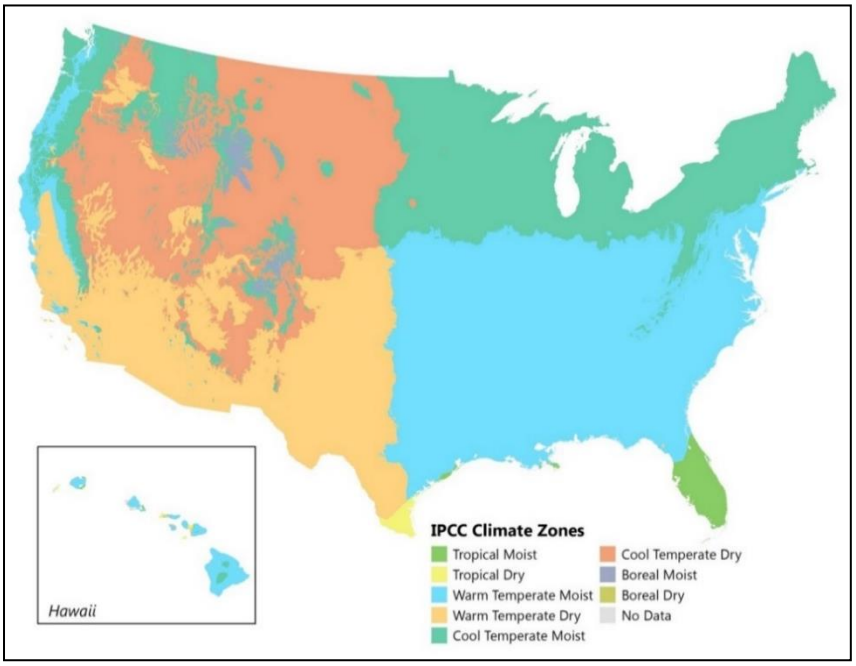


Table A-212: U.S. Soil Groupings Based on the IPCC Categories and Dominant Taxonomic Soil, and Reference Carbon Stocks (Metric Tons C/ha)

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)
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 are 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).

To estimate the land use, management and input factors, 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 are 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 are not aggregated for the C stock measurements; each depth increment (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) is included as a separate point in the dataset. Similarly, time series data are not aggregated in these datasets. Linear regression models assume that the underlying data are independent observations, but this is not the case with data from the same experimental site, or plot in a time series. These data are more related to each other than data from other sites (i.e., not independent). Consequently, random effects are 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 are estimated for the effect of management practices at 20 years for the top 30 cm of the soil (Table A-213). Variance is 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 C stock changes in 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.[101] 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 are insufficient field studies to derive factor values for these systems from the published literature, and, thus, estimates from IPCC (2006) are 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 is provided for these factors in IPCC (2006), which is used to construct PDFs.

[101] Improved grasslands are identified in the 2012 *National Resources Inventory* as grasslands that are irrigated or seeded with legumes, in addition to those reclassified as improved with manure amendments.

Table A-213: 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-Asidea (n=142)	1.25	1.31±0.06	1.26±0.04	1.14±0.06	1.10±0.05
Improved Grassland Factors					
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[b]	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[b]	1.2	1.38±0.06	1.34±0.08	1.38±0.06	1.34±0.08

[a] Factors in the IPCC documentation (IPCC 2006) are converted to represent changes in SOC storage from a cultivated condition rather than a native condition.

[b] U.S.-specific factors are 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 (2006) are used as the best estimates of these impacts.

Note: The "n" values refer to sample size.

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 is 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-214). A PDF with a normal density is 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 is 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 standard deviation are used to construct a PDF with a normal density (Table A-214).

Table A-214: Rate and standard deviation for the Initial Increase and Subsequent Annual Mass Accumulation Rate (Mg C/ha-yr) in Soil Organic 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

Note: Mass accumulation rate represents additional gains in C for mineral soils after the first 10 years (Euliss and Gleason 2002).

Estimate Annual Changes in Mineral Soil Organic C Stocks: In accordance with IPCC methodology, annual changes in mineral soil C are calculated by subtracting the beginning stock from the ending stock and then dividing by 20.[102] For this analysis, stocks are estimated for each year and difference between years is the stock change. From the final distribution of 50,000 values, a 95 percent confidence interval is generated based on the simulated values at the 2.5 and 97.5 percentiles in the distribution (Ogle et al. 2003). Soil organic C stock changes are provided in Table A-215 through Table A-220.

[102] The difference in C stocks is divided by 20 because the stock change factors represent change over a 20-year time period.

Step 2e: Estimate Additional Changes in Soil Organic C Stocks Due to CRP Enrollment after 2010 and Sewage Sludge Amendments

There are two additional land use and management activities in U.S. agricultural lands that are not estimated in Steps 2a and 2b. The first activity involves 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 is assumed that sewage sludge for agricultural land application is 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 is 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-213), by calculating the effect of converting nominal, medium-input grassland to high input improved grassland. The assumptions are that reference C stock are 50 metric tonnes C/ha, which represents a mid-range value of reference C stocks for the cropland soils in the United States,[103] that the land use factor for grassland of 1.4 and 1.11 for high input improved grassland are representative of typical conditions, and that the change in stocks are occurring over a 20 year (default value) time period (i.e., $[50 \times 1.4 \times 1.11 - 50 \times 1.4] / 20 = 0.38$). A nominal ±50 percent uncertainty is 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 influence of sewage sludge on soil organic C stocks are provided in Table A-221.

The second activity is the change in enrollment for the Conservation Reserve Program after 2012 for mineral soils. Relative to the enrollment in 2012, the total area in the Conservation Reserve Program has decreased from 2013 to 2015 (USDA-FSA 2015). An average annual change in SOC of 0.5 metric tonnes C/ha-yr is 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-213) by estimating the impact of setting aside a medium input cropping system in the Conservation Reserve Program. The assumptions are that reference C stock are 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 is 1.2 for setting-aside cropland from production, with the change in stocks occurring over a 20 year (default value) time period equal to 0.5 (i.e., $[50 \times 1.2 - 50] / 20 = 0.5$). A nominal ±50 percent uncertainty is attached to these estimates due to limited information about the enrollment trends at subregional scales, which creates uncertainty in the rate of soil C stock change (stock change factors for set-aside lands vary by climate region). Estimates are provided in Table A-230.

[103] Reference C stocks are based on cropland soils for the Tier 2 method applied in this Inventory.

Table A-215: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Non-Federal Cropland Land Base Estimated with the Tier 2 Analysis using U.S. Factor Values (MMT CO_2 Eq./year)

Non-Federal Croplands:	Cropland Remaining Cropland		Grassland Converted to Cropland		Forest Converted to Cropland		Other Land Converted to Cropland		Settlements Converted to Cropland		Wetlands Converted to Cropland	
Year	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Mineral Soils												
1990	-5.44	(7.97) to (2.99)	1.32	(0.72) to 2.26	0.22	(0.12) to .38	0.16	(0.09) to 0.28	0.06	(0.04) to 0.11	0.11	(0.06) to 0.19
1991	-6.19	(8.94) to (3.53)	1.26	(0.84) to 2.25	0.20	(0.13) to .36	0.15	(0.10) to 0.27	0.06	(0.04) to 0.11	0.10	(0.07) to 0.18
1992	-6.19	(9.77) to (3.63)	1.29	(1.07) to 2.32	0.19	(0.16) to .35	0.16	(0.13) to 0.29	0.06	(0.05) to 0.11	0.10	(0.08) to 0.18
1993	-6.95	(10.16) to (3.79)	1.35	(0.75) to 2.45	0.18	(0.10) to .32	0.17	(0.09) to 0.31	0.06	(0.04) to 0.12	0.12	(0.07) to 0.22
1994	-6.70	(9.93) to (3.52)	1.48	(0.37) to 2.63	0.18	(0.05) to .33	0.19	(0.05) to 0.35	0.07	(0.02) to 0.12	0.15	(0.04) to 0.26
1995	-6.46	(9.52) to (3.48)	1.59	(0.35) to 2.76	0.19	(0.04) to .32	0.21	(0.05) to 0.36	0.07	(0.02) to 0.13	0.15	(0.03) to 0.27
1996	-6.10	(9.09) to (3.14)	1.65	(0.35) to 2.86	0.19	(0.04) to .33	0.22	(0.05) to 0.37	0.07	(0.02) to 0.13	0.16	(0.03) to 0.28
1997	-7.63	(11.37) to (3.99)	1.41	(0.47) to 2.63	0.15	(0.05) to .29	0.19	(0.06) to 0.35	0.06	(0.02) to 0.12	0.14	(0.05) to 0.25
1998	-7.33	(11.0) to (3.79)	1.63	(0.38) to 3.01	0.15	(0.04) to .28	0.20	(0.05) to 0.36	0.08	(0.02) to 0.14	0.15	(0.03) to 0.27
1999	-7.06	(10.56) to (3.71)	1.49	(0.33) to 2.79	0.13	(0.03) to .24	0.19	(0.04) to 0.35	0.07	(0.02) to 0.13	0.14	(0.03) to 0.25
2000	-6.75	(10.09) to (3.56)	1.48	(0.39) to 2.78	0.12	(0.03) to .22	0.22	(0.06) to 0.42	0.07	(0.02) to 0.14	0.14	(0.04) to 0.26
2001	-6.71	(9.94) to (3.62)	1.54	(0.36) to 2.85	0.10	(0.02) to .18	0.23	(0.05) to 0.42	0.08	(0.02) to 0.14	0.14	(0.03) to 0.26
2002	-6.72	(9.79) to (3.79)	1.45	(0.30) to 2.66	0.09	(0.02) to .16	0.20	(0.04) to 0.36	0.07	(0.02) to 0.14	0.13	(0.03) to 0.25
2003	-6.05	(8.97) to (3.30)	1.42	(0.24) to 2.59	0.08	(0.01) to .15	0.19	(0.03) to 0.34	0.07	(0.01) to 0.12	0.13	(0.02) to 0.23
2004	-5.42	(8.24) to (2.74)	1.60	(0.18) to 2.79	0.08	(0.01) to .15	0.21	(0.02) to 0.37	0.07	(0.01) to 0.12	0.14	(0.02) to 0.25
2005	-5.39	(7.97) to (2.97)	1.53	(0.18) to 2.70	0.08	(0.01) to .13	0.19	(0.02) to 0.34	0.07	(0.01) to 0.12	0.13	(0.02) to 0.23
2006	-4.36	(6.67) to (2.21)	1.77	(0.19) to 2.89	0.09	(0.01) to .14	0.23	(0.02) to 0.37	0.08	(0.01) to 0.13	0.15	(0.02) to 0.25
2007	-3.96	(6.14) to (1.97)	1.83	(0.13) to 2.92	0.08	(0.01) to .13	0.23	(0.02) to 0.36	0.09	(0.01) to 0.14	0.14	(0.01) to 0.23
2008	-3.37	(5.37) to (1.53)	1.86	(0.06) to 2.98	0.06	0 to 0.10	0.24	(0.01) to 0.38	0.08	0 to 0.13	0.14	0 to 0.22
2009	-3.52	(5.32) to (1.88)	1.70	(0.02) to 2.72	0.06	0 to 0.09	0.22	0 to 0.36	0.07	0 to 0.12	0.11	0 to 0.18
2010	-3.58	(5.45) to (1.91)	1.68	0.02 to 2.68	0.06	0 to 0.09	0.22	0 to 0.35	0.08	0 to 0.12	0.11	0 to 0.18
2011	-3.49	(5.17) to (1.99)	1.70	0.01 to 2.68	0.06	0 to 0.09	0.22	0 to 0.35	0.09	0 to 0.14	0.12	0 to 0.19
2012	-2.88	(4.40) to (1.55)	1.69	(0.01) to 2.64	0.06	0 to 0.10	0.22	0 to 0.34	0.09	0 to 0.15	0.12	0 to 0.19
2013	-2.69	(4.17) to (1.39)	1.70	0 to 2.64	0.06	0 to 0.10	0.22	0 to 0.34	0.09	0 to 0.15	0.12	0 to 0.19
2014	-2.74	(4.24) to (1.42)	1.70	0 to 2.65	0.06	0 to 0.10	0.22	0 to 0.34	0.09	0 to 0.15	0.12	0 to 0.19
2015	-2.70	(4.20) to (1.40)	1.70	0.01 to 2.65	0.06	0 to 0.10	0.22	0 to 0.34	0.09	0 to 0.15	0.12	0 to 0.19

Note: Estimates after 2012 are based on NRI data from 2012 and therefore do not fully reflect changes occurring in the latter part of the time series.

Table A-216: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Federal Cropland Land Base Estimated with the Tier 2 Analysis using U.S. Factor Values (MMT CO_2 Eq./year)

Federal Croplands:	Cropland Remaining Cropland		Grassland Converted to Cropland		Forest Converted to Cropland		Other Land Converted to Cropland		Settlements Converted to Cropland		Wetlands Converted to Cropland	
Year	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Mineral Soils												
1990	0.00	(0.01) to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1991	0.00	(0.01) to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1992	0.00	(0.02) to 0.02	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1993	0.00	(0.02) to 0.02	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1994	0.00	(0.03) to 0.02	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1995	0.00	(0.03) to 0.03	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1996	0.00	(0.03) to 0.02	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1997	-0.01	(0.05) to 0.02	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1998	0.00	(0.01) to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
1999	0.00	(0.01) to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2000	0.00	(0.01) to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2001	0.00	(0.01) to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2002	0.00	(0.01) to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2003	0.00	(0.01) to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2004	0.00	(0.01) to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2005	0.00	(0.01) to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2006	0.00	(0.01) to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2007	0.00	(0.01) to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2008	0.00	(0.01) to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2009	0.00	0.0 to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2010	0.00	0.0 to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2011	0.00	0.0 to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2012	0.00	0.0 to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2013	0.00	0.0 to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2014	0.00	0.0 to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01
2015	0.00	0.0 to 0.0	0.00	0.0 to 0.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.01

Note: Estimates after 2012 are based on NRI data from 2012 and therefore do not fully reflect changes occurring in the latter part of the time series.

Table A-217: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Total Cropland Land Base Estimated with the Tier 2 Analysis using U.S. Factor Values (MMT CO_2 Eq./year)

Total Croplands:	Cropland Remaining Cropland		Grassland Converted to Cropland		Forest Converted to Cropland		Other Land Converted to Cropland		Settlements Converted to Cropland		Wetlands Converted to Cropland	
Year	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Mineral Soils												

1990	-5.44	(7.97) to (3.0)	1.32	(.72) to 2.26	0.22	(.12) to .38	0.16	(.09) to .28	0.06	(0.04) to 0.11	0.11	(0.06) to 0.19
1991	-6.19	(8.94) to (3.53)	1.26	(.84) to 2.25	0.20	(.13) to .36	0.15	(.10) to .27	0.06	(0.04) to 0.11	0.10	(0.07) to 0.18
1992	-6.19	(9.77) to (3.63)	1.29	(1.07) to 2.32	0.19	(.16) to .35	0.16	(.13) to .29	0.06	(0.05) to 0.11	0.10	(0.08) to 0.18
1993	-6.95	(10.17) to (3.79)	1.35	(.75) to 2.45	0.18	(.10) to .32	0.17	(.09) to .31	0.06	(0.04) to 0.12	0.12	(0.07) to 0.22
1994	-6.71	(9.94) to (3.52)	1.48	(.37) to 2.63	0.18	(.05) to .33	0.19	(.05) to .35	0.07	(0.02) to 0.12	0.15	(0.04) to 0.26
1995	-6.46	(9.52) to (3.48)	1.59	(.35) to 2.76	0.19	(.04) to .32	0.21	(.05) to .36	0.07	(0.02) to 0.13	0.15	(0.03) to 0.27
1996	-6.10	(9.10) to (3.15)	1.65	(.35) to 2.86	0.19	(.04) to .33	0.22	(.05) to .37	0.07	(0.02) to 0.13	0.16	(0.03) to 0.28
1997	-7.64	(11.38) to (4.0)	1.41	(.47) to 2.63	0.15	(.05) to .29	0.19	(.06) to .35	0.06	(0.02) to 0.12	0.14	(0.05) to 0.25
1998	-7.33	(11.0) to (3.79)	1.63	(.37) to 3.01	0.15	(.04) to .28	0.20	(.05) to .36	0.08	(0.02) to 0.14	0.15	(0.03) to 0.28
1999	-7.07	(10.57) to (3.71)	1.49	(.33) to 2.79	0.13	(.03) to .24	0.19	(.04) to .35	0.07	(0.02) to 0.13	0.14	(0.03) to 0.26
2000	-6.75	(10.09) to (3.56)	1.48	(.39) to 2.78	0.12	(.03) to .22	0.22	(.06) to .42	0.07	(0.02) to 0.14	0.14	(0.04) to 0.26
2001	-6.71	(9.94) to (3.62)	1.54	(.35) to 2.85	0.10	(.02) to .18	0.23	(.05) to .42	0.08	(0.02) to 0.14	0.14	(0.03) to 0.26
2002	-6.72	(9.79) to (3.80)	1.45	(.30) to 2.66	0.09	(.02) to .16	0.20	(.04) to .36	0.07	(0.02) to 0.14	0.14	(0.03) to 0.25
2003	-6.05	(8.97) to (3.30)	1.42	(.24) to 2.59	0.08	(.01) to .15	0.19	(.03) to .34	0.07	(0.01) to 0.12	0.13	(0.02) to 0.24
2004	-5.43	(8.24) to (2.75)	1.60	(.17) to 2.79	0.08	(.01) to .15	0.21	(.02) to .37	0.07	(0.01) to 0.12	0.14	(0.01) to 0.25
2005	-5.40	(7.97) to (2.98)	1.53	(.18) to 2.70	0.08	(.01) to .13	0.19	(.02) to .34	0.07	(0.01) to 0.12	0.13	(0.01) to 0.23
2006	-4.36	(6.67) to (2.22)	1.77	(.19) to 2.89	0.09	(.01) to .14	0.23	(.02) to .37	0.08	(0.01) to 0.13	0.15	(0.01) to 0.25
2007	-3.96	(6.14) to (1.98)	1.83	(.13) to 2.92	0.08	(.01) to .13	0.23	(.02) to .36	0.09	(0.01) to 0.14	0.15	(0.01) to 0.23
2008	-3.37	(5.38) to (1.53)	1.86	(.06) to 2.98	0.06	.0 to .10	0.24	(.01) to .38	0.08	0.0 to 0.13	0.14	0.0 to 0.22
2009	-3.52	(5.33) to (1.88)	1.70	(.02) to 2.72	0.06	.0 to .09	0.22	.0 to .36	0.07	0.0 to 0.12	0.12	0.0 to 0.18
2010	-3.58	(5.45) to (1.91)	1.68	.02 to 2.68	0.06	.0 to .09	0.22	.0 to .35	0.08	0.0 to 0.12	0.11	0.0 to 0.18
2011	-3.49	(5.17) to (1.99)	1.70	.01 to 2.68	0.06	.0 to .09	0.22	.0 to .35	0.09	0.0 to 0.14	0.12	0.0 to 0.19
2012	-2.88	(4.41) to (1.55)	1.70	(.01) to 2.64	0.06	.0 to .10	0.22	.0 to .34	0.09	0.0 to 0.15	0.12	0.0 to 0.19
2013	-2.69	(4.17) to (1.39)	1.70	.0 to 2.65	0.06	.0 to .10	0.22	.0 to .34	0.09	0.0 to 0.15	0.12	0.0 to 0.19
2014	-2.74	(4.24) to (1.42)	1.71	.0 to 2.65	0.06	.0 to .10	0.22	.0 to .34	0.09	0.0 to 0.15	0.12	0.0 to 0.19
2015	-2.71	(4.20) to (1.40)	1.71	.01 to 2.65	0.06	.0 to .10	0.22	.0 to .34	0.09	0.0 to 0.15	0.12	0.0 to 0.19
Organic Soils												
1990	20.02	43.38 to 2.52	1.46	3.95 to 0.11	0.06	0.18 to 0.10	0.00	0.22 to 0.03	0.00	0.06 to 0.62	0.30	1.07 to 7.21
1991	19.76	42.59 to 2.55	1.53	3.87 to 0.11	0.06	0.18 to 0.10	0.00	0.24 to 0.03	0.00	0.07 to 0.63	0.29	1.10 to 7.16
1992	19.60	42.96 to 2.58	1.50	4.0 to 0.10	0.05	0.17 to 0.04	0.00	0.14 to 0.03	0.00	0.06 to 0.63	0.34	1.03 to 7.08
1993	19.53	42.63 to 2.71	1.60	4.16 to 0.10	0.06	0.17 to 0.10	0.00	0.24 to 0.03	0.00	0.06 to 0.81	0.48	1.23 to 7.03
1994	19.32	42.42 to 2.71	1.62	4.14 to 0.10	0.05	0.17 to 0.10	0.00	0.23 to 0.05	0.02	0.09 to 0.96	0.56	1.48 to 6.99
1995	19.27	42.49 to 2.93	1.71	4.50 to 0.09	0.05	0.16 to 0.10	0.00	0.24 to 0.04	0.01	0.07 to 0.99	0.61	1.49 to 6.93
1996	19.18	42.44 to 3.02	1.76	4.66 to 0.10	0.05	0.17 to 0.10	0.00	0.24 to 0.05	0.02	0.09 to 10.01	0.59	1.55 to 6.85
1997	19.19	42.51 to 3.0	1.79	4.61 to 0.10	0.05	0.17 to 0.10	0.00	0.24 to 0.04	0.01	0.07 to 10.0	0.58	1.55 to 6.77
1998	18.80	42.07 to 3.51	1.82	5.76 to 0.09	0.04	0.17 to 0.06	0.00	0.20 to 0.04	0.01	0.08 to 0.95	0.55	1.49 to 6.67
1999	15.81	35.47 to 3.53	1.82	5.80 to 0.09	0.04	0.16 to 0.06	0.00	0.20 to 0.04	0.01	0.08 to 0.95	0.54	1.50 to 6.62
2000	15.85	35.55 to 3.25	1.76	5.24 to 0.09	0.04	0.16 to 0.06	0.00	0.20 to 0.04	0.01	0.08 to 0.86	0.48	1.36 to 6.50
2001	18.76	42.52 to 4.18	1.92	7.59 to 0.08	0.04	0.15 to 0.06	0.00	0.20 to 0.04	0.01	0.08 to 0.83	0.44	1.33 to 6.20
2002	19.09	42.88 to 4.18	1.91	7.52 to 0.06	0.02	0.12 to 0.06	0.00	0.20 to 0.04	0.01	0.08 to 0.81	0.44	1.29 to 6.14
2003	19.33	43.45 to 3.99	1.78	7.27 to 0.08	0.03	0.15 to 0.06	0.00	0.20 to 0.03	0.00	0.06 to 0.69	0.36	1.13 to 6.05
2004	19.52	43.88 to 3.39	1.51	6.05 to 0.05	0.01	0.10 to 0.06	0.00	0.20 to 0.03	0.00	0.07 to 0.72	0.40	1.14 to 6.01
2005	19.26	43.32 to 3.33	1.47	5.93 to 0.04	0.01	0.10 to 0.06	0.00	0.20 to 0.03	0.00	0.08 to 0.71	0.40	1.14 to 5.97
2006	19.24	43.36 to 3.26	1.49	5.77 to 0.04	0.01	0.09 to 0.06	0.00	0.20 to 0.03	0.00	0.08 to 0.71	0.40	1.14 to 5.76
2007	19.33	42.90 to 3.23	1.39	5.83 to 0.02	0.01	0.05 to 0.06	0.00	0.20 to 0.05	0.02	0.10 to 0.69	0.36	1.16 to 5.73
2008	19.18	42.70 to 3.0	1.25	5.54 to 0.03	0.01	0.07 to 0.06	0.00	0.20 to 0.05	0.01	0.11 to 0.55	0.31	0.87 to 5.69

2009	19.31	43.44 to 2.94	1.20	5.41 to 0.03	0.01	0.07 to 0.06	0.00	0.20 to 0.05	0.01	0.10 to 0.50	0.29	0.78 to 5.68
2010	19.31	43.32 to 2.87	1.23	5.30 to 0.03	0.01	0.07 to 0.0	0.00	0.0 to 0.05	0.01	0.10 to 0.50	0.28	0.80 to 5.64
2011	18.31	40.44 to 2.98	1.09	5.61 to 0.02	0.00	0.05 to 0.0	0.00	0.0 to 0.07	0.02	0.15 to 0.53	0.30	0.84 to 5.61
2012	18.47	40.58 to 3.03	1.18	5.65 to 0.02	0.00	0.03 to 0.0	0.00	0.0 to 0.09	0.04	0.17 to 0.53	0.31	0.83 to 5.53
2013	18.47	40.43 to 3.03	1.27	5.54 to 0.02	0.00	0.03 to 0.0	0.00	0.0 to 0.09	0.03	0.18 to 0.53	0.30	0.83 to 5.51
2014	18.50	40.61 to 3.03	1.27	5.59 to 0.02	0.00	0.03 to 0.0	0.00	0.0 to 0.09	0.03	0.18 to 0.53	0.30	0.83 to 5.51
2015	18.44	40.35 to 3.02	1.26	5.55 to 0.02	0.00	0.03 to 0.0	0.00	0.0 to 0.09	0.03	0.18 to 0.53	0.30	0.83 to 5.52

Note: Estimates after 2012 are based on NRI data from 2012 and therefore do not fully reflect changes occurring in the latter part of the time series.

Table A-218: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Non-Federal Grasslands Land Base Estimated with the Tier 2 Analysis using U.S. Factor Values (MMT CO_2 Eq./year)

Non-Federal Grasslands:	Grassland Remaining Grassland		Cropland Converted to Grassland		Forest Converted to Grassland		Other Land Converted to Grassland		Settlements Converted to Grassland		Wetlands Converted to Grassland	
Year	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Mineral Soils												
1990	-0.43	(1.02) to (.03)	-2.90	(4.17) to (1.74)	-0.75	(1.09) to (0.45)	-0.54	(0.78) to (0.33)	-0.08	(0.12) to (0.05)	-0.32	(0.46) to (0.19)
1991	-0.54	(1.18) to (.08)	-2.90	(4.16) to (1.75)	-0.77	(1.10) to (0.46)	-0.56	(0.81) to (0.34)	-0.09	(0.13) to (0.05)	-0.39	(0.56) to (0.23)
1992	-0.54	(1.50) to (.13)	-2.79	(4.01) to (1.68)	-0.75	(1.08) to (0.45)	-0.58	(0.83) to (0.35)	-0.09	(0.12) to (0.05)	-0.46	(0.66) to (0.28)
1993	-0.44	(1.05) to (.04)	-2.94	(4.22) to (1.77)	-0.74	(1.07) to (0.45)	-0.67	(0.96) to (0.40)	-0.10	(0.14) to (0.06)	-0.48	(0.69) to (0.29)
1994	-0.09	(0.52) to 0.28	-3.10	(4.46) to (1.86)	-0.72	(1.04) to (0.44)	-0.79	(1.14) to (0.47)	-0.11	(0.15) to (0.06)	-0.50	(0.72) to (0.30)
1995	-0.09	(0.49) to 0.26	-2.89	(4.16) to (1.73)	-0.70	(1.01) to (0.42)	-0.80	(1.15) to (0.48)	-0.10	(0.15) to (0.06)	-0.48	(0.70) to (0.29)
1996	-0.10	(0.49) to 0.23	-2.69	(3.87) to (1.62)	-0.70	(1.0) to (0.42)	-0.79	(1.13) to (0.47)	-0.11	(0.16) to (0.07)	-0.47	(0.67) to (0.28)
1997	-0.22	(0.65) to 0.07	-2.59	(3.69) to (1.59)	-0.70	(0.99) to (0.43)	-0.84	(1.20) to (0.51)	-0.11	(0.16) to (0.07)	-0.47	(0.66) to (0.29)
1998	-0.09	(0.51) to 0.27	-3.22	(4.61) to (1.94)	-0.70	(1.01) to 0(.42)	-0.92	(1.32) to (0.56)	-0.12	(0.18) to (0.07)	-0.49	(0.70) to (0.29)
1999	-0.06	(0.45) to 0.29	-3.11	(4.46) to (1.89)	-0.69	(0.99) to (0.42)	-0.96	(1.37) to (0.58)	-0.13	(0.18) to (0.08)	-0.48	(0.69) to (0.29)
2000	-0.13	(0.54) to 0.17	-3.16	(4.52) to (1.91)	-0.70	(1.01) to (0.43)	-1.12	(1.61) to (0.68)	-0.13	(0.19) to (0.08)	-0.50	(0.71) to (0.30)
2001	-0.10	(0.48) to 0.21	-3.06	(4.39) to (1.84)	-0.67	(0.96) to (0.40)	-1.16	(1.66) to (0.70)	-0.14	(0.20) to (0.08)	-0.49	(0.70) to (0.29)
2002	-0.06	(0.41) to 0.24	-2.78	(4.0) to (1.67)	-0.62	(0.90) to (0.37)	-1.09	(1.57) to (0.65)	-0.14	(0.19) to (0.08)	-0.45	(0.65) to (0.27)
2003	-0.01	(0.32) to 0.29	-2.51	(3.62) to (1.49)	-0.55	(0.79) to (0.33)	-1.03	(1.49) to (0.61)	-0.12	(0.17) to (0.07)	-0.42	(0.61) to (0.25)
2004	0.06	(0.23) to 0.39	-2.65	(3.83) to (1.58)	-0.53	(0.76) to (0.31)	-1.07	(1.54) to (0.64)	-0.12	(0.18) to (0.07)	-0.44	(0.63) to (0.26)
2005	0.05	(0.24) to 0.39	-2.43	(3.51) to (1.44)	-0.47	(0.68) to (0.28)	-1.08	(1.56) to (0.64)	-0.12	(0.18) to (0.07)	-0.43	(0.62) to (0.26)
2006	0.05	(0.25) to 0.40	-1.91	(2.82) to (1.07)	-0.35	(0.52) to (0.20)	-0.90	(1.33) to (0.51)	-0.11	(0.16) to (0.06)	-0.36	(0.53) to (0.20)
2007	0.10	(0.17) to 0.43	-1.59	(2.37) to (0.88)	-0.29	(0.43) to (0.16)	-0.83	(1.25) to (0.46)	-0.10	(0.15) to (0.05)	-0.32	(0.48) to (0.18)
2008	0.16	(0.08) to 0.52	-1.45	(2.15) to (0.80)	-0.25	(0.37) to (0.14)	-0.83	(1.24) to (0.46)	-0.09	(0.14) to (0.05)	-0.26	(0.39) to (0.15)
2009	0.26	(0.02) to 0.69	-1.38	(2.06) to (0.77)	-0.24	(0.36) to (0.14)	-0.85	(1.26) to (0.47)	-0.09	(0.13) to (0.05)	-0.23	(0.34) to (0.13)
2010	0.31	0.02 to 0.73	-1.31	(1.95) to (0.73)	-0.23	(0.34) to (0.13)	-0.84	(1.25) to (0.47)	-0.09	(0.14) to (0.05)	-0.19	(0.29) to (0.11)
2011	0.31	0.02 to 0.76	-1.22	(1.83) to (0.67)	-0.21	(0.31) to (0.12)	-0.81	(1.22) to (0.45)	-0.09	(0.14) to (0.05)	-0.16	(0.23) to (0.09)
2012	0.24	(0.01) to 0.65	-1.16	(1.73) to (0.64)	-0.20	(0.29) to (0.11)	-0.80	(1.19) to (0.44)	-0.09	(0.14) to (0.05)	-0.11	(0.17) to (0.06)
2013	0.27	0.0 to 0.68	-1.15	(1.73) to (0.63)	-0.19	(0.29) to (0.11)	-0.79	(1.19) to (0.44)	-0.09	(0.14) to (0.05)	-0.11	(0.16) to (0.06)
2014	0.28	0.0 to 0.72	-1.15	(1.73) to (0.63)	-0.19	(0.29) to (0.11)	-0.79	(1.19) to (0.44)	-0.09	(0.14) to (0.05)	-0.11	(0.16) to (0.06)
2015	0.29	0.01 to 0.73	-1.15	(1.73) to (0.63)	-0.19	(0.29) to (0.11)	-0.79	(1.19) to (0.44)	-0.09	(0.14) to (0.05)	-0.11	(0.16) to (0.06)

Note: Estimates after 2012 are based on NRI data from 2012 and therefore do not fully reflect changes occurring in the latter part of the time series.

Table A-219: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Federal Grasslands Land Base Estimated with the Tier 2 Analysis using U.S. Factor Values (MMT CO_2 Eq./year)

Federal Grasslands:	Grassland Remaining Grassland		Cropland Converted to Grassland		Forest Converted to Grassland		Other Land Converted to Grassland		Settlements Converted to Grassland		Wetlands Converted to Grassland	
Year	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Mineral Soils												
1990	-0.20	(8.94) to 9.45	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1991	-0.30	(9.28) to 8.76	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1992	-0.30	(10.08) to 8.06	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1993	-1.16	(11.03) to 7.60	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1994	-1.50	(11.79) to 7.18	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1995	-1.52	(12.0) to 7.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1996	-0.90	(10.65) to 7.01	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1997	-0.83	(10.42) to 7.27	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0	0.00	0.0 to 0.0
1998	-1.62	(13.58) to 7.15	0.00	(0.03) to 0.02	-0.10	(0.75) to 0.52	-0.01	(0.04) to 0.03	0.00	0.0 to 0.0	-0.01	(0.05) to 0.03
1999	-1.44	(13.27) to 7.24	0.00	(0.03) to 0.02	-0.10	(0.74) to 0.52	-0.01	(0.04) to 0.03	0.00	0.0 to 0.0	-0.01	(0.05) to 0.03
2000	-1.70	(12.68) to 6.38	0.00	(0.03) to 0.02	-0.10	(0.74) to 0.51	-0.01	(0.04) to 0.03	0.00	0.0 to 0.0	-0.01	(0.05) to 0.03
2001	-1.71	(12.81) to 6.44	0.00	(0.03) to 0.02	-0.10	(0.73) to 0.51	-0.01	(0.04) to 0.03	0.00	0.0 to 0.0	-0.01	(0.05) to 0.03
2002	-2.72	(14.63) to 7.05	0.00	(0.03) to 0.02	-0.11	(0.70) to 0.45	-0.01	(0.04) to 0.03	0.00	0.0 to 0.0	-0.01	(0.04) to 0.03
2003	-2.73	(14.72) to 7.76	0.00	(0.03) to 0.02	-0.11	(0.70) to 0.45	-0.01	(0.04) to 0.03	0.00	0.0 to 0.0	-0.01	(0.04) to 0.03
2004	-1.28	(11.29) to 8.85	0.00	(0.03) to 0.02	-0.11	(0.70) to 0.46	-0.01	(0.04) to 0.03	0.00	0.0 to 0.0	-0.01	(0.04) to 0.03
2005	-1.37	(11.44) to 8.50	0.00	0.0 to 0.0	-0.07	(0.86) to 0.70	0.00	(0.02) to 0.02	0.00	0.0 to 0.0	0.00	(0.04) to 0.03
2006	-1.51	(11.82) to 8.56	0.00	0.0 to 0.0	-0.07	(0.86) to 0.70	0.00	(0.02) to 0.02	0.00	0.0 to 0.0	0.00	(0.04) to 0.03
2007	-1.63	(11.93) to 8.11	0.00	0.0 to 0.0	-0.07	(0.86) to 0.70	0.00	(0.02) to 0.02	0.00	0.0 to 0.0	0.00	(0.04) to 0.03
2008	-1.67	(12.11) to 8.20	0.00	0.0 to 0.0	-0.07	(0.86) to 0.70	0.00	(0.02) to 0.02	0.00	0.0 to 0.0	0.00	(0.04) to 0.03
2009	-1.46	(11.57) to 7.14	0.00	0.0 to 0.0	-0.07	(0.85) to 0.70	0.00	(0.02) to 0.02	0.00	0.0 to 0.0	0.00	(0.04) to 0.03
2010	-1.53	(11.51) to 7.48	0.00	0.0 to 0.0	-0.07	(0.86) to 0.69	0.00	(0.02) to 0.02	0.00	0.0 to 0.0	0.00	(0.04) to 0.03
2011	-1.15	(10.79) to 8.01	0.00	0.0 to 0.0	-0.07	(0.85) to 0.69	0.00	(0.02) to 0.02	0.00	0.0 to 0.0	0.00	(0.04) to 0.03
2012	-0.67	(9.89) to 8.69	0.00	0.0 to 0.0	-0.07	(0.85) to 0.69	0.00	(0.02) to 0.02	0.00	0.0 to 0.0	0.00	(0.04) to 0.03
2013	-0.38	(9.23) to 9.19	0.00	0.0 to 0.0	-0.06	(0.85) to 0.69	0.00	(0.02) to 0.02	0.00	0.0 to 0.0	0.00	(0.04) to 0.03
2014	-0.36	(9.27) to 9.45	0.00	0.0 to 0.0	-0.06	(0.85) to 0.69	0.00	(0.02) to 0.02	0.00	0.0 to 0.0	0.00	(0.04) to 0.03
2015	-0.98	(10.56) to 9.30	0.00	0.0 to 0.0	-0.06	(0.85) to 0.69	0.00	(0.02) to 0.02	0.00	0.0 to 0.0	0.00	(0.04) to 0.03

Note: Estimates after 2012 are based on NRI data from 2012 and therefore do not fully reflect changes occurring in the latter part of the time series.

Table A-220: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Total Grassland Land Base Estimated with the Tier 2 Analysis using U.S. Factor Values (MMT CO_2 Eq./year)

Total Grasslands:	Grassland Remaining Grassland		Cropland Converted to Grassland		Forest Converted to Grassland		Other Land Converted to Grassland		Settlements Converted to Grassland		Wetlands Converted to Grassland	
Year	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Mineral Soils												
1990	-0.62	(9.39) to 9.03	-2.90	(4.17) to (1.74)	-0.75	(1.09) to (0.45)	-0.54	(0.78) to (0.33)	-0.08	(0.12) to (0.05)	-0.32	(0.46) to (0.19)
1991	-0.84	(9.85) to 8.23	-2.90	(4.16) to (1.75)	-0.77	(1.10) to (0.46)	-0.56	(0.81) to (0.34)	-0.09	(0.13) to (0.05)	-0.39	(0.56) to (0.23)

1992	-0.84	(10.83) to 7.36	-2.79	(4.01) to (1.68)	-0.75	(1.08) to (0.45)	-0.58	(0.83) to (0.35)	-0.09	(0.12) to (0.05)	-0.46	(0.66) to (0.28)
1993	-1.60	(11.49) to 7.16	-2.94	(4.22) to (1.77)	-0.74	(1.07) to (0.45)	-0.67	(0.96) to (0.40)	-0.10	(0.14) to (0.06)	-0.48	(0.69) to (0.29)
1994	-1.59	(11.89) to 7.09	-3.10	(4.46) to (1.86)	-0.72	(1.04) to (0.44)	-0.79	(1.14) to (0.47)	-0.11	(0.15) to (0.06)	-0.50	(0.72) to (0.30)
1995	-1.61	(12.10) to 6.93	-2.89	(4.16) to (1.73)	-0.70	(1.01) to (0.42)	-0.80	(1.15) to (0.48)	-0.10	(0.15) to (0.06)	-0.48	(0.70) to (0.29)
1996	-1.00	(10.76) to 6.92	-2.69	(3.87) to (1.62)	-0.70	(1.0) to (0.42)	-0.79	(1.13) to (0.47)	-0.11	(0.16) to (0.07)	-0.47	(0.67) to (0.28)
1997	-1.05	(10.65) to 7.06	-2.59	(3.69) to (1.59)	-0.70	(.99) to (0.43)	-0.84	(1.20) to (0.51)	-0.11	(0.16) to (0.07)	-0.47	(0.66) to (0.29)
1998	-1.71	(13.68) to 7.07	-3.22	(4.61) to (1.95)	-0.80	(1.52) to (0.12)	-0.92	(1.32) to (0.56)	-0.12	(0.18) to (0.07)	-0.49	(0.71) to (0.30)
1999	-1.49	(13.34) to 7.19	-3.12	(4.46) to (1.89)	-0.79	(1.50) to (0.12)	-0.96	(1.38) to (0.58)	-0.13	(0.18) to (0.08)	-0.49	(0.70) to (0.29)
2000	-1.84	(12.83) to 6.25	-3.16	(4.52) to (1.91)	-0.80	(1.51) to (0.14)	-1.13	(1.61) to (0.68)	-0.13	(0.19) to (0.08)	-0.50	(0.72) to (0.30)
2001	-1.81	(12.91) to 6.35	-3.06	(4.39) to (1.84)	-0.77	(1.46) to (0.10)	-1.17	(1.67) to (0.70)	-0.14	(0.20) to (0.08)	-0.49	(0.71) to (0.30)
2002	-2.78	(14.69) to 7.0	-2.78	(4.0) to (1.67)	-0.74	(1.38) to (0.12)	-1.10	(1.57) to (0.66)	-0.14	(0.19) to (0.08)	-0.46	(0.66) to (0.28)
2003	-2.74	(14.73) to 7.75	-2.51	(3.62) to (1.49)	-0.66	(1.30) to (0.06)	-1.04	(1.50) to (0.62)	-0.12	(0.17) to (0.07)	-0.43	(0.62) to (0.25)
2004	-1.22	(11.23) to 8.91	-2.66	(3.84) to (1.58)	-0.63	(1.27) to (0.03)	-1.08	(1.55) to (0.64)	-0.12	(0.18) to (0.07)	-0.45	(0.65) to (0.26)
2005	-1.32	(11.39) to 8.56	-2.43	(3.51) to (1.44)	-0.54	(1.36) to 0.25	-1.08	(1.56) to (0.64)	-0.12	(0.18) to (0.07)	-0.43	(0.63) to (0.25)
2006	-1.45	(11.77) to 8.62	-1.91	(2.82) to (1.07)	-0.42	(1.23) to 0.36	-0.90	(1.34) to (0.51)	-0.11	(0.16) to (0.06)	-0.36	(0.54) to (0.20)
2007	-1.53	(11.84) to 8.21	-1.59	(2.37) to (.88)	-0.35	(1.16) to 0.42	-0.84	(1.25) to (0.46)	-0.10	(0.15) to (0.05)	-0.33	(0.49) to (0.18)
2008	-1.50	(11.95) to 8.37	-1.45	(2.15) to (.80)	-0.31	(1.12) to 0.46	-0.84	(1.24) to (0.47)	-0.09	(0.14) to (0.05)	-0.26	(0.40) to (0.14)
2009	-1.20	(11.32) to 7.41	-1.38	(2.06) to (.77)	-0.31	(1.10) to 0.46	-0.85	(1.26) to (0.47)	-0.09	(0.13) to (0.05)	-0.23	(0.34) to (0.12)
2010	-1.22	(11.20) to 7.80	-1.31	(1.95) to (.73)	-0.29	(1.09) to 0.47	-0.84	(1.25) to (0.47)	-0.09	(0.14) to (0.05)	-0.20	(0.30) to (0.10)
2011	-0.84	(10.48) to 8.34	-1.22	(1.83) to (.67)	-0.28	(1.07) to 0.49	-0.82	(1.23) to (0.45)	-0.09	(0.14) to (0.05)	-0.16	(0.24) to (0.08)
2012	-0.43	(9.65) to 8.94	-1.16	(1.73) to (.64)	-0.26	(1.05) to 0.50	-0.80	(1.19) to (0.44)	-0.09	(0.14) to (0.05)	-0.11	(0.18) to (0.05)
2013	-0.11	(8.97) to 9.47	-1.15	(1.73) to (.64)	-0.26	(1.05) to 0.50	-0.79	(1.19) to (0.44)	-0.09	(0.14) to (0.05)	-0.11	(0.18) to (0.05)
2014	-0.08	(8.99) to 9.74	-1.15	(1.73) to (.63)	-0.26	(1.05) to 0.50	-0.79	(1.19) to (0.44)	-0.09	(0.14) to (0.05)	-0.11	(0.18) to (0.05)
2015	-0.69	(10.27) to 9.60	-1.15	(1.73) to (.63)	-0.26	(1.05) to 0.50	-0.79	(1.19) to (0.44)	-0.09	(0.14) to (0.05)	-0.11	(0.18) to (0.05)
Organic Soils												
1990	4.07	11.35 to 0.53	0.23	0.98 to 0.01	0.00	0.03 to 0.04	0.01	0.09 to 0.0	0.00	0.0 to 0.12	0.05	0.23 to 0.0
1991	4.00	11.43 to 0.53	0.23	0.97 to 0.01	0.00	0.03 to 0.04	0.01	0.09 to 0.0	0.00	0.0 to 0.12	0.05	0.22 to 0.0
1992	3.95	11.25 to 0.51	0.22	0.94 to 0.01	0.00	0.03 to 0.04	0.01	0.09 to 0.0	0.00	0.0 to 0.12	0.02	0.30 to 0.0
1993	3.90	11.26 to 0.57	0.26	1.0 to 0.02	0.01	0.04 to 0.04	0.01	0.09 to 0.0	0.00	0.01 to 0.18	0.07	0.36 to 0.0
1994	3.91	11.08 to 0.70	0.32	1.27 to 0.02	0.01	0.04 to 0.04	0.01	0.09 to 0.01	0.00	0.02 to 0.24	0.11	0.42 to 0.0
1995	3.88	11.02 to 0.70	0.31	1.27 to 0.02	0.01	0.03 to 0.04	0.01	0.09 to 0.01	0.00	0.02 to 0.24	0.12	0.40 to 0.0
1996	3.82	10.90 to 0.68	0.30	1.24 to 0.02	0.01	0.03 to 0.04	0.01	0.09 to 0.01	0.00	0.02 to 0.24	0.13	0.39 to 0.0
1997	3.77	10.77 to 0.69	0.32	1.23 to 0.02	0.01	0.03 to 0.03	0.00	0.07 to 0.01	0.00	0.03 to 0.24	0.13	0.40 to 0.0
1998	3.70	10.68 to 0.86	0.43	1.49 to 0.02	0.00	0.03 to 0.03	0.00	0.07 to 0.02	0.00	0.04 to 0.25	0.13	0.41 to 0.0
1999	3.67	10.58 to 0.84	0.41	1.44 to 0.01	0.00	0.03 to 0.03	0.00	0.07 to 0.02	0.00	0.04 to 0.25	0.13	0.41 to 0.0
2000	3.61	10.34 to 0.88	0.44	1.51 to 0.05	0.01	0.10 to 0.03	0.00	0.07 to 0.02	0.00	0.04 to 0.30	0.16	0.48 to 0.0
2001	3.42	9.91 to 0.99	0.50	1.67 to 0.06	0.02	0.12 to 0.03	0.00	0.08 to 0.02	0.00	0.04 to 0.30	0.16	0.49 to 0.0
2002	3.39	9.79 to 1.10	0.55	1.84 to 0.06	0.02	0.12 to 0.03	0.00	0.08 to 0.02	0.00	0.04 to 0.28	0.15	0.45 to 0.0
2003	3.33	9.69 to 1.03	0.53	1.74 to 0.07	0.03	0.14 to 0.03	0.00	0.08 to 0.02	0.00	0.04 to 0.24	0.14	0.38 to 0.0
2004	3.28	9.65 to 1.13	0.57	1.91 to 0.09	0.04	0.16 to 0.04	0.01	0.09 to 0.02	0.00	0.04 to 0.24	0.13	0.39 to 0.0
2005	3.27	9.58 to 1.13	0.58	1.91 to 0.09	0.04	0.16 to 0.04	0.01	0.09 to 0.02	0.00	0.04 to 0.26	0.14	0.42 to 0.0
2006	3.12	9.33 to 1.13	0.57	1.90 to 0.09	0.04	0.17 to 0.04	0.01	0.09 to 0.02	0.00	0.04 to 0.28	0.15	0.44 to 0.0
2007	3.11	9.26 to 1.11	0.57	1.87 to 0.09	0.04	0.17 to 0.04	0.01	0.09 to 0.02	0.00	0.04 to 0.28	0.15	0.45 to 0.0
2008	3.08	9.18 to 1.07	0.54	1.82 to 0.10	0.04	0.19 to 0.05	0.01	0.10 to 0.02	0.00	0.04 to 0.28	0.16	0.46 to 0.0
2009	3.08	9.17 to 1.15	0.59	1.92 to 0.10	0.04	0.18 to 0.03	0.01	0.07 to 0.02	0.00	0.04 to 0.33	0.19	0.52 to 0.0
2010	3.07	9.12 to 1.15	0.59	1.92 to 0.10	0.04	0.18 to 0.03	0.01	0.07 to 0.02	0.00	0.04 to 0.34	0.19	0.54 to 0.0

2011	3.05	9.08 to 1.14	0.58	1.93 to 0.10	0.04	0.19 to 0.05	0.02	0.11 to 0.02	0.00	0.04 to 0.33	0.19	0.53 to 0.0
2012	3.00	8.91 to 1.12	0.57	1.88 to 0.10	0.04	0.19 to 0.05	0.02	0.11 to 0.02	0.00	0.04 to 0.33	0.19	0.52 to 0.0
2013	2.99	8.87 to 1.12	0.58	1.87 to 0.10	0.05	0.19 to 0.05	0.02	0.11 to 0.02	0.00	0.04 to 0.33	0.19	0.52 to 0.0
2014	3.00	8.90 to 1.12	0.57	1.89 to 0.10	0.04	0.19 to 0.05	0.02	0.11 to 0.02	0.00	0.04 to 0.33	0.19	0.53 to 0.0
2015	3.00	8.87 to 1.12	0.57	1.88 to 0.10	0.04	0.19 to 0.05	0.02	0.11 to 0.02	0.00	0.04 to 0.33	0.19	0.53 to 0.0

1 Note: Estimates after 2012 are based on NRI data from 2012 and therefore do not fully reflect changes occurring in the latter part of the time series.

Step 3: Estimate Soil Organic C Stock Changes and Direct N_2O Emissions from Organic Soils

In this step, soil organic C losses and N_2O emissions are estimated for organic soils that are drained for agricultural production.

Step 3a: Direct N_2O Emissions Due to Drainage of Organic Soils in Cropland and Grassland

To estimate annual N_2O emissions from drainage of organic soils in cropland and grassland, the area of drained organic soils in croplands and grasslands for temperate regions is multiplied by the IPCC (2006) default emission factor for temperate soils and the corresponding area in sub-tropical regions is 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 is 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 3b: Soil Organic C Stock Changes Due to Drainage of Organic Soils in Cropland and Grassland

Change in soil organic C stocks due to drainage of cropland and grassland soils are estimated annually from 1990 through 2012, based on the land-use and management activity data in conjunction with appropriate loss rate emission factors. The activity data are based on annual data from 1990 through 2012 from the NRI. The results for 2012 are applied to the years 2013 through 2015. Organic Soil emission factors representative of U.S. conditions have been estimated from published studies (Ogle et al. 2003), based on subsidence studies in the United States and Canada (Table A-222). PDFs are constructed as normal densities based on the mean C loss rates and associated variances. Input values are randomly selected from PDFs in a Monte Carlo analysis to estimate SOC change for 50,000 times and produce a 95 percent confidence interval for the inventory results. Losses of soil organic C from drainage of cropland and grassland soils are provided in Table A-215 and Table A-218.

Step 4: Estimate Indirect N_2O Emissions for Croplands and Grasslands

In this step, N_2O emissions are estimated for the two indirect emission pathways (N_2O emissions due to volatilization, and N_2O emissions due to leaching and runoff of N), which are summed to yield total indirect N_2O emissions from croplands and grasslands.

Step 4a: Indirect Soil N_2O Emissions Due to Volatilization

Indirect emissions from volatilization of N inputs from synthetic and commercial organic fertilizers, and PRP manure, are calculated according to the amount of mineral N that is transported in gaseous forms from the soil profile and later emitted as soil N_2O following atmospheric deposition. See Step 1e for additional information about the methods used to compute N losses due to volatilization. The estimated N volatilized is multiplied by the IPCC default emission factor of 0.01 kg N_2O-N/kg N (IPCC 2006) to estimate total N_2O emissions from volatilization. The uncertainty is estimated 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). The estimates are provided in Table A-223 and implied Tier 3 emission factors are in Table A-226 and Table A-227.

Step 4b: Indirect Soil N_2O Emissions Due to Leaching and Runoff

The amount of mineral N from synthetic fertilizers, commercial organic fertilizers, PRP manure, crop residue, N mineralization, asymbiotic fixation that is transported from the soil profile in aqueous form is used to calculate indirect emissions from leaching of mineral N from soils and losses in runoff of water associated with overland flow. See Step 1e 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 is 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 emission estimates are provided in Table A-224 and implied Tier 3 emission factors are in Tables Table A-226 and Table A-227. The uncertainty is estimated 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 Soil Organic C Stock Changes and N_2O Emissions for U.S. Soils

Step 5a: Estimate Total Soil N_2O Emissions

Total N_2O emissions are estimated by adding total direct emissions (from mineral cropland soils, drainage and cultivation of organic soils, and grassland management) to indirect emissions. Uncertainties in the final estimate are combined using simple error propagation methods (IPCC 2006), and expressed as a 95 percent confidence interval. Estimates are provided in Table A-225.

Direct and indirect simulated emissions of soil N_2O vary regionally in croplands as a function of N input amount and timing of fertilization, tillage intensity, crop rotation sequence, weather, and soil type. Note that there are other management practices, such as fertilizer formulation (Halvorson et al. 2013), that influence emissions but are not represented in the model simulations. The highest total N_2O emissions occur in Iowa, Illinois, Kansas, Minnesota, Nebraska and Texas (Table A-229). On a per area unit basis, direct N_2O emissions are high in some Northeast, Midwest, and many of the Mississippi River Basin states where there are high N inputs to hay, corn and soybean crops, and in some western states where irrigated crops are grown that require high N inputs. Note that although the total crop area in the northeast is relatively low, emissions are high on a per unit area basis because of freeze/thaw cycles during spring that saturate surface soil layers and enhance denitrification rates.

Direct emissions from non-federal grasslands are typically lower than the emissions from croplands (Table A-229) because N inputs tend to be lower, particularly from synthetic fertilizer. Texas, Oklahoma, Kansas, Montana, Missouri, and Kentucky are the highest emitters for this category due to large land areas used for pastures and rangeland (Table A-229). On a per unit of area basis, direct N_2O emissions are higher in the some of the Southeastern, Appalachians, and Midwestern states because these grasslands 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, and therefore there are lower indirect N_2O emissions.

Step 5b: Estimate Total Soil Organic Stock Change

The sum of total CO_2 emissions and removals from the Tier 3 DAYCENT Model Approach, Tier 2 IPCC Methods and additional land-use and management considerations are provided in Table A-229.

The states with highest total amounts of C sequestration are California, Illinois, Iowa, Kentucky, Missouri, North Dakota and Tennessee (Table A-231). For organic soils, emission rates are highest in the regions that contain the majority of drained organic soils, including California, Florida, Indiana, Michigan, Minnesota, North Carolina and Wisconsin. On a per unit of area basis, the emission rate patterns are very similar to the total emissions in each state, with the highest rates in coastal states of the Southeast, states surrounding the Great Lakes, and California.

Step 5c: Estimate Total CH_4 Emissions from Rice Cultivation

The sum of total CH_4 emissions from the Tier 3 DAYCENT Model Approach and Tier 1 IPCC Methods are provided in Table A- 228. The states with highest total emissions are Arkansas, California, Louisiana and Texas (Table A-232). These states also have the largest areas of rice cultivation, and Louisiana and Texas have a relatively large proportion of fields with a second ratoon crop each year. Ratoon crops extend the period of time under flooded conditions, which leads to more CH_4 emissions.

Table A-221: Assumptions and Calculations to Estimate the Contribution to Soil Organic Carbon Stocks from Application of Sewage Sludge to Mineral Soils

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Sewage Sludge N Applied to Agricultural Land (Mg N)[a]	51,848	67,505	83,523	98,400	101,314	104,222	107,123	110,018	112,909	115,797	118,681	121,563	124,443	127,322
Assimilative Capacity (Mg N/ha)[b]	0.12	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]	432,067	553,322	684,612	806,559	830,447	854,276	878,055	901,790	925,487	949,154	972,796	996,417	1,020,025	1,043,622
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
Contribution to Soil C (MMT CO_2/yr)[e,f]	-0.60	-0.77	-0.95	-1.12	-1.16	-1.19	-1.22	-1.26	-1.29	-1.32	-1.36	-1.39	-1.42	-1.45

[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 1993-2015.
[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.
Note: Values in parentheses indicate net C storage.

Table A-222: Carbon Loss Rates for Organic Soils under Agricultural Management in the United States, and IPCC Default Rates (Metric Ton C/ha-yr)

	Cropland		Grassland	
Region	IPCC	U.S. Revised	IPCC	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	1	11.2±2.5	0.25	2.8±0.5[a]

[a] There are 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 is an assumption that is used for the IPCC default organic soil C losses on grassland.

Table A-223: Indirect N_2O Emissions from Volatilization and Atmospheric Deposition (MMT CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Croplands	12.0	13.3	12.8	12.6	12.7	13.1	13.0	13.0	13.6	13.4	13.2	12.7	13.1	12.9	12.7	12.5	12.5	12.7
Grasslands	4.3	4.5	4.2	4.4	4.4	4.4	4.8	4.5	4.5	4.5	4.4	4.5	4.6	4.2	4.2	4.2	4.2	4.2
Total	**16.4**	**17.8**	**17.0**	**17.0**	**17.1**	**17.6**	**17.8**	**17.5**	**18.1**	**17.8**	**17.7**	**17.2**	**17.7**	**17.2**	**16.9**	**16.7**	**16.6**	**16.9**

Table A-224: Indirect N_2O Emissions from Leaching and Runoff (MMT CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Croplands	25.0	23.7	19.4	25.2	21.9	24.2	28.6	21.4	24.9	26.8	29.1	29.2	28.6	29.0	18.9	18.4	18.4	18.4
Grasslands	3.2	3.0	2.5	3.2	3.3	2.6	3.5	2.5	2.8	3.2	3.3	3.6	2.8	3.5	2.6	2.6	2.6	2.6
Total	**28.2**	**26.7**	**21.8**	**28.4**	**25.2**	**26.8**	**32.1**	**23.9**	**27.7**	**30.1**	**32.4**	**32.8**	**31.5**	**32.5**	**21.5**	**21.0**	**20.9**	**21.1**

Table A-225: Total N_2O Emissions from Agricultural Soil Management (MMT CO_2 Eq.)

Activity	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total Direct	**212.0**	**213.7**	**214.0**	**218.5**	**223.6**	**229.2**	**222.1**	**226.4**	**231.1**	**220.4**	**215.6**	**212.8**	**212.4**	**213.3**
Direct Emissions from Mineral Cropland Soils	**144.1**	**146.2**	**149.2**	**150.6**	**153.1**	**157.4**	**153.3**	**154.1**	**159.5**	**155.1**	**153.5**	**151.0**	**151.1**	**151.4**
Synthetic Fertilizer	53.6	53.2	55.9	54.6	56.2	58.2	55.7	53.7	55.0	58.0	60.4	58.3	58.2	58.3
Organic Amendment[a]	10.0	10.5	11.0	10.9	11.3	11.4	11.2	11.1	11.0	11.2	11.3	11.3	11.2	11.4
Residue N[b]	22.1	23.3	23.1	22.9	22.6	22.8	21.7	22.1	24.0	23.9	23.5	23.7	23.8	23.9
Mineralization and Asymbiotic Fixation	58.4	59.2	59.2	62.2	63.0	64.9	64.7	67.2	69.6	62.1	58.2	57.8	57.8	57.8
Direct Emissions from Drained Organic Cropland Soils	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**	**3.2**	**3.2**	**3.2**	**3.2**	**3.2**	**3.2**	**3.2**
Direct Emissions from Mineral Grassland Soils	**61.3**	**61.0**	**58.2**	**61.1**	**63.7**	**65.1**	**62.2**	**65.8**	**65.1**	**58.8**	**55.7**	**55.3**	**54.9**	**55.4**
Synthetic Mineral Fertilizer	0.9	0.8	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.7	0.7	0.7	0.7
PRP Manure	16.1	16.5	14.6	13.8	14.4	13.7	13.5	14.1	13.7	13.6	13.3	13.0	12.5	13.2
Managed Manure	0.9	0.9	1.0	1.1	1.1	1.1	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Sewage Sludge	0.2	0.3	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6
Residue[b]	14.5	15.0	13.9	15.8	15.6	16.5	15.5	15.4	16.5	14.8	14.2	14.2	14.2	14.2
Mineralization and Asymbiotic Fixation	28.5	27.5	27.5	29.2	31.3	32.6	30.9	33.8	32.4	28.1	25.8	25.8	25.8	25.7
Direct Emissions from Drained Organic Grassland Soils	**3.3**	**3.3**	**3.4**	**3.5**	**3.5**	**3.4**	**3.4**	**3.4**	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**
Total Indirect	**44.6**	**44.5**	**38.8**	**41.4**	**45.8**	**47.9**	**50.1**	**50.1**	**49.2**	**49.7**	**38.4**	**37.7**	**37.6**	**38.0**
Volatilization	16.4	17.8	17.0	17.5	18.1	17.8	17.7	17.2	17.7	17.2	16.9	16.7	16.6	16.9
Leaching/Runoff	28.2	26.7	21.8	23.9	27.7	30.1	32.4	32.8	31.5	32.6	21.5	21.0	20.9	21.1
Total Emissions	**256.6**	**258.2**	**252.8**	**259.8**	**269.3**	**277.1**	**272.2**	**276.4**	**280.3**	**270.1**	**254.1**	**250.5**	**250.0**	**251.3**

[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-226: Implied Tier 3 Cropland Indirect Emission Factors

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Indirect N Inputs														
N Inputs Volatilization (N fertilizer + N manure)	10,500	10,174	10,674	10,618	10,382	11,242	10,787	10,743	10,926	10,950	11,127	11,127	11,127	11,127
N Inputs Leachnig (N fertilizer + N manure + N residue)	14,379	14,357	14,897	14,836	14,464	15,413	14,755	14,815	15,411	15,376	15,497	15,497	15,497	15,497
Total Indirect Activity														
Volatilization	866.3	906.5	965.0	998.3	989.5	991.1	979.6	995.5	1101.7	996.5	925.2	917.4	917.4	917.4
Leaching/Runoff	6330.6	5841.1	4591.5	5232.5	6129.7	6739.7	7415.4	7543.1	7333.1	7323.4	4375.4	4339.9	4340.1	4340.5
Implied EF Volotilization	**0.083**	**0.089**	**0.090**	**0.094**	**0.095**	**0.088**	**0.091**	**0.093**	**0.101**	**0.091**	**0.083**	**0.082**	**0.082**	**0.082**
Implied EF Leaching	**0.440**	**0.407**	**0.308**	**0.353**	**0.424**	**0.437**	**0.503**	**0.509**	**0.476**	**0.476**	**0.282**	**0.280**	**0.280**	**0.280**

Table A-227: Implied Tier 3 Grassland Indirect Emission Factors

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Indirect N Inputs														
N Inputs Volatilization (N fertilizer + N PRP manure + N managed manure)	3,875	4,287	4,172	4,261	4,318	4,231	4,195	4,194	4,179	4,074	3,992	3,989	3,990	3,975
N Inputs Leachnig (N residue)	7,967	8,588	8,131	8,722	8,070	8,757	8,454	8,242	8,903	8,508	9,005	8,997	8,988	8,980
N Inputs Leachnig (N fertilizer + N PRP manure + N managed manure + N residue)	11,841	12,875	12,304	12,984	12,389	12,988	12,649	12,436	13,082	12,582	12,997	12,986	12,979	12,955
Total Indirect Activity														
Volatilization	701.5	731.8	695.9	779.0	776.7	788.2	771.1	782.9	798.3	722.7	716.7	716.0	715.6	715.1
Leaching/Runoff	664.2	599.1	493.0	515.6	599.6	731.8	759.1	844.4	612.7	802.0	545.9	544.8	545.0	545.1
Implied Fraction of N Volatilization	**0.181**	**0.171**	**0.167**	**0.183**	**0.180**	**0.186**	**0.184**	**0.187**	**0.191**	**0.177**	**0.180**	**0.180**	**0.179**	**0.180**
Implied Fraction of N Leaching/Runoff	**0.056**	**0.047**	**0.040**	**0.040**	**0.048**	**0.056**	**0.060**	**0.068**	**0.047**	**0.064**	**0.042**	**0.042**	**0.042**	**0.042**

Table A- 228: Total CH_4 Emissions from Cultivation of Rice Estimated with Tier 1 and 3 Inventory Approaches (MMT CO_2 Eq.)

	Rice Methane (MMT CO_2 Eq)													
Approach	**1990**	**1995**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Tier 1	1.63	1.53	3.29	1.74	1.48	1.40	1.59	1.70	1.79	1.51	1.38	1.40	1.50	1.30
Tier 3	14.39	14.23	14.98	14.93	11.38	12.54	9.92	12.76	14.09	12.59	9.96	9.95	9.90	9.92
Total	**16.02**	**15.76**	**18.27**	**16.68**	**12.86**	**13.94**	**11.51**	**14.45**	**15.88**	**14.10**	**11.34**	**11.34**	**11.39**	**11.22**

Table A-229: Total 2015 N_2O Emissions (Direct and Indirect) from Agricultural Soil Management by State (MMT CO_2 Eq.)

State	Croplands[a]	Grasslands[b]	Total	Lower Bound	Upper Bound
AL	1.57	1.27	3.00	2.44	4.13
AR	4.84	1.38	6.50	5.18	9.10
AZ	0.55	0.87	1.84	1.45	3.14
CA	4.17	1.12	8.69	5.85	18.38
CO	2.87	2.06	5.13	4.33	6.80
CT	0.11	0.02	0.14	0.10	0.24
DE	0.16	0.01	0.19	0.13	0.34
FL	1.91	2.98	5.72	4.45	10.09
GA	2.47	0.94	3.68	2.76	5.69
HI[c4]	0.01	0.13	0.14	0.04	0.27
IA	13.34	1.38	15.12	12.13	20.45
ID	2.74	0.86	3.81	3.04	5.67
IL	12.68	0.71	13.40	10.32	18.72
IN	7.58	0.63	8.19	6.24	11.80
KS	10.22	2.93	13.44	11.16	17.35
KY	3.26	2.33	5.60	4.62	7.31
LA	3.09	0.98	4.51	3.65	6.13
MA	0.14	1.26	0.20	0.15	0.30
MD	0.73	0.12	1.00	0.75	1.57
ME	0.23	0.17	0.38	0.27	0.58
MI	3.99	0.65	5.08	4.03	7.26
MN	9.62	0.91	11.33	9.22	14.99
MO	7.33	3.08	10.61	8.64	14.08
MS	3.45	0.94	4.44	3.52	6.13
MT	3.29	3.04	6.34	5.33	7.94
NC	2.84	0.68	3.76	2.75	6.03
ND	6.02	1.05	7.02	5.61	9.08
NE	9.49	1.42	11.27	9.13	15.34
NH	0.07	0.02	0.13	0.09	0.20
NJ	0.15	0.11	0.23	0.17	0.36
NM	0.74	2.30	2.95	2.41	4.28
NV	0.25	1.23	0.76	0.61	1.18
NY	2.93	0.73	4.01	3.13	6.12
OH	6.39	0.71	8.32	6.51	12.36
OK	3.05	3.61	6.75	5.68	8.68
OR	1.25	1.02	2.51	2.06	3.63
PA	2.76	0.57	3.68	2.85	5.74
RI	0.01	0.01	0.02	0.01	0.04
SC	1.13	0.40	1.51	1.08	2.39
SD	5.33	1.83	7.16	5.86	9.23
TN	2.50	1.80	4.35	3.53	5.83
TX	12.07	11.64	24.67	20.69	31.66
UT	0.59	0.76	1.44	1.16	2.16
VA	1.43	1.24	2.71	2.23	3.60
VT	0.45	0.12	0.64	0.48	1.04
WA	2.05	0.63	3.06	2.54	4.35
WI	5.84	1.01	7.64	6.24	11.05
WV	0.28	0.41	0.70	0.58	0.91
WY	0.95	1.56	2.76	2.33	3.77

[a] Emissions from non-manure organic N inputs for crops not simulated by DAYCENT were not estimated (NE) at the state level.
[b] Emissions from sewage sludge applied to grasslands and were not estimated (NE) at the state level
[c] N_2O emissions are not reported for Hawaii except from cropland organic soils.

Table A-230: 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 (MMT CO_2 Eq.)

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013[a]	2014[a]	2015[a]
Net emissions based on Tier 3 Century-based analysis (Step 2)														
CRC	(65.7)	(49.2)	(65.4)	(50.8)	(47.5)	(45.6)	(34.4)	(29.3)	(29.4)	(43.6)	(46.6)	(42.7)	(42.7)	(42.7)
GCC	20.6	20.0	13.0	12.4	13.2	11.8	12.7	12.6	14.5	14.3	13.4	6.7	6.7	6.7
GRG	(10.2)	(1.0)	(33.1)	2.0	(14.8)	1.8	(10.1)	(5.7)	1.3	(16.0)	(24.6)	3.7	3.8	3.9
CCG	(5.1)	(6.4)	(10.5)	(10.2)	(12.2)	(10.9)	(10.8)	(10.6)	(10.8)	(11.0)	(11.2)	(10.2)	(10.2)	(10.2)
Net emissions based on the IPCC Tier 2 analysis (Step 3)														
Mineral Soils														
CRC	(5.4)	(6.5)	(6.7)	(5.4)	(4.4)	(4.0)	(3.4)	(3.5)	(3.6)	(3.5)	(2.9)	(2.7)	(2.7)	(2.7)
GCC	1.3	1.6	1.5	1.5	1.8	1.8	1.9	1.7	1.7	1.7	1.7	1.7	1.7	1.7
FCC	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
OCC	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
SCC	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
WCC	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
GRG	(0.6)	(1.6)	(1.8)	(1.3)	(1.5)	(1.5)	(1.5)	(1.2)	(1.2)	(0.8)	(0.4)	(0.1)	(0.1)	(0.7)
CCG	(2.9)	(2.9)	(3.2)	(2.4)	(1.9)	(1.6)	(1.4)	(1.4)	(1.3)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
FCG	(0.8)	(0.7)	(0.8)	(0.5)	(0.4)	(0.4)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
OCG	(0.5)	(0.8)	(1.1)	(1.1)	(0.9)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
SCG	(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)
WCG	(0.3)	(0.5)	(0.5)	(0.4)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils														
CRC	30.3	29.3	24.5	29.7	29.6	29.5	29.3	29.7	29.6	27.9	28.1	28.1	28.1	28.0
GCC	2.5	2.9	3.3	3.3	3.3	3.2	3.0	2.9	2.9	3.0	3.0	3.0	3.0	3.0
FCC	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OCC	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
SCC	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.1
WCC	0.6	1.0	0.9	0.7	0.7	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
GRG	7.2	6.9	6.5	6.0	5.8	5.7	5.7	5.7	5.6	5.6	5.5	5.5	5.5	5.5
CCG	0.5	0.7	0.9	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
FCG	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
OCG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
SCG	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
WCG	0.1	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Additional changes in net emissions from mineral soils based on application of sewage sludge to agricultural land (Step 4)														
GRG	(0.6)	(0.8)	(1.0)	(1.1)	(1.2)	(1.2)	(1.2)	(1.3)	(1.3)	(1.3)	(1.4)	(1.4)	(1.4)	(1.5)
Additional changes in net emissions from mineral soils based on additional enrollment of CRP land (Step 4)														
CRC	-	-	-	-	-	-	-	-	-	-	-	1.6	2.5	3.3
Total Stock Changes by Land Use/Land-Use Change Category (Step 5)														
CRC	(40.9)	(26.3)	(47.7)	(26.5)	(22.2)	(20.1)	(8.5)	(3.2)	(3.4)	(19.1)	(21.4)	(15.6)	(14.8)	(14.0)
GCC	24.5	24.6	17.7	17.3	18.2	16.9	17.5	17.2	19.1	19.0	18.1	11.4	11.4	11.4
FCC	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
OCC	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2
SCC	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2

WCC	0.7	1.1	1.0	0.8	0.9	0.8	0.7	0.6	0.6	0.7	0.7	0.7	0.7	0.7
GRG	(4.2)	3.6	(29.4)	5.5	(11.7)	4.8	(7.1)	(2.4)	4.5	(12.5)	(20.8)	7.7	7.8	7.3
CCG	(7.5)	(8.6)	(12.8)	(11.5)	(13.0)	(11.4)	(11.2)	(10.9)	(10.9)	(11.0)	(11.3)	(10.2)	(10.2)	(10.2)
FCG	(0.7)	(0.7)	(0.8)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
OCG	(0.5)	(0.8)	(1.1)	(1.0)	(0.9)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.7)	(0.7)	(0.7)	(0.7)
SCG	(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)
WCG	(0.2)	(0.2)	(0.2)	(0.2)	(0.1)	(0.0)	0.0	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Total[a]	**(28.3)**	**(6.7)**	**(72.8)**	**(15.8)**	**(28.7)**	**(9.6)**	**(9.1)**	**0.9**	**9.4**	**(23.5)**	**(35.0)**	**(6.3)**	**(5.4)**	**(5.2)**

Note: Totals may not sum due to independent rounding.

[a] Quality control uncovered errors in the estimate and uncertainty for 2013, 2014, 2015, which will be updated following public review. Corrected estimates are provided in the emission summary tables for Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, and Land Converted to Grassland sections in the LULUCF Chapter of this report.

Table A-231: Soil C Stock Change for Mineral and Organic Soils in 2015 within individual states (MMT CO_2 Eq.)

State	Mineral Soil[a]	Organic Soil	Total
AL	(1.45)	0.01	(1.43)
AR	(0.81)	-	(0.81)
AZ	(0.02)	-	(0.02)
CA	(3.24)	1.58	(1.66)
CO	(0.53)	0.00	(0.52)
CT	(0.07)	0.01	(0.07)
DE	(0.09)	-	(0.09)
FL	(0.13)	12.21	12.07
GA	(0.92)	-	(0.92)
HI	(0.08)	0.77	0.69
IA	(5.89)	0.73	(5.16)
ID	(1.83)	0.03	(1.80)
IL	(4.74)	0.52	(4.22)
IN	(2.66)	2.36	(0.31)
KS	(1.91)	-	(1.91)
KY	(3.34)	-	(3.34)
LA	(1.64)	0.51	(1.12)
MA	(0.08)	0.28	0.20
MD	(0.42)	0.01	(0.41)
ME	(0.20)	0.01	(0.19)
MI	(0.50)	3.40	2.90
MN	(2.88)	7.65	4.77
MO	(5.23)	-	(5.23)
MS	(0.96)	0.01	(0.95)
MT	6.25	0.15	6.40
NC	(1.96)	1.89	(0.07)
ND	(2.01)	0.01	(1.99)
NE	(1.06)	0.00	(1.06)
NH	(0.08)	0.02	(0.06)
NJ	(0.09)	0.12	0.03
NM	2.60	-	2.60
NV	(1.73)	0.00	(1.72)
NY	(1.87)	0.53	(1.33)
OH	(1.97)	0.48	(1.49)
OK	0.41	-	0.41
OR	(0.83)	0.30	(0.53)
PA	(1.37)	0.05	(1.32)
RI	0.00	0.02	0.02
SC	(0.92)	0.02	(0.90)
SD	0.53	-	0.53
TN	(2.21)	-	(2.21)
TX	1.12	-	1.12
UT	0.50	0.08	0.57
VA	(1.43)	0.00	(1.43)
VT	(0.16)	0.06	(0.09)
WA	(0.82)	0.38	(0.44)
WI	0.04	2.90	2.94
WV	(0.69)	-	(0.69)
WY	1.47	-	1.47

Note: Parentheses indicate net C accumulation. Estimates do not include soil C stock change associated with federal croplands and grasslands, CRP enrollment after 2012, 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 2012 are not included, and differences arise due to rounding of values in this table.

[a] Quality control uncovered errors in the mineral soil C stock change estimate and uncertainty for 2015, which will be updated following public review. Corrected estimates are provided in the emission summary tables for *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland* sections in the LULUCF Chapter of this report.

Table A-232: Total 2015 CH_4 Emissions from Rice Cultivation by State (MMT CO_2 Eq.)

State	Total
AL	-
AR	3.75
AZ	-
CA	2.04
CO	-
CT	-
DE	-
FL	-
GA	-
HI	-
IA	-
ID	-
IL	-
IN	-
KS	-
KY	-
LA	3.79
MA	-
MD	-
ME	-
MI	-
MN	0.03
MO	0.29
MS	0.47
MT	-
NC	-
ND	-
NE	-
NH	-
NJ	-
NM	-
NV	-
NY	-
OH	-
OK	-
OR	-
PA	-
RI	-
SC	-
SD	-
TN	-
TX	0.85
UT	-
VA	-
VT	-
WA	-
WI	-
WV	-
WY	-

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3.13. Methodology for Estimating Net Carbon Stock Changes in *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*

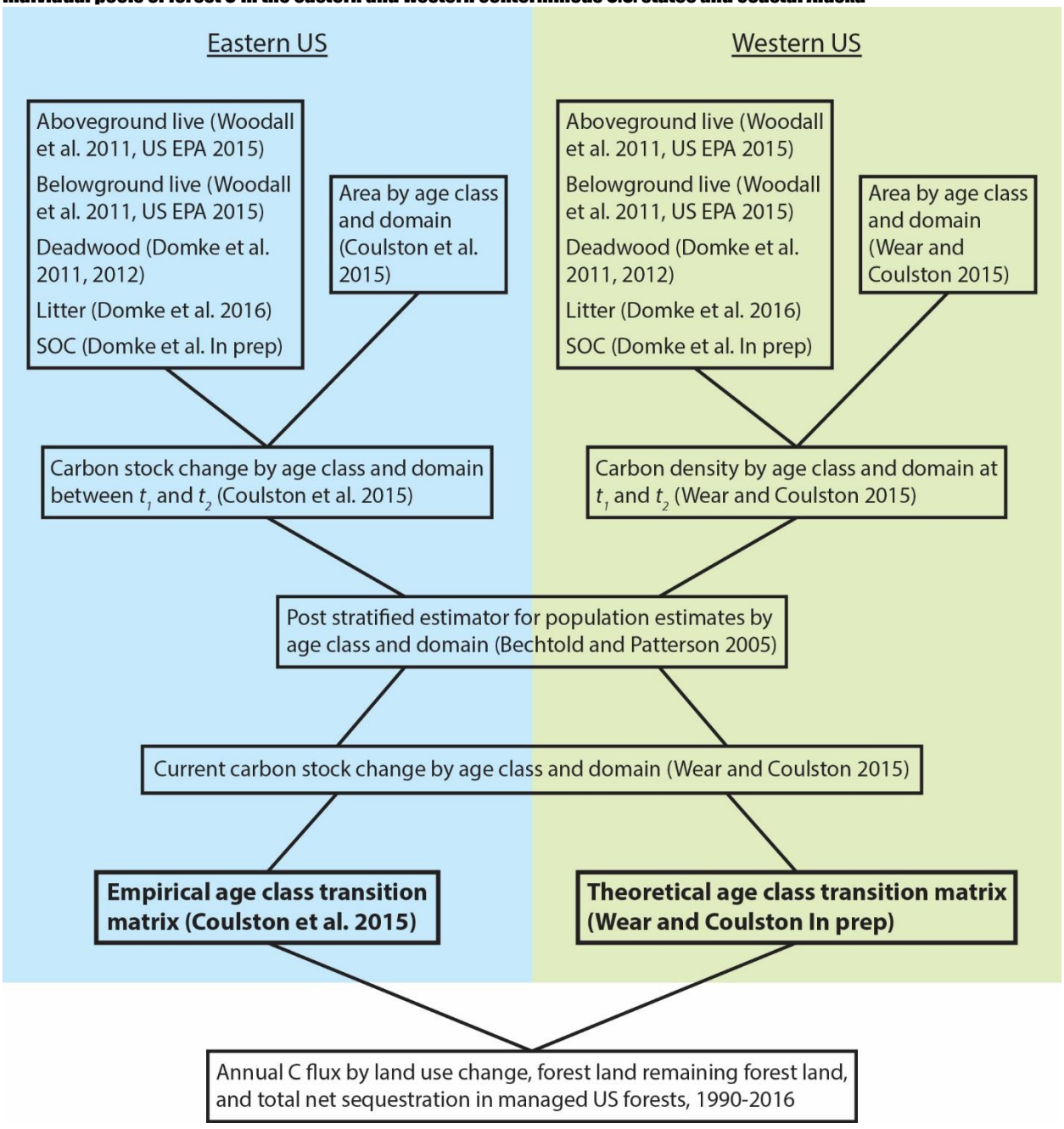
This sub-annex expands on the methodology used to estimate net changes in carbon (C) stocks in forest ecosystems and harvested wood products for *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* as well as non-CO_2 emissions from forest fires. Full details of the C conversion factors and procedures may be found in the cited references. For details on the methods used to estimate changes in soil C stocks in the *Land Converted to Forest Land* section please refer to Annex 3.12.

Carbon stocks and net stock change in forest ecosystems

The inventory-based methodologies for estimating forest C stocks are based on a combination of approaches (Woodall et al 2015a) and are consistent with IPCC (2003, 2006) stock-difference methods. Estimates of ecosystem C are based on data from the a network of annual inventory plots established and measured by the Forest Inventory and Analysis program within the USDA Forest Service; either direct measurements or attributes of forest inventories are the basis for estimating metric tons of C per hectare in IPCC pools (i.e., above- and belowground biomass, dead wood, litter, and soil organic carbon). Plot-level estimates are used to inform land area (by use) and stand age transition matrices across time which can be summed annually for an estimate of forest C stock change for *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. Recent publications (Coulston et al. 2015; Woodall et al. 2015a) detail the land use and stand age transition matrices that are informed by the annual forest inventory of the U.S. and were used in the accounting framework used in this Inventory. The annual forest inventories in the eastern U.S. have been remeasured which allows for empirical estimation of forest C stock net change within the accounting framework. In contrast, as numerous western states have not yet been remeasured, theoretical age transition matrices have been developed (Figure A-16).

The following subsections of this annex will describe the estimation system used this year (Figure A-16) including the methods for estimating individual pools of forest C in addition to the eastern versus western approach to informing land use and stand age transitions.

Figure A-16: Flowchart of the inputs necessary in the accounting framework, including the methods for estimating individual pools of forest C in the eastern and western conterminous U.S. states and coastal Alaska



Note: An empirical age class transition matrix was used in the Eastern U.S. while a theoretical age class transition matrix was used in the Western U.S.

Forest Land Definition

The definition of forest land within the U.S. and used for this Inventory is defined in Oswalt et al. (2014) as "Land at least 120 feet (37 meters) wide and at least 1 acre (0.4 hectare) in size with at least 10 percent cover (or equivalent stocking) by live trees including land that formerly had such tree cover and that will be naturally or artificially regenerated. Trees are woody plants having a more or less erect perennial stem(s) capable of achieving at least 3 inches (7.6 cm) in

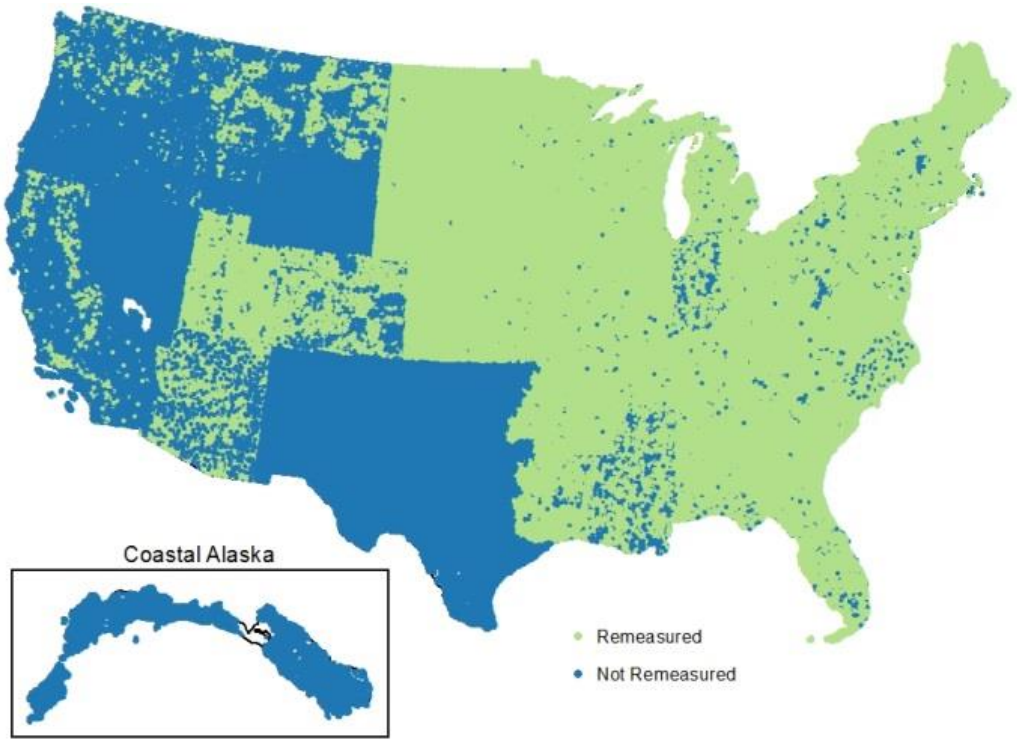
diameter at breast height, or 5 inches (12.7 cm) diameter at root collar, and a height of 16.4 feet (5 meters) at maturity in situ. The definition here includes all areas recently having such conditions and currently regenerating or capable of attaining such condition in the near future. Forest land also includes transition zones, such as areas between forest and non-forest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet (36.6 meters) wide or an acre (0.4 hectare) in size. Forest land does not include land that is predominantly under agricultural or urban land use." Timberland is productive forest land, which is on unreserved land and is producing or capable of producing crops of industrial wood. This is an important subclass of forest land because timberland is the primary source of C incorporated into harvested wood products. Productivity for timberland is at a minimum rate of 20 cubic feet per acre (1.4 cubic meters per hectare) per year of industrial wood (Woudenberg and Farrenkopf 1995). There are about 205 million hectares of timberland in the conterminous U.S., which represents 80 percent of all forest lands over the same area (Oswalt et al. 2014).

Forest Inventory Data

The estimates of forest C stocks are based on data from forest inventory surveys. Forest inventory data were obtained from the USDA Forest Service, Forest Inventory and Analysis (FIA) Program (Frayer and Furnival 1999; USDA Forest Service 2015a; USDA Forest Service 2015b). Forest Inventory and Analysis data include remote sensing information and a collection of measurements in the field at sample locations called plots. Tree measurements include diameter at breast height, height, and species. On a subset of plots, additional measurements or samples are taken of downed dead wood, litter, and soil attributes. The technical advances needed to estimate C stocks from these data are ongoing (Woodall et al. 2015a) with the latest research incorporated on an annual basis (see Domke et al. 2016, Domke et. al. In press). The field protocols are thoroughly documented and available for download from the USDA Forest Service (2015c). Bechtold and Patterson (2005) provide the estimation procedures for standard forest inventory results. The data are freely available for download at USDA Forest Service (2011b) as the FIA Database (FIADB) Version 6.0 (USDA Forest Service 2015b; USDA Forest Service 2015c); these data are the primary sources of forest inventory data used to estimate forest C stocks. In addition to the field sampling component, fine-scale remotely sensed imagery (National Agriculture Imagery Program; NAIP 2015; Woodall et al. 2015b) is used to assign the land use at each sample location which has a nominal spatial resolution (raster cell size) of 1 m2. Prior to field measurement of each year's collection of annual plots due for measurement (i.e., panel), each sample location in the panel (i.e., systematic distribution of plots within each state each year) is photo-interpreted manually by a forester to determine land use. As annual forest inventories have only just begun in the U.S. territories and in Hawaii, there is an assumption 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). These inventory data are publicly available for 6.2 million hectares of forest land, and these inventoried lands, representing an estimated 12 percent of the total forest land in Alaska, contribute to the forest C 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.

A national plot design and annualized sampling (USDA Forest Service 2015a) were introduced by FIA with most new annual inventories beginning after 1998. These are the only forest inventories used in the current accounting framework and subsequently in this submission. These surveys involve the sampling of all forest land including reserved and lower productivity lands. Almost all states have annualized inventory data available with substantial remeasurement in the eastern United States (Figure A-17). 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 U.S. 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 within the state, 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 one or two cycles of the annualized inventories, and some western states have begun remeasuring with a second annual cycle. Annually updated estimates of forest C stocks are affected by the 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 annual inventory data can affect trend estimates of C stocks and stock changes (e.g., estimates based on 60 percent of an inventory cycle will be different than estimates with a complete (100 percent) cycle). 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 (i.e., 2016) is the exception because it is included in stock change calculations in order to include the most recent available data for each state. The specific inventories used in this report are listed in Table A-233 and this list can be compared with the full set of summaries available for download (USDA Forest Service 2015b).

Figure A-17: Annual FIA plots (remeasured and not remeasured) across the U.S. including coastal Alaska through the 2015 field season



Note: Due to the vast number of plots (where land use is measured even if no forest is present) they appear as spatially contiguous when displayed at the scale and resolution presented in this figure.

It should be noted that as the FIA program explores expansion of its vegetation inventory beyond the forest land use to other land uses (e.g., woodlands and urban areas) subsequent inventory observations will need to be delineated between forest and other land uses as opposed to a strict forest land use inventory. The forest C estimates provided here represent C stocks and stock change on managed forest lands (IPCC 2006, see Section 6.1 Representation of the U.S. Land Base), which is how all forest lands are classified on the 48 conterminous states. However, Alaska is considered to have significant areas of both managed and unmanaged forest lands. A new model delineating managed versus unmanaged lands for the U.S. (Ogle et al. in preparation), and used in this Inventory, is consistent with the assumption of managed forest lands on the 48 states. However, the model of Ogle et al. (in preparation) identifies some of the forest land in south central and southeastern coastal Alaska as unmanaged; this is in contrast to past assumptions of "managed" for these forest lands included in the FIA program. Therefore, the estimates for coastal Alaska as included here reflect that adjustment, which effectively reduces the forest area included here by about 5 percent. A second modification to the use of the FIADB-defined forest land introduced this year is to identify plots that do not meet the height component of the definition of forestland (Coulston et al. 2016). These plots were identified as "other wooded lands" (i.e., not forest land use) and were removed from forest estimates and classified as grassland.[104] Note that minor differences in identifying and classifying woodland as "forest" versus "other wooded" exist between the current Resources Planning Act Assessment (RPA) data (Oswalt et al. 2014) and the FIADB (USDA Forest Service 2015b) due to a refined modelling approach developed specifically for this report (Coulston et al. 2016).

[104] See the *Grassland Remaining Grassland* section for details.

Table A-233: Specific annual forest inventories by state used in development of forest C stock and stock change estimates

Remeasured Annual Plots			Split Annual Cycle Plots		
State	Time 1 Year Range	Time 2 Year Range	State	Time 1 Year Range	Time 2 Year Range
Alabama	2001 - 2011	2006 - 2015	Alaska (Coastal)	2004 - 2008	2009 - 2013
Arkansas	2006 - 2010	2011 - 2015	Arizona	2004 - 2008	2009 - 2013
Connecticut	2005 - 2010	2010 - 2015	California	2001 - 2005	2006 - 2010
Delaware	2005 - 2010	2010 - 2015	Colorado	2004 - 2008	2009 - 2013
Florida	2002 - 2011	2010 - 2014	Idaho	2004 - 2008	2009 - 2013
Georgia	2005 - 2009	2010 - 2014	Montana	2004 - 2008	2009 - 2013
Illinois	2005 - 2010	2010 - 2015	Nevada	2004 - 2008	2009 - 2013
Indiana	2005 - 2010	2010 - 2015	New Mexico	1999	2005 - 2013
Iowa	2005 - 2010	2010 - 2015	Oklahoma (West)	2009 - 2010	2011 - 2013
Kansas	2005 - 2010	2010 - 2015	Oregon	2001 - 2005	2006 - 2010
Kentucky	2000 - 2009	2006 - 2013	Texas (West)	2004 - 2007	2008 - 2012
Louisiana	2001 - 2008	2009 - 2014	Utah	2004 - 2008	2009 - 2013
Maine	2006 - 2010	2011 - 2015	Washington	2002 - 2006	2007 - 2011
Maryland	2004 - 2009	2009 - 2014	Wyoming	2000	2011 - 2013
Massachusetts	2005 - 2010	2010 - 2015			
Michigan	2005 - 2010	2010 - 2015			
Minnesota	2006 - 2010	2011 - 2015			
Mississippi	2006	2009 - 2014			
Missouri	2005 - 2010	2010 - 2015			
Nebraska	2005 - 2010	2010 - 2015			
New Hampshire	2004 - 2010	2010 - 2015			
New Jersey	2004 - 2009	2009 - 2014			
New York	2003 - 2009	2009 - 2014			
North Carolina	2003 - 2007	2009 - 2015			
North Dakota	2005 - 2010	2010 - 2015			
Ohio	2003 - 2009	2009 - 2014			
Oklahoma (East)	2008	2010 - 2014			
Pennsylvania	2005 - 2010	2010 - 2015			
Rhode Island	2005 - 2010	2010 - 2015			
South Carolina	2002 - 2011	2009 - 2015			
South Dakota	2005 - 2010	2010 - 2015			
Tennessee	2000 - 2009	2005 - 2013			
Texas (East)	2002 - 2008	2005 - 2012			
Vermont	2005 - 2010	2010 - 2015			
Virginia	2002 - 2011	2009 - 2014			
West Virginia	2004 - 2009	2009 - 2014			
Wisconsin	2005 - 2010	2010 - 2015			

Note: Remeasured annual plots represent a complete inventory cycle between measurements of the same plots while spilt annual cycle plots represent a single inventory cycle of plots that are split where remeasurements have yet to occur.

Estimating Forest Inventory Plot-Level C-Density

For each inventory plot in each state, field data from the FIA program are used alone or in combination with auxiliary information (e.g., climate, surficial geology, elevation) to predict C density for each IPCC pool (i.e., aboveground and belowground biomass, dead wood, litter, SOC). In the past, most of the conversion factors and models used for inventory-based forest C estimates (Smith et al. 2010; Heath et al. 2011) were initially developed as an offshoot of the forest C simulation model FORCARB (Heath et al. 2010). The conversion factors and model coefficients were usually categorized by region and forest type. Thus, region and type are specifically defined for each set of estimates. More recently, the coarse

approaches of the past have been updated with empirical information regarding C attributes of individual forest C pools such as dead wood and litter (e.g., Domke et al. 2013 and Domke et al. 2016). Factors are applied to the forest inventory data at the scale of FIA inventory plots which are a systematic sample of all forests attributes and land uses within each state. The results are estimates of C density (T per hectare) for the various forest pools. Carbon density for live trees, standing dead trees, understory vegetation, downed dead wood, litter, and soil organic matter are estimated. All non-soil C pools except litter can be separated into aboveground and belowground components. The live tree and understory C pools are combined into the biomass pool in this inventory. Similarly, standing dead trees and downed 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 (2006).

Live tree C pools

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at diameter breast height (d.b.h.) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates are made for above- and below-ground biomass components. If inventory plots include data on individual trees, tree C is based on Woodall et al. (2011), which is also known as the component ratio method (CRM), and is a function of volume, species, diameter, and, in some regions, tree height and site quality. The estimated sound volume (i.e., after rotten/missing deductions) provided in the tree table of the FIADB is the principal input to the CRM biomass calculation for each tree (Woodall et al. 2011). The estimated volumes of wood and bark are converted to biomass based on the density of each. Additional components of the trees such as tops, branches, and coarse roots, are estimated according to adjusted component estimates from Jenkins et al. (2003). Live trees with d.b.h of less than 12.7 cm do not have estimates of sound volume in the FIADB, and CRM biomass estimates follow a separate process (see Woodall et al. 2011 for details). An additional component of foliage, which was not explicitly included in Woodall et al. (2011), was added to each tree following the same CRM method. Carbon is estimated by multiplying the estimated oven-dry biomass by a C constant of 0.5 because biomass is 50 percent of dry weight (IPCC 2006). Further discussion and example calculations are provided in Woodall et al. 2011 and Domke et al. 2012.

Understory vegetation

Understory vegetation is a minor component of total forest ecosystem 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 model:

$$\text{Ratio} = e(A - B \times \ln(\text{live tree C density})) \quad (1)$$

In this model, the ratio is the ratio of understory C density (T C/ha) to live tree C density (above- and below-ground) according to Jenkins et al. (2003) and expressed in T C/ha. An additional coefficient is provided as a maximum ratio; that is, any estimate predicted from the model that is greater than the maximum ratio is set equal to the maximum ratio. A full set of coefficients are in Table A-234. 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:

$$\text{Understory (T C/ha)} = (\text{live tree C density}) \times e(0.855 - 1.03 \times \ln(\text{tree C density})) \quad (2)$$

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 model. Second, the minimum ratio is set to 0.005 (Birdsey 1996). Third, nonstocked (i.e., currently lacking tree cover but still in the forest land use) and pinyon/juniper forest types (see Table A-234) are set to coefficient A, which is a C density (T C/ha) for these types only.

Table A-234: Coefficients for Estimating the Ratio of C Density of Understory Vegetation (above- and belowground, T C/ha) by Region and Forest Type

Region[b]	Forest Type[b]	A	B	Maximum ratio[c]
	Aspen-Birch	0.855	1.032	2.023
	MBB/Other Hardwood	0.892	1.079	2.076
NE	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 model: 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 T C/ha. Note that this ratio is multiplied by tree C density on each plot to produce understory vegetation.
[b] Regions and types as defined in Smith et al. (2003).
[c] Maximum ratio: any estimate predicted from the model that is greater than the maximum ratio is set equal to the maximum ratio.

Dead Wood

The standing dead tree estimates are primarily based on plot-level measurements (Domke et al. 2011; Woodall et al. 2011). This C pool includes aboveground and belowground (coarse root) mass and includes trees of at least 12.7 cm d.b.h. Calculations follow the basic CRM method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss. In addition to the lack of foliage, two characteristics of standing dead trees that can significantly affect C mass are decay, which affects density and thus specific C content (Domke et al. 2011; Harmon et al. 2011), and structural loss such as branches and bark (Domke et al. 2011). Dry weight to C mass conversion is by multiplying by 0.5.

Downed dead wood, inclusive of logging residue, are sampled on a subset of FIA plots. Despite a reduced sample intensity, a single down woody material population estimate (Woodall et al. 2010; Domke et al. 2013; Woodall et al. 2013) per state is now incorporated into these empirical downed dead wood estimates. Downed 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. It also includes stumps and roots of harvested trees. Ratio estimates of downed dead wood to live tree biomass were developed using FORCARB2 simulations and applied at the plot level (Smith et al. 2004). Estimates for downed 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-235. An additional component of downed 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-236. These amounts are added to explicitly account for downed dead wood following harvest. The sum of these two components are then adjusted by the ratio of population totals; that is, the ratio of plot-based to modeled estimates (Domke et al. 2013). An example of this 3-part calculation for downed dead wood in a 25-year-old naturally regenerated loblolly pine forest with 82.99 T C/ha in live trees (Jenkins et al. 2003) in Louisiana is as follows:

First, an initial estimate from live tree C density and Table A-235 (SC, Natural Pine)

$$\text{C density} = 82.99 \times 0.068 = 5.67 \text{ (T C/ha)}$$

Second, an average logging residue from age and Table A-235 (SC, softwood)

$$\text{C density} = 5.5 \times e(-25/17.9) = 1.37 \text{ (T C/ha)}$$

Third, adjust the sum by the downed dead wood ratio plot-to-model for Louisiana, which was 27.6/31.1 = 0.886

$$\text{C density} = (5.67 + 1.37) \times 0.886 = 6.24 \text{ (T C/ha)}$$

Table A-235: Ratio for Estimating Downed Dead Wood by Region and Forest Type

Region[a]	Forest type[a]	Ratio[b]
NE	Aspen-Birch	0.078
	MBB/Other Hardwood	0.071
	Oak-Hickory	0.068
	Oak-Pine	0.061
	Other Pine	0.065
	Spruce-Fir	0.092
	White-Red-Jack Pine	0.055
	Nonstocked	0.019
NLS	Aspen-Birch	0.081
	Lowland Hardwood	0.061
	Maple-Beech-Birch	0.076
	Oak-Hickory	0.077
	Pine	0.072
	Spruce-Fir	0.087
	Nonstocked	0.027
NPS	Conifer	0.073

	Lowland Hardwood	0.069
	Maple-Beech-Birch	0.063
	Oak-Hickory	0.068
	Oak-Pine	0.069
	Nonstocked	0.026
PSW	Douglas-fir	0.091
	Fir-Spruce	0.109
	Hardwoods	0.042
	Other Conifer	0.100
	Pinyon-Juniper	0.031
	Redwood	0.108
	Nonstocked	0.022
PWE	Douglas-fir	0.103
	Fir-Spruce	0.106
	Hardwoods	0.027
	Lodgepole Pine	0.093
	Pinyon-Juniper	0.032
	Ponderosa Pine	0.103
	Nonstocked	0.024
PWW	Douglas-fir	0.100
	Fir-Spruce	0.090
	Other Conifer	0.073
	Other Hardwoods	0.062
	Red Alder	0.095
	Western Hemlock	0.099
	Nonstocked	0.020
RMN	Douglas-fir	0.062
	Fir-Spruce	0.100
	Hardwoods	0.112
	Lodgepole Pine	0.058
	Other Conifer	0.060
	Pinyon-Juniper	0.030
	Ponderosa Pine	0.087
	Nonstocked	0.018
RMS	Douglas-fir	0.077
	Fir-Spruce	0.079
	Hardwoods	0.064
	Lodgepole Pine	0.098
	Other Conifer	0.060
	Pinyon-Juniper	0.030
	Ponderosa Pine	0.082
	Nonstocked	0.020
SC	Bottomland Hardwood	0.063
	Misc. Conifer	0.068
	Natural Pine	0.068
	Oak-Pine	0.072
	Planted Pine	0.077
	Upland Hardwood	0.067
	Nonstocked	0.013
SE	Bottomland Hardwood	0.064
	Misc. Conifer	0.081
	Natural Pine	0.081
	Oak-Pine	0.063
	Planted Pine	0.075
	Upland Hardwood	0.059
	Nonstocked	0.012

[a] Regions and types as defined in Smith et al. (2003).

[b] The ratio is multiplied by the live tree C density on a plot to produce downed dead wood C density (T C/ha).

Table A-236: Coefficients for Estimating Logging Residue Component of Downed Dead Wood

Region[a]	Forest Type Group[b] (softwood/ hardwood)	Initial C Density (T/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

Carbon in the litter layer is currently sampled on a subset of the FIA plots. 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. Because litter attributes are only collected on a subset of FIA plots, a model was developed to predict C density based on plot/site attributes for plots that lacked litter information (Domke et al. 2016).

As the litter, or forest floor, estimates are an entirely new model this year, a more detailed overview of the methods is provided here. The first step in model development was to evaluate all relevant variables—those that may influence the formation, accumulation, and decay of forest floor organic matter—from annual inventories collected on FIADB plots (P2) using all available estimates of forest floor C (n = 4,530) from the P3 plots (hereafter referred to as the research dataset) compiled from 2000 through 2014 (Domke et al. 2016).

Random forest, a machine learning tool (Domke et al. 2016), was used to evaluate the importance of all relevant forest floor C predictors available from P2 plots in the research dataset. Given many of the variables were not available due to regional differences in sampling protocols during periodic inventories, the objective was to reduce the random forest regression model to the minimum number of relevant predictors without substantial loss in explanatory power. The form of the full random forest model was:

$$P(FFC_{Full}) = f(lat, lon, elev, fortypgrp, above, ppt, t\max, gmi) + u \quad (3)$$

where: *lat* = latitude, *lon* = longitude, *elev* = elevation, *fortypgrp* = forest type group, *above* = aboveground live tree C (trees ≥ 2.54 cm dbh), *ppt* = mean annual precipitation, *tmax* = average maximum temperature, *gmi* = the ratio of precipitation to potential evapotranspiration, *u* = the uncertainty in the prediction resulting from the sample-based estimates of the model parameters and observed residual variability around this prediction.

For each replacement, u was independently and randomly generated from a $N(0,\sigma)$ distribution with σ incorporating the variability from both sources. This process of randomly selecting and incorporating u may be considered an imputation. Each model prediction was replaced independently m times and m separate estimates were combined where m = 1,000 in this analysis.

Due to data limitation in certain regions and inventory periods a series of reduced random forest regression models were used rather than replacing missing variables with imputation techniques in random forest. Database records used to compile estimates for this report were grouped by variable availability and the approaches described herein were applied to replace forest floor model predictions from Smith and Heath (2002). Forest floor C predictions are expressed in T•ha−1.

Soil organic carbon

Soil organic carbon (SOC) is the largest terrestrial C sink, and management of this pool is a critical component of efforts to mitigate atmospheric C concentrations. In the U.S., SOC in forests is monitored by the national forest inventory conducted by the FIA program (O'Neill et al. 2005). In previous C inventory submissions, SOC predictions were based, in part, on a model using the State Soil Geographic (STATSGO) database compiled by the Natural Resources Conservation Service (NRCS) (Amichev and Glabraith 2004), hereafter referred to as the country-specific (*CSsoc*) model. Estimates of forest SOC found in the STATSGO database may be based on expert opinion and/or lack systematic field observations, but these country-specific model predictions have been used in past C inventory submissions. The FIA program has been consistently measuring soil attributes as part of the inventory since 2001 and has amassed an extensive inventory of SOC in forest land in the conterminous U.S. and coastal Alaska (O'Neill et al. 2005). More than 5,000 profile observations of SOC on forest land from FIA and the International Soil Carbon Monitoring Network (ISCN 2015) were used to develop and implement a modeling framework that includes site-, stand-, and climate-specific variables that yield predictions of SOC stocks and stock changes specific to forest land in the U.S. This section provides a summary of the methodology used to predict SOC for this report. A complete description of the approach is in Domke et al. (In prep.).

The data used to develop the new modeling framework to predict SOC on forest land came from the FIA program and the ISCN. Since 2001, the FIA program has collected soil samples on every 16th base intensity plot distributed approximately every 38,848 ha, where at least one forested condition exists (Woodall et al. 2010). On fully forested plots, mineral and organic soils were sampled adjacent to subplots 2, 3, and 4 by taking a single core at each location from two layers: 0 to 10.16 cm and 10.16 to 20.32 cm. The texture of each soil layer was estimated in the field, and physical and chemical properties were determined in the laboratory (U.S. Forest Service 2011). For this analysis, estimates of SOC from the FIA program were calculated following O'Neill et al. (2005):

$$\sum SOC_{FIA\_TOTAL} = C_i \cdot BD_i \cdot t_i \cdot ucf \quad (4)$$

Where $\sum SOC_{FIA\_TOTAL}$ = total mass (Mg C ha-1) of the mineral and organic soil C over all *i*th layers, C_i = percent organic C in the *i*th layer, BD_i = bulk density calculated as weight per unit volume of soil (g·cm-3) at the *i*th soil layer, t_i = thickness (cm) of the *i*th soil layer (either 0 to 10.16 cm or 10.16 to 20.32 cm), and *ucf* = unit conversion factor (100).

The SOC_{FIA_TOTAL} estimates from each plot were assigned by forest condition on each plot, resulting in 3,667 profiles with SOC layer observations at 0 to 10.16 and 10.16 to 20.32 cm depths. Since the U.S. has historically reported SOC estimates to a depth of 100 cm (Heath et al. 2011, USEPA 2015), ISCN data from forests in the U.S. were harmonized with the FIA soil layer observations to develop model functions of SOC by soil order to a depth of 100 cm. All observations used from the ISCN were contributed by the Natural Resources Conservation Service. A total of 16,504 soil layers from 2,037 profiles were used from ISCN land uses defined as deciduous, evergreen, or mixed forest. The FIA-ISCN harmonized dataset used for model selection and prediction included a total of 5,704 profiles with 23,838 layer observations at depths ranging from 0 to 1,148 cm.

The modeling framework developed to predict SOC for this report was built around strategic-level forest and soil inventory information and auxiliary variables available for all FIA plots in the U.S. The first phase of the new estimation approach involved fitting models using the midpoint of each soil layer from the harmonized dataset and SOC estimates at those midpoints. Several linear and nonlinear models were evaluated, and a log-log model provided the optimal fit to the harmonized data:

$$\log_{10} SOC_i = I + \log_{10} Depth \quad (5)$$

Where $\log_{10} SOC_i$ = SOC density (Mg C ha-1 cm depth-1) at the midpoint depth, I = intercept, $\log_{10} Depth$ = profile midpoint depth (cm).

The model was validated by partitioning the complete harmonized dataset multiple times into training and testing groups and then repeating this step for each soil order to evaluate model performance by soil order. Extra sum of squares F tests were used to evaluate whether there were statistically significant differences between the model coefficients from the model fit to the complete harmonized dataset and models fit to subsets of the data by soil order. Model coefficients for each

soil order were used to predict SOC for the 20.32 to 100 cm layer for all FIA plots with soil profile observations. Next, the SOC layer observations from the FIA and predictions over the 100 cm profile for each FIA plot were summed:

$$SOC_{100} = SOC_{FIA\_TOTAL} + SOC_{20–100} \quad (6)$$

Where SOC_{100} = total estimated SOC density from 0-100 cm for each forest condition with a soil sample in the FIA database, SOC_{FIA_TOTAL} as previously defined in model (4), $SOC_{20–100}$ = predicted SOC from 20.32 to 100 cm from model (5).

In the second phase of the modeling framework, SOC_{100} estimates for FIA plots were used to predict SOC for plots lacking SOC_{100} estimates using Random forests , a machine learning tool that uses bootstrap aggregating (i.e., bagging) to develop models to improve prediction (Breimen 2001). Random forests also relies on random variable selection to develop a forest of uncorrelated regression trees. These trees recognize the relationship between a dependent variable, in this case SOC_{100}, and a set of predictor variables. All relevant predictor variables—those that may influence the formation, accumulation, and loss of SOC—from annual inventories collected on all base intensity plots and auxiliary climate, soil, and topographic variables obtained from the PRISM climate group (Northwest Alliance 2015), Natural Resources Conservation Service (NRCS 2015), and U.S. Geological Survey (Danielson and Gesch 2011), respectively, were included in the RF analysis. Due to regional differences in sampling protocols, many of the predictor variables included in the RF variable selection process were not available for all base intensity plots. To avoid problems with data limitations, pruning was used to reduce the RF models to the minimum number of relevant predictors (including both continuous and categorical variables) without substantial loss in explanatory power or increase in root mean squared error (RMSE). The general form of the full RF models were:

$$P(SOC) = f(lat, lon, elev, fortypgrp, ppt, t\max, gmi, order, surfgeo) \quad (7)$$

where lat = latitude, lon = longitude, $elev$ = elevation, $fortypgrp$ = forest type group, ppt = mean annual precipitation, $t\max$ = average maximum temperature, gmi = the ratio of precipitation to potential evapotranspiration, $order$ = soil order, $surfgeo$ = surficial geological description.

Moving the Annual Forest Inventory Backwards and Forwards in Time: Transition Matrices

The accounting framework used this year is fundamentally driven by the annual forest inventory system conducted by the FIA program of the U.S. Forest Service (2015a-d). Unfortunately, the annual inventory system does not extend into the 1990's and the periodic data are not consistent (e.g., different plot design) with the annual inventory necessitating the adoption of a system to "backcast" the annual C estimates. Likewise, forecasting the annual inventory can enable the monitoring of U.S. greenhouse gas emission reduction targets, however, that is an activity beyond the scope of this document. To facilitate the backcasting of the U.S. annual forest inventory C estimates, the accounting framework is comprised of a forest dynamics module (age transition matrices) and a land use dynamics module (land area transition matrices). The forest dynamics module assesses forest sequestration, forest aging, and disturbance effects (i.e., disturbances such as wind, fire, and floods identified by foresters on inventory plots). The land use dynamics module assesses C stock transfers associated with afforestation and deforestation (e.g., Woodall et al. 2015b). Both modules are developed from land use area statistics and C stock change or C stock transfer by age class. The required inputs are estimated from more than 625,000 forest and nonforest observations in the FIA national database (U.S. Forest Service 2015a-c). Model predictions for before or after the annual inventory period are constructed from the accounting framework using only the annual observations. This modeling framework includes opportunities for user-defined scenarios to evaluate the impacts of land use change and disturbance rates on future C stocks and stock changes. As annual forest inventories in the eastern U.S. have largely completed at least one cycle and been remeasured, age and area transition matrices can be empirically informed. In contrast, as annual inventories in western states are still undergoing their first complete cycle they are still in the process of being remeasured, and as a result theoretical transition matrices need to be developed.

Wear and Coulston (2015) and Coulston et al. (2015) provide the framework for the projection model. The overall objective is to estimate unmeasured historical changes and future changes in forest C consistent with annual forest inventory

measurements. For most regions, forest conditions are observed at time t0 and at a subsequent time t1=t0+s, where s is the time step (time measured in years) and is indexed by discrete (5 year) forest age classes. The inventory from t0 is then backcasted to the year 1990 (on average about 16 years) and projected from t1 to 2016 (about 5 years for the next Inventory report). This backcasting/projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying C density estimates for each age class. For the North, South (except for west Texas and west Oklahoma), and Rocky Mountains regions of the country, age class transition matrices are estimated from observed changes in age classes between t0 and t1. In the remainder of the regions (Pacific Coast including Alaska, west Texas, and west Oklahoma), only one inventory was available (t0) so transition matrices were derived from theory but informed by the condition of the observed inventory to backcast from t0 to 1990 and project from t0 to 2016.

Theoretical Age Transition Matrices

Without any mortality-inducing disturbance, a projection of forest conditions would proceed by increasing all forest ages by the length of the time step until all forest resided in a terminal age class where the forest is retained indefinitely (this is by assumption, where forest C per unit area reaches a stable maximum). For the most basic case, disturbances (e.g., wildfire or timber harvesting) can reset some of the forest to the first age class. Disturbance can also alter the age class in more subtle ways. If a portion of trees in a multiple-age forest dies, the trees comprising the average age calculation change, thereby shifting the average age higher or lower (generally by one age class).

With *n* age classes**,** the age transition matrix (**T)** is an n x n matrix, and each element ($\mathbf{T}_{qr}$) defines the proportion of forest area in class *q* transitioning to class *r* during the time step (*s*). The values of the elements of **T** depend on a number of factors, including forest disturbances such as harvests, fire, storms, and the value of s, especially relative to the span of the age classes. For example, holding area fixed, allowing for no mortality, defining the time step *s* equivalent to the span of age classes, and defining five age classes results in:

$$\boldsymbol{T} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{pmatrix} \tag{9}$$

where all forest area progresses to the next age class and forests within the terminal age class are retained forever. With this version of **T**, after five time steps all forests would be in the terminal age class. Relaxing these assumptions changes the structure of **T**. If all disturbances, including harvesting and fire, that result in stand regeneration are accounted for and stochastic elements in forest aging are allowed, **T** defines a traditional Lefkovitch matrix population model (e.g., Caswell 2001) and becomes:

$$\boldsymbol{T} = \begin{pmatrix} 1-t_1-d_1 & d_2 & d_3 & d_4 & d_5 \\ t_1 & 1-t_2-d_2 & 0 & 0 & 0 \\ 0 & t_2 & 1-t_3-d_3 & 0 & 0 \\ 0 & 0 & t_3 & 1-t_4-d_4 & 0 \\ 0 & 0 & 0 & t_4 & 1-d_5 \end{pmatrix} \tag{10}$$

Where $\mathrm{t_q}$ is the proportion of forest of age class q transitioning to age class q+1, d_q is the proportion of age class q that experiences a stand-replacing disturbance, and $(1 - t_q - d_q)$ is the proportion retained within age class q ($\mathbf{T}_{qr}$).

Projections and Backcast for Pacific Coast, Rocky Mountains, West Texas, and West Oklahoma

Projections of forest C in the Pacific (including Alaska), Rocky Mountains, west Texas and west Oklahoma are based on a life stage model:

$$\Delta \mathrm{C_t} = \mathrm{C_{t+m}} - \mathrm{C_t} = (\mathbf{F_t T} - \mathbf{F_t}) \cdot \mathbf{Den} + \mathbf{L_t} \cdot \mathbf{Den} \tag{11}$$

In this framework **T** is an age transition matrix that shifts the age distribution of the forest **F**. The difference in forest area by age class between time *t* and *t*+*s* is **F**t**T**-**F**t. This quantity is multiplied by C density by age class (**Den**) to estimate C stock change of forest remaining forest between *t* and *t*+*s*. Land use change is accounted for by the addition of **L**t·**Den,** where **L**t identifies the age distribution of net land shifts into or out of forests. A query of the forest inventory

databases provides estimates of **F** and **Den**, while inventory observations and modeling assumptions are used to estimate **T**. By expanding **Den** to a matrix of C contained in all the constituent pools of forest carbon, projections for all pools are generated.

Land use change is incorporated as a 1 x n vector **L,** with positive entries indicating increased forest area and negative entries indicating loss of forest area, which provides insights of net change only. Implementing a forest area change requires some information and assumptions about the distribution of the change across age classes (the n dimension of **L**). In the eastern states, projections are based on the projection of observed gross area changes by age class. In western states, total forest area changes are applied using rules. When net gains are positive, the area is added to the youngest forest age class; when negative, area is subtracted from all age classes in proportion to the area in each age class category.

Backcasting forest C inventories generally involve the same concepts as forecasting. An initial age class distribution is shifted at regular time steps backwards through time, using a transition matrix (B):

$$\boldsymbol{F}_{t-s} = \boldsymbol{F}_t \cdot \boldsymbol{B} \quad (12)$$

B is constructed based on similar logic used for creating **T**. The matrix cannot simply be derived as the inverse of **T** ($\boldsymbol{F}_{t-s} = \boldsymbol{F}_t\boldsymbol{T}^{-1}$) because of the accumulating final age class (i.e., **T** does not contain enough information to determine the proportion of the final age class derived from the n-1 age class and the proportion that is retained in age class n from the previous time step).[105] However, **B** can be constructed using observed changes from the inventory and assumptions about transition/accumulation including nonstationary elements of the transition model:

$$\boldsymbol{B} = \begin{pmatrix} 1-\sum_q d_q & \mathrm{b}_2 & 0 & 0 & 0 \\ d_1 & 1-b_2 & \mathrm{b}_3 & 0 & 0 \\ d_2 & 0 & 1-b_3 & \mathrm{b}_4 & 0 \\ d_3 & 0 & 0 & 1-b_4 & \mathrm{b}_r \\ d_4 & 0 & 0 & 0 & 1-\mathrm{b}_r \end{pmatrix} \quad (13)$$

Forest area changes need to be accounted for in the backcasts as well:

$$\boldsymbol{F}_{t-s} = \boldsymbol{F}_t\boldsymbol{B} - \boldsymbol{L}_t \quad (14)$$

Where **Lt** is the forest area change between t1 and t0 as previously defined.

In the Rocky Mountains, age class transition matrices were empirically derived from observed changes in age classes between t0 and t1. The frequency of transitions was constructed between age classes observed at t0 and t1 to define **T** and between age classes t1 and t0 to define **B.** In the Pacific Coast region, including Alaska, west Texas, and west Oklahoma, the theoretical life-stage models described by matrices (9) and (10) were applied. The disturbance factors (d) in both **T** and **B** are derived from the current inventory by assuming that the area of forest in age class 1 resulted from disturbance in the previous period, the area in age class 2 resulted from disturbance in the period before that, and so on. The source of disturbed forest was assumed to be proportional to the area of forest in each age class. For projections (**T**), the average of implied disturbance for the previous two periods was applied. For the backcast (**B**), we move the disturbance frequencies implied by the age class distribution for each time step. For areas with empirical transition matrices, change in forest area (**L**t) was backcasted/projected using the change in forest area observed for the period t0 to t1. In the Pacific, including Alaska, west Texas, and west Oklahoma, it was assumed that total forest land area remained constant for the time period examined.

Projections and Backcast for North, South, east Texas, and east Oklahoma

For the eastern U.S. a full set of remeasured plots were available. When remeasured data are available, the previously described approach is extended to estimate change more directly; in this case $\Delta Ct = Ft \cdot \delta C$, where ΔC is net stock

[105] Simulation experiments show that a population that evolves as a function of **T** can be precisely backcast using $\mathbf{T}^{-1}$. However, applying the inverse to a population that is not consistent with the long-run outcomes of the transition model can result in projections of negative areas within some stage age classes.

change by pool within the analysis area, F is as previously defined, and δC is an *n* x cp matrix of per unit area forest C stock change per year by pool (cp) arrayed by forest age class. Inter-period forest C dynamics are previously described, and the age transition matrix (T) is estimated from the observed data directly. Forest C change at the end of the next period is defined as: $\Delta Ct+s = Ft \cdot T \cdot \delta C$. Land use change and disturbances such as cutting, fire, weather, insects, and diseases were incorporated by generalizing to account for the change vectors and undisturbed forest remaining as undisturbed forest:

$$\Delta C_{t+s} = \sum_{d \in L} (A_{td} \cdot T_d \cdot \delta C_d) \quad (15)$$

Where Atd = area by age class of each mutually exclusive land category in L which includes d disturbances at time t.

L = (FF, NFF, FNF, Fcut, Ffire, Fweather, Fid) where FF=undisturbed forest remaining as undisturbed forest, NFF=nonforest to forest conversion, FNF=forest to nonforest conversion, Fcut=cut forest remaining as forest, Ffire=forest remaining as forest disturbed by fire, Fweather=forest remaining as forest disturbed by weather, and Fid=forest remaining as forest disturbed by insects and diseases. In the case of land transfers (FNF and NFF), Td is an n x n identity matrix and δCd is a C stock transfer rate by age. Paired measurements for all plots in the inventory provide direct estimates of all elements of $\delta C, T_d,$ and A_{td} matrices.

Projections are developed by specifying either Ft+s or At+sd for either a future or a past state. To move the system forward, T is specified so that the age transition probabilities are set up as the probability between a time 0 and a time 1 transition. To move the system backward, T is replaced by B so that the age transition probabilities are for transitions from time 1 to time 0. Forecasts were developed by assuming the observed land use transitions and disturbance rates would continue for the next 5 years. Backcasts were developed using a Markov Chain process for land use transitions, observed disturbance rates for fire, weather, and insects. Historical forest cutting was incorporated by using the relationship between the area of forest cutting estimated from the inventory plots and the volume of roundwood production from the Timber Products Output program (U.S. Forest Service 2015d). This relationship allowed for the modification of Fcut such that it followed trends described by Oswalt et al. (2014).

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 and the U.S. forest products module (Ince et al. 2011). These methods are based on IPCC (2006) guidance for estimating HWP C. 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 C 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 C to and from the atmosphere within national boundaries. Carbon 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 U.S. uses the production accounting approach (as in previous years) to report HWP Contribution (Table A-237). 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-235. 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) Carbon in imports of wood, pulp, and paper to the United States,

(4) Carbon in exports of wood, pulp and paper from the United States, and

(5) Carbon in annual harvest of wood from forests in the United States. The sum of these variables yield estimates for HWP contribution under the production accounting approach.

Table A-237: Harvested Wood Products from Wood Harvested in the U.S.—Annual Additions of C to Stocks and Total Stocks under the Production Approach (Parentheses Indicate Net C Sequestration (i.e., a Net Removal of C from the Atmosphere)

Year	Net C additions per year (MMT C per year)			Total C stocks (MMT C)		
	Total	Products in use	Products in SWDS			
		Total	Total	Total	Products in use	Products in SWDS
1990	-35.9	-17.7	-18.3	1,895	1,249	646
1991	-33.8	-14.9	-18.8	1,929	1,264	665
1992	-33.8	-16.3	-17.4	1,963	1,280	683
1993	-32.9	-15.0	-17.9	1,996	1,295	701
1994	-33.4	-15.9	-17.5	2,029	1,311	718
1995	-32.3	-15.1	-17.2	2,061	1,326	735
1996	-30.6	-14.1	-16.5	2,092	1,340	752
1997	-32.0	-14.7	-17.3	2,124	1,355	769
1998	-31.1	-13.4	-17.7	2,155	1,368	787
1999	-32.5	-14.1	-18.4	2,188	1,382	805
2000	-30.8	-12.8	-18.0	2,218	1,395	823
2001	-25.5	-8.7	-16.8	2,244	1,404	840
2002	-26.8	-9.6	-17.2	2,271	1,414	857
2003	-25.6	-9.5	-16.2	2,296	1,423	873
2004	-28.6	-12.3	-16.3	2,325	1,435	890
2005	-28.1	-11.8	-16.3	2,353	1,447	906
2006	-29.5	-12.2	-17.3	2,382	1,459	923
2007	-28.1	-10.7	-17.4	2,411	1,470	941
2008	-20.9	-3.8	-17.1	2,431	1,474	958
2009	-14.6	2.1	-16.7	2,446	1,472	974
2010	-16.2	0.4	-16.6	2,462	1,471	991
2011	-18.3	-1.6	-16.8	2,481	1,473	1,008
2012	-17.9	-1.1	-16.9	2,498	1,474	1,025
2013	-18.9	-1.9	-17.0	2,517	1,476	1,042
2014	-20.6	-3.5	-17.1	2,538	1,479	1,059
2015	-20.8	-3.7	-17.1	2,559	1,483	1,076
2016	-	-	-	2,585	1,491	1,093

- Not reported or zero

Table A-238: Comparison of Net Annual Change in Harvested Wood Products C Stocks Using Alternative Accounting Approaches (kt CO_2 Eq./year)

	HWP Contribution to LULUCF Emissions/ removals (MMT CO_2 Eq.)		
Inventory Year	Stock-Change Approach	Atmospheric Flow Approach	Production Approach
1990	(129,622)	(138,416)	(131,772)
1991	(116,345)	(131,436)	(123,758)
1992	(119,985)	(131,633)	(123,791)
1993	(126,805)	(127,819)	(120,708)
1994	(129,954)	(129,882)	(122,498)
1995	(125,981)	(128,010)	(118,411)
1996	(122,340)	(122,495)	(112,219)
1997	(131,434)	(127,378)	(117,344)
1998	(137,218)	(122,781)	(114,188)
1999	(147,057)	(127,427)	(119,182)

2000	(141,195)	(120,395)	(112,969)
2001	(125,039)	(100,417)	(93,479)
2002	(130,714)	(103,339)	(98,188)
2003	(125,812)	(98,663)	(93,967)
2004	(143,193)	(108,453)	(104,747)
2005	(142,102)	(107,342)	(103,215)
2006	(138,130)	(113,897)	(108,034)
2007	(115,181)	(111,489)	(102,984)
2008	(73,134)	(88,392)	(76,807)
2009	(41,284)	(68,789)	(53,386)
2010	(47,980)	(78,261)	(59,367)
2011	(50,802)	(90,214)	(67,279)
2012	(54,008)	(89,470)	(65,710)
2013	(64,774)	(94,413)	(69,154)
2014	(80,511)	(102,379)	(75,552)
2015	(85,209)	(102,765)	(76,356)

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Table A-239: Harvested Wood Products Sectoral Background Data for LULUCF—U.S.

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 plus wood fuel, pulp, recovered paper, roundwood/ chips	4 Annual Exports of wood, and paper products plus wood fuel, pulp, recovered paper, roundwood/ chips	5 Annual Domestic Harvest	6 Annual release of C to the atmosphere from HWP consumption (from fuelwood and products in use and products in SWDS)	7 Annual release of C 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 CO_2 emissions/ removals
	ΔCHWP IU DC	ΔCHWP SWDS DC	ΔC HWP IU DH	ΔCHWP SWDS DH	PIM	PEX	H	↑CHWP DC	↑CHWP DH	
									kt C/yr	kt 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	19,654	17,769	13,404	17,738	18,994	15,057	134,206	100,720	103,064	(114,188)
1999	21,444	18,662	14,146	18,359	20,599	15,245	134,193	99,440	101,689	(119,182)
2000	20,000	18,508	12,840	17,970	21,858	16,185	133,694	100,859	102,884	(112,969)
2001	16,491	17,610	8,713	16,781	22,051	15,336	127,896	100,510	102,402	(93,479)
2002	17,414	18,235	9,566	17,213	23,210	15,744	126,866	98,683	100,087	(98,188)
2003	16,986	17,326	9,453	16,175	23,707	16,303	123,606	96,698	97,978	(93,967)
2004	21,409	17,644	12,273	16,294	26,428	16,953	118,852	89,274	90,284	(104,747)
2005	20,990	17,765	11,826	16,324	26,793	17,312	120,393	91,118	92,244	(103,215)
2006	19,085	18,587	12,158	17,306	25,445	18,836	118,544	87,481	89,080	(108,034)
2007	13,104	18,309	10,661	17,425	21,663	20,657	115,827	85,421	87,740	(102,984)
2008	2,434	17,512	3,825	17,122	16,997	21,159	101,525	77,418	80,577	(76,807)
2009	(5,364)	16,623	(2,098)	16,657	13,115	20,616	90,576	71,815	76,016	(53,386)
2010	(3,191)	16,277	(383)	16,574	14,162	22,420	92,792	71,448	76,601	(59,367)
2011	(2,281)	16,136	1,559	16,790	13,923	24,672	97,134	72,530	78,785	(67,279)
2012	(1,299)	16,028	1,055	16,866	13,580	23,252	99,934	75,533	82,013	(65,710)
2013	1,555	16,110	1,900	16,960	14,700	22,783	103,331	77,582	84,471	(69,154)
2014	5,600	16,358	3,535	17,070	16,881	22,845	118,155	90,233	97,550	(75,552)
2015	6,764	16,475	3,731	17,094	17,478	22,266	108,071	80,044	87,247	(76,356)

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-262. 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-241. 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-237 and Table A-238. The decline in net additions to HWP C stocks continued through 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 C 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 C additions to HWP in use and in landfills combined.

A key assumption for estimating these variables is that products exported from the U.S. 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 *Land Converted to Forest Land* – Soil C Methods.

Table A-240: 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 C in harvested wood products for the U.S." *Forest Products Journal* 58:56–72.

Table A-241: 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	Percent
Percentage of wood in landfills that is subject to decay	23	Percent
Percentage of paper in landfills that is subject to decay	56	Percent
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 C in harvested wood products for the U.S." *Forest Products Journal* 58:56–72

Table A- 242: Net CO_2 Flux from Forest Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT CO_2 Eq.)

Carbon Pool	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Forest	**(574.7)**	**(577.4)**	**(523.0)**	**(518.3)**	**(521.3)**	**(524.6)**	**(526.3)**	**(557.3)**	**(563.8)**	**(572.2)**	**(578.9)**	**(584.5)**	**(602.0)**	**(605.0)**	**(598.5)**	**(596.1)**	**(593.7)**	**(571.1)**
Aboveground Biomass	(327.9)	(328.8)	(268.6)	(272.9)	(275.0)	(277.0)	(279.2)	(314.4)	(314.5)	(320.3)	(324.7)	(328.0)	(334.4)	(337.2)	(331.5)	(329.6)	(327.7)	(310.0)
Belowground Biomass	(70.0)	(70.2)	(56.4)	(57.4)	(57.8)	(58.2)	(58.6)	(66.6)	(66.4)	(67.5)	(68.4)	(69.0)	(70.3)	(71.0)	(69.7)	(69.2)	(68.7)	(64.6)
Dead Wood	(33.5)	(38.3)	(45.6)	(35.1)	(35.3)	(35.6)	(34.5)	(40.3)	(42.3)	(42.7)	(43.2)	(43.8)	(45.6)	(48.5)	(49.1)	(49.2)	(49.2)	(43.7)
Litter	(17.0)	(16.8)	(12.8)	(13.5)	(13.6)	(13.7)	(13.9)	(14.3)	(14.0)	(14.1)	(14.3)	(14.1)	(16.5)	(16.5)	(16.3)	(16.3)	(16.3)	(15.2)
Soil (Mineral)	(126.1)	(123.3)	(139.6)	(139.4)	(139.6)	(140.0)	(140.1)	(121.7)	(126.6)	(127.6)	(128.4)	(129.6)	(135.3)	(131.9)	(132.0)	(131.9)	(131.9)	(137.6)
Soil (Organic)	(0.110)	(0.073)	(0.037)	(0.037)	(0.037)	0.000	0.000	(0.037)	0.037	0.000	0.073	0.037	0.073	0.110	0.110	0.073	0.110	0.110
Harvested Wood	**(123.8)**	**(112.2)**	**(93.5)**	**(98.2)**	**(94.0)**	**(104.7)**	**(103.2)**	**(108.0)**	**(103.0)**	**(76.8)**	**(53.4)**	**(59.4)**	**(67.3)**	**(65.7)**	**(69.2)**	**(75.6)**	**(76.4)**	**(95.9)**
Products in Use	(54.8)	(51.7)	(31.9)	(35.1)	(34.7)	(45.0)	(43.4)	(44.6)	(39.1)	(14.0)	7.7	1.4	(5.7)	(3.9)	(7.0)	(13.0)	(13.7)	(31.4)
SWDS	(69.0)	(60.5)	(61.5)	(63.1)	(59.3)	(59.7)	(59.9)	(63.5)	(63.9)	(62.8)	(61.1)	(60.8)	(61.6)	(61.8)	(62.2)	(62.6)	(62.7)	(64.4)
Total Net Flux	**(698.4)**	**(689.5)**	**(616.4)**	**(616.5)**	**(615.2)**	**(629.3)**	**(629.5)**	**(665.3)**	**(666.8)**	**(649.0)**	**(632.4)**	**(643.9)**	**(669.4)**	**(670.8)**	**(667.8)**	**(671.7)**	**(670.1)**	**(667.0)**

Table A- 243: Net C Flux from Forest Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

Carbon Pool	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Forest	**(156.7)**	**(157.5)**	**(142.6)**	**(141.4)**	**(142.2)**	**(143.1)**	**(143.5)**	**(152.0)**	**(153.8)**	**(156.0)**	**(157.9)**	**(159.4)**	**(164.2)**	**(165.0)**	**(163.2)**	**(162.6)**	**(161.9)**	**(155.7)**
Aboveground Biomass	(89.4)	(89.7)	(73.3)	(74.4)	(75.0)	(75.6)	(76.2)	(85.7)	(85.8)	(87.3)	(88.5)	(89.4)	(91.2)	(92.0)	(90.4)	(89.9)	(89.4)	(84.6)
Belowground Biomass	(19.1)	(19.2)	(15.4)	(15.7)	(15.8)	(15.9)	(16.0)	(18.2)	(18.1)	(18.4)	(18.7)	(18.8)	(19.2)	(19.4)	(19.0)	(18.9)	(18.7)	(17.6)
Dead Wood	(9.1)	(10.4)	(12.4)	(9.6)	(9.6)	(9.7)	(9.4)	(11.0)	(11.5)	(11.6)	(11.8)	(11.9)	(12.4)	(13.2)	(13.4)	(13.4)	(13.4)	(11.9)
Litter	(4.6)	(4.6)	(3.5)	(3.7)	(3.7)	(3.7)	(3.8)	(3.9)	(3.8)	(3.9)	(3.9)	(3.9)	(4.5)	(4.5)	(4.4)	(4.4)	(4.4)	(4.1)
Soil (Mineral)	(34.4)	(33.6)	(38.1)	(38.0)	(38.1)	(38.2)	(38.2)	(33.2)	(34.5)	(34.8)	(35.0)	(35.3)	(36.9)	(36.0)	(36.0)	(36.0)	(36.0)	(37.5)
Soil (Organic)	(0.030)	(0.020)	(0.010)	(0.010)	(0.010)	0.000	0.000	(0.010)	0.010	0.000	0.020	0.010	0.020	0.030	0.030	0.020	0.030	0.030
Harvested Wood	**(33.8)**	**(30.6)**	**(25.5)**	**(26.8)**	**(25.6)**	**(28.6)**	**(28.1)**	**(29.5)**	**(28.1)**	**(20.9)**	**(14.6)**	**(16.2)**	**(18.3)**	**(17.9)**	**(18.9)**	**(20.6)**	**(20.8)**	**(26.1)**
Products in Use	(14.9)	(14.1)	(8.7)	(9.6)	(9.5)	(12.3)	(11.8)	(12.2)	(10.7)	(3.8)	2.1	0.4	(1.6)	(1.1)	(1.9)	(3.5)	(3.7)	(8.6)
SWDS	(18.8)	(16.5)	(16.8)	(17.2)	(16.2)	(16.3)	(16.3)	(17.3)	(17.4)	(17.1)	(16.7)	(16.6)	(16.8)	(16.9)	(17.0)	(17.1)	(17.1)	(17.6)
Total Net Flux	**(190.5)**	**(188.1)**	**(168.1)**	**(168.1)**	**(167.8)**	**(171.6)**	**(171.7)**	**(181.5)**	**(181.9)**	**(177.0)**	**(172.5)**	**(175.6)**	**(182.6)**	**(183.0)**	**(182.1)**	**(183.2)**	**(182.8)**	**(181.9)**

Table A- 244 Forest area (1,000 ha) and C Stocks in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Forest Area (1000 ha)	**262,119**	**263,516**	**265,022**	**267,479**	**268,044**	**268,618**	**269,163**	**269,710**	**270,258**	**270,654**	**271,064**	**271,512**	**271,812**	**272,113**	**272,260**
Carbon Pools															
Forest	**46,967**	**47,753**	**48,510**	**49,223**	**49,375**	**49,529**	**49,685**	**49,843**	**50,002**	**50,166**	**50,331**	**50,494**	**50,657**	**50,819**	**50,975**
Aboveground Biomass	11,889	12,335	12,748	13,122	13,208	13,294	13,381	13,470	13,559	13,650	13,742	13,833	13,922	14,012	14,096

Belowground Biomass	2,439		2,534		2,622		2,700	2,718	2,737	2,755	2,774	2,792	2,812	2,831	2,850	2,869	2,888	2,905
Dead Wood	2,262		2,310		2,373		2,424	2,435	2,446	2,458	2,470	2,482	2,494	2,507	2,521	2,534	2,548	2,560
Litter	2,568		2,591		2,612		2,630	2,634	2,638	2,642	2,646	2,650	2,654	2,659	2,663	2,668	2,672	2,676
Soil (Mineral)	27,456		27,630		27,804		27,994	28,027	28,062	28,097	28,132	28,167	28,204	28,240	28,276	28,312	28,348	28,385
Soil (Organic)	352		352		352		352	352	352	352	352	352	352	352	352	352	352	352
Harvested Wood	**1,895**		**2,061**		**2,218**		**2,353**	**2,382**	**2,411**	**2,431**	**2,446**	**2,462**	**2,481**	**2,498**	**2,517**	**2,538**	**2,559**	**2,585**
Products in Use	1,249		1,326		1,395		1,447	1,459	1,470	1,474	1,472	1,471	1,473	1,474	1,476	1,479	1,483	1,492
SWDS	646		735		823		906	923	941	958	974	991	1,008	1,025	1,042	1,059	1,076	1,093
Total Stock	**48,862**		**49,814**		**50,729**		**51,576**	**51,757**	**51,939**	**52,116**	**52,289**	**52,464**	**52,647**	**52,830**	**53,012**	**53,195**	**53,378**	**53,560**

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Land Converted to Forest Land

The following section includes a description of the methodology used to estimate stock changes in all forest C pools for *Land Converted to Forest Land*. Forest Inventory and Analysis data and IPCC (2006) defaults for reference C stocks were used to compile separate estimates for the five C storage pools within an age class transition matrix for the 20 year conversion period (where possible). The 2009 USDA National Resources Inventory (NRI) land-use survey points were classified according to land-use history records starting in 1982 when the NRI survey began. Consequently the classifications from 1990 to 2001 were based on less than 20 years. Furthermore, the FIA data used to compile estimates of carbon sequestration in the age class transition matrix are based on 5- to 10-yr remeasurements so the exact conversion period was limited to the remeasured data over the time series. Estimates for Aboveground and Belowground Biomass, Dead wood and Litter were based on data collected from the extensive array of permanent, annual forest inventory plots and associated models (e.g., live tree belowground biomass) in the U.S. (USDA Forest Service 2015b, 2015c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. To ensure consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, all soil estimates are based on methods from Ogle et al. (2003, 2006) and IPCC (2006).

Live tree C pools

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at diameter breast height (d.b.h.) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates are made for above- and below-ground biomass components. If inventory plots include data on individual trees, tree C is based on Woodall et al. (2011), which is also known as the component ratio method (CRM), and is a function of volume, species, diameter, and, in some regions, tree height and site quality. The estimated sound volume (i.e., after rotten/missing deductions) provided in the tree table of the FIADB is the principal input to the CRM biomass calculation for each tree (Woodall et al. 2011). The estimated volumes of wood and bark are converted to biomass based on the density of each. Additional components of the trees such as tops, branches, and coarse roots, are estimated according to adjusted component estimates from Jenkins et al. (2003). Live trees with d.b.h of less than 12.7 cm do not have estimates of sound volume in the FIADB, and CRM biomass estimates follow a separate process (see Woodall et al. 2011 for details). An additional component of foliage, which was not explicitly included in Woodall et al. (2011), was added to each tree following the same CRM method. Carbon is estimated by multiplying the estimated oven-dry biomass by a C constant of 0.5 because biomass is 50 percent of dry weight (IPCC 2006). Further discussion and example calculations are provided in Woodall et al. 2011 and Domke et al. 2012.

Understory vegetation

Understory vegetation is a minor component of total forest ecosystem 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. See model (1) in the *Forest Land Remaining Forest Land* section of the Annex.

In this model, the ratio is the ratio of understory C density (T C/ha) to live tree C density (above- and below-ground) according to Jenkins et al. (2003) and expressed in T C/ha. An additional coefficient is provided as a maximum ratio; that is, any estimate predicted from the model that is greater than the maximum ratio is set equal to the maximum ratio. A full set of coefficients are in Table A-234. Regions and forest types are the same classifications described in Smith et al. (2003). An example example calculation for understory C in aspen-birch forests in the Northeast is is provided in the Forest Land Remaining Forest Land section of the Annex.

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 model. Second, the minimum ratio is set to 0.005 (Birdsey 1996). Third, nonstocked (i.e., currently lacking tree cover but still in the forest land use) and pinyon/juniper forest types (see Table A-234) are set to coefficient A, which is a C density (T C/ha) for these types only.

Dead wood

The standing dead tree estimates are primarily based on plot-level measurements (Domke et al. 2011; Woodall et al. 2011). This C pool includes aboveground and belowground (coarse root) mass and includes trees of at least 12.7 cm d.b.h. Calculations follow the basic CRM method applied to live trees (Woodall et al. 2011) with additional modifications

to account for decay and structural loss. In addition to the lack of foliage, two characteristics of standing dead trees that can significantly affect C mass are decay, which affects density and thus specific C content (Domke et al. 2011; Harmon et al. 2011), and structural loss such as branches and bark (Domke et al. 2011). Dry weight to C mass conversion is by multiplying by 0.5.

Downed dead wood, inclusive of logging residue, are sampled on a subset of FIA plots. Despite a reduced sample intensity, a single down woody material population estimate (Woodall et al. 2010; Domke et al. 2013; Woodall et al. 2013) per state is now incorporated into these empirical downed dead wood estimates. Downed 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. It also includes stumps and roots of harvested trees. Ratio estimates of downed dead wood to live tree biomass were developed using FORCARB2 simulations and applied at the plot level (Smith et al. 2004). Estimates for downed 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-235. An additional component of downed 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-236. These amounts are added to explicitly account for downed dead wood following harvest. The sum of these two components are then adjusted by the ratio of population totals; that is, the ratio of plot-based to modeled estimates (Domke et al. 2013).

Litter carbon

Carbon in the litter layer is currently sampled on a subset of the FIA plots. 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. Because litter attributes are only collected on a subset of FIA plots, a model was developed to predict C density based on plot/site attributes for plots that lacked litter information (Domke et al. 2016).

As the litter, or forest floor, estimates are an entirely new model this year, a more detailed overview of the methods is provided here. The first step in model development was to evaluate all relevant variables—those that may influence the formation, accumulation, and decay of forest floor organic matter—from annual inventories collected on FIADB plots (P2) using all available estimates of forest floor C (n = 4,530) from the P3 plots (hereafter referred to as the research dataset) compiled from 2000 through 2014 (Domke et al. 2016).

Random forest, a machine learning tool (Domke et al. 2016), was used to evaluate the importance of all relevant forest floor C predictors available from P2 plots in the research dataset. Given many of the variables were not available due to regional differences in sampling protocols during periodic inventories, the objective was to reduce the random forest regression model to the minimum number of relevant predictors without substantial loss in explanatory power. The model (3) and parameters are described in the *Forest Land Remaining Forest Land* section of the Annex.

Due to data limitation in certain regions and inventory periods a series of reduced random forest regression models were used rather than replacing missing variables with imputation techniques in random forest. Database records used to compile estimates for this report were grouped by variable availability and the approaches described herein were applied to replace forest floor model predictions from Smith and Heath (2002). Forest floor C predictions are expressed in T•ha−1.

Mineral Soil

A Tier 2 method is applied to estimate soil C stock changes for *Land Converted to Forest Land* (Ogle et al. 2003, 2006; IPCC 2006). For this method, land is stratified by climate, soil types, land-use, and land management activity, and then assigned reference C levels and factors for the forest land and the previous land use. The difference between the stocks is reported as the stock change under the assumption that the change occurs over 20 years. Reference C stocks have been estimated from data in the National Soil Survey Characterization Database (USDA-NRCS 1997), and U.S.-specific stock change factors have been derived from published literature (Ogle et al. 2003; Ogle et al. 2006). Land use and land use change patterns are determined from a combination of the Forest Inventory and Analysis Dataset (FIA), the 2010 National Resources Inventory (NRI) (USDA-NRCS 2013), and National Land Cover Dataset (NLCD) (Homer et al. 2007). See Annex 3.12 for more information about this method (Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Soil Management).

Table A- 245 summarizes the annual change in mineral soil C stocks from U.S. soils that were estimated using a Tier 2 method (MMT C/year). The range is a 95 percent confidence interval from 50,000 simulations (Ogle et al. 2003, 2006).

Table A- 246 summarizes the total land areas by land use/land use change subcategory for mineral soils between 1990 and 2015 estimated with a Tier 2 approach and based on analysis of USDA National Resources Inventory data (USDA-NRCS 2013).

Table A- 245: Annual change in Mineral Soil C stocks from U.S. agricultural soils that were estimated using a Tier 2 method (MMT C/year)

Category	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cropland Converted to Forest Land	0.01	0.01	0.03	0.02	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
	(0.01 to -0.01)	(0.01 to -0.01)	(0.03 to -0.01)	(0.02 to -0.02)	(-0.01 to -0.02)	(-0.01 to -0.03)	(-0.01 to -0.03)	(-0.01 to -0.03)	(-0.01 to -0.02)	(-0.01 to -0.02)	(-0.01 to -0.02)	(-0.01 to -0.02)	(-0.01 to -0.02)	(-0.01 to -0.02)
Grassland Converted to Forest Land	0.03	0.05	0.09	0.06	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	(0.03 to -0.03)	(0.05 to -0.04)	(0.09 to -0.04)	(0.06 to -0.05)	(-0.02 to -0.07)	(-0.02 to -0.08)	(-0.02 to -0.08)	(-0.02 to -0.09)	(-0.02 to -0.09)	(-0.02 to -0.08)	(-0.02 to -0.08)	(-0.02 to -0.09)	(-0.02 to -0.09)	(-0.02 to -0.09)
Other Lands Converted to Forest Land	0.00	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	(0 to 0)	(0.01 to -0.01)	(0.02 to -0.01)	(0.01 to -0.01)	(0 to -0.02)	(0 to -0.02)	(0 to -0.01)	(0 to -0.01)	(0 to -0.01)	(0 to -0.01)	(0 to -0.01)	(0 to -0.01)	(0 to -0.01)	(0 to -0.01)
Settlements Converted to Forest Land	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)
Wetlands Converted to Forest Land	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)	(0 to 0)
Total Lands Converted to Forest Lands	0.05	0.08	0.15	0.10	-0.02	-0.03	-0.03	-0.04	-0.03	-0.03	-0.04	-0.04	-0.04	-0.04

Note: The range is a 95 percent confidence interval from 50,000 simulations (Ogle et al. 2003, 2006).

Table A- 246: Total land areas (hectares) by land use/land use change subcategory for mineral soils between 1990 and 2015

Conversion Land Areas (Hectares x 106)	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cropland Converted to Forest Land	0.21	0.20	0.23	0.23	0.24	0.25	0.25	0.22	0.22	0.21	0.21	0.20	0.19	0.18	0.18	0.18	0.17	0.17
Grassland Converted to Forest Land	0.71	0.79	0.85	0.88	0.85	0.81	0.78	0.72	0.70	0.67	0.64	0.62	0.59	0.57	0.60	0.60	0.60	0.60
Other Lands Converted to Forest Land	0.09	0.10	0.11	0.11	0.12	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.12	0.12	0.10	0.10	0.10	0.09
Settlements Converted to Forest Land	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Wetlands Converted to Forest Land	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total Lands Converted to Forest Lands	**1.04**	**1.13**	**1.23**	**1.27**	**1.25**	**1.23**	**1.20**	**1.10**	**1.08**	**1.05**	**1.01**	**0.98**	**0.94**	**0.91**	**0.91**	**0.91**	**0.90**	**0.90**

Note: Estimated with a Tier 2 approach and based on analysis of USDA National Resources Inventory data (USDA-NRCS 2013).

Uncertainty Analysis

The uncertainty analyses for total net flux of forest C (see Table 6-14 in the FLRFL section) are consistent with the IPCC-recommended Tier 1 methodology (IPCC 2006). Specifically, they are considered approach 1 (propagation of error [Section 3.2.3.1]) (IPCC 2006). To better understand the effects of covariance, the contributions of sampling error and modeling error were parsed out. In addition, separate analyses were produced for forest ecosystem and HWP flux.

Estimates of forest C stocks in the U.S. are based on C estimates assigned to each of several thousand inventory plots from a regular grid. Uncertainty in these estimates and uncertainty associated with change estimates arise from many sources including sampling error and modeling error. Here we focus on these two types of error but acknowledge several other sources of error are present in the overall stock and stock change estimates. In terms of sampling based uncertainty, Design based estimators described by Bechtold and Patterson (2005) were used to quantify the variance of C stock estimates. In this section we denote the estimate of C stock at time *t* as Ct and the variances of the estimate of C stock for time *t* as Var(Ct). These calculations follow Bechtold and Patterson (2005). The variance of stock change is then:

$$\mathrm{Var}(Ct2\text{-}Ct1)=\mathrm{Var}(Ct2)+\mathrm{Var}(Ct1)-2\cdot\mathrm{Cov}(Ct2,Ct1) \quad (16)$$

The uncertainty of a stock estimate associated with sampling error is U(Ct)s= Var(Ct)0.5. The uncertainty of a stock changes estimate associated with sampling error is U(ΔC)s=Var(Ct2-Ct1)0.5.

Model-based uncertainty is important because the pool-level C models have error. The total modeling mean-squared error (MSEm) is approximately 1,622 $(Mg/ha)^2$. The percent modeling error at time *t* is

$$\%U(Ct)m = 100\cdot MSEm/dt \quad (17)$$

Where dt is the total C stock density at time t calculated as Ct/At where At is the forest area at time *t*.

The uncertainty of Ct from modeling error is

$$U(Ct)m=Ct\cdot\%U(Ct)m/100 \quad (18)$$

The model-based uncertainty with respect to stock change is then

$$U(\Delta C)m=(\,U(Ct1)m + U(Ct2)m - 2\cdot\mathrm{Cov}(U(Ct1m,Ct2m)))0.5 \quad (19)$$

The sampling and model based uncertainty are combined for an estimate of total uncertainty. We considered these sources of uncertainty independent and combined as follow for stock change for stock change (ΔC):

$$U(\Delta C)=(\,U(\Delta C)m2+ U(\Delta C)s2)0.5 \text{ and the 95 percent confidence bounds was } +\text{-}\ 2\cdot U(\Delta C) \quad (20)$$

The mean square error (MSE) of pool models was (MSE, $[Mg\ C/ha]^2$): soil C (1143.0), litter (78.0), live tree (259.6), dead trees (101.5), understory (0.9), down dead wood (38.9), total MSE (1,621.9).

Numerous assumptions were adopted for creation of the forest ecosystem uncertainty estimates. Potential pool error correlations were ignored. Given the magnitude of the MSE for soil, including correlation among pool error would not appreciably change the modeling error contribution. Modeling error correlation between time 1 and time 2 was assumed to be 1. Because the MSE was fixed over time we assumed a linear relationship dependent on either the measurements at two points in time or an interpolation of measurements to arrive at annual flux estimates. Error associated with interpolation to arrive at annual flux is not included.

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 U.S. harvest, compared to storage in the United States.

The uncertainty about HWP and forest ecosystem net C flux were combined and assumed to be additive. Typically when propagating error from two estimates the variances of the estimates are additive. However, the uncertainty around the HWP flux was approximated using a Monte Carlo approach which resulted in the lack of a variance estimate for HWP C

flux. Therefore, we considered the uncertainty additive between the HWP sequestration and the *Forest Land Remaining Forest Land* sequestration. Further, we assumed there was no covariance between the two estimates which is plausible as the observations used to construct each estimate are independent.

Emissions from Forest Fires

CO_2 Emissions from Forest Fires

As stated in other sections, the forest inventory approach implicitly accounts for emissions due to disturbances. Net C stock change is estimated from successive C stock estimates. A disturbance, such as a forest fire, removes C from the forest. The inventory data, on which net C stock estimates are based, already reflects the C loss from such disturbances 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, CH_4, and N_2O emissions from disturbances such as fire. These estimated emissions from forest fires are based on IPCC (2006) methodology, which includes a combination of U.S.-specific data on area burned and potential fuel available for combustion along with IPCC default combustion and emission factors.

Emissions were calculated following IPCC (2006) methodology, according to equation 2.27 of IPCC (2006, Volume 4, Chapter 2), which in general terms is:

$$\text{Emissions} = \text{Area burned} \times \text{Fuel available} \times \text{Combustion factor} \times \text{Emission factor} \times 10^{-3} \quad (21)$$

Where the estimate for emissions is in units of metric tons (MT), which is generally summarized as million metric tons (MMT) per year. Area burned is the annual total area of forest fire in hectares. Fuel available is the mass of fuel available for combustion in metric tons dry weight per hectare. Combustion factor is the proportion of fuel consumed by fire and is unitless. The emission factor is gram of emission (in this case CO_2) per kilogram dry matter burnt, and the "10^{-3}" balances units. The first two factors are based on datasets specific to U.S. forests, whereas the last two factors employ IPCC (2006) default values.

Area burned is based on annual area of forest fires according to Monitoring Trends in Burn Severity (MTBS) MTBS Data Summaries 2015; Eidenshink et al. 2007) dataset summaries,[106] which include fire data for all 49 states that are a part of these estimates. That is, the MTBS data used here include the 48 conterminous states as well as Alaska, including interior Alaska; but note that the fire data used are also reduced to only include managed land. Summary information includes fire identity, year, location, area burned, fire intensity, and other fire characteristics. In addition to forest fires, the MTBS data include all wildland and prescribed fires on other ecosystems such as grasslands and rangelands; the "forest fire" distinction is not included as a part of identifying information for each fire. An additional spatial dataset – National MTBS Burned Area Boundaries–provides information to locate fires.[107] These individual-fire boundary data were used to partition the area burned in each fire to forest versus non-forest.

The MTBS fire data records include land cover information from the National Land Cover (NLCD) dataset (Homer et al. 2015), which can be used to distinguish forest fires from other wildland fires within the MTBS data. However, the forest land cover of the NLCD data, including the 2011 land cover (Homer et al. 2015) provides an estimate of forest land that is approximately 20 percent lower than forest area identified by the forest inventory of the USDA Forest Service (USDA Forest Service 2015b, e.g., data as of 2 June 2015) for the conterminous United States. This suggests that annual area of forest fires identified with the NLCD cover data may underestimate area of forest burned, but the difference between USDA Forest Service (2015) and Homer et al. (2015) for each individual fire, if any, is dependent on specific areas where the fires actually occur. As an alternative data source, forest area for conterminous United States and Alaska are defined by Ruefenacht et al. (2008). The forest area for the conterminous states representative of approximately 2002 is within 2 percent of the forest areas estimated for 1990 through 2015 in U.S. EPA (2016). These data were used to partition the perimeter data to forest for each fire (that is, area of forest relative to entire area of the fire for each MTBS fire). We assume that while changes in forests have occurred both before and since the data for Ruefenacht et al. (2008) were compiled, changes in forest versus non-forest status on lands subject to wildfires are likely minimal enough to make this dataset appropriate for this use. In addition, the Alaska forest area was allocated to managed and unmanaged areas according to Ogle et al. (in preparation), as discussed in more detail above.

[106] See <http://www.mtbs.gov/dataaccess.html>.
[107] See <http://www.mtbs.gov/dataaccess.html>.

The burned area perimeter dataset also was used to identify Alaska fires that were co-located with the area of permanent inventory plots of the USDA Forest Service's (2015b) forest inventory along the southern coastal portion of the state. The only MTBS-identified burned forest areas in Alaska that coincide with the Forest Service's permanent plot inventoried area were on the northern (or Cook Inlet) side of the Kenai Peninsula, which is generally identified as boreal forest. From this, all MTBS fires of interest identified in Alaska are considered boreal forests.

Estimates of fuel availability are based on plot level forest inventory data, which are summarized by state and applied to all fires within the respective states. Plot level C stocks are defined by C conversion factors applied to current USDA Forest Service inventory data (USDA Forest Service 2015b; U.S. EPA 2015; Smith et al. 2010) and summarized by state. We assume that while changes in forests have occurred over the years since the 1990 start of the reporting interval, the current general range of plot level C densities as determined by forest types and stand structures can be used as a representation of the potential fuel availability over the forest lands of a given state. We use the current forest inventory data[108] and the distribution of metric tons dry matter per hectare as the inputs for fuel availability. Fuel estimated for wildfires included all aboveground biomass (live trees and understory) as well as standing dead trees, down dead wood, and forest floor litter; whereas, fuel estimated for prescribed fires was based on the non-living components only.

The combustion factor used here for temperate forests is 0.45 (see Table 2.6 Volume 4, Chapter 2 of IPCC 2006). Similarly, the emission factor is an IPCC (2006) default, which for CO_2 is 1,569 g CO_2 per kg dry matter of fuel (see Table 2.5 Volume 4, Chapter 2 of IPCC 2006). With the application of equation 2.27 of IPCC (2006, in Volume 4, Chapter 2) defaults were used for mass of fuel available for the Alaska estimates because of the very limited coverage of boreal forests in the available U.S. forest inventories (see Table 2.4 Volume 4, Chapter 2 of IPCC 2006). Note that the values used for Alaska (Table 2.4 of IPCC 2006) represent the product of fuel available and the combustion factor.

Table A- 247 provides summary values of annual area burned, area identified as forest fire, and emissions calculated according to equation 2.27 of IPCC (2006, in Volume 4, Chapter 2). The emission factor for CO_2 from Table 2.5 Volume 4, Chapter 2 of IPCC (2006) is provided in Table A-248. Separate calculations were made for each wild and prescribed fire in each state for each year. The results as MT CO_2 were summed to the MMT CO_2 per year values represented in Table A- 247, and C emitted per year (Table A- 247 and Table A-250) was based on multiplying by the conversion factor 12/44 (IPCC 2006).

[108] Retrieved from <http://apps.fs.fed.us/fiadb-downloads/datamart.html> on June 2, 2015.

Table A- 247: Areas (Hectares) from Wildfire Statistics and Corresponding Estimates of C and CO_2 (MMT/year) Emissions for Wildfires and Prescribed Fires[a]

		1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015[b]
Conterminous 48 States - Wildfires	Reported area burned (1000 ha)	462.8	544.0	2,257.6	1,723.9	3,603.2	3,219.6	1,608.5	1,489.9	579.2	3,187.2	3,421.8	1,092.1	1,994.5	1,994.5
	Forest area burned (1000 ha)	184.2	128.7	1,016.2	603.3	946.2	1,488.2	724.4	493.5	142.6	1,242.1	1,451.7	640.0	679.0	679.0
	C emitted (MMT/yr)	6.2	2.5	26.5	11.9	27.5	41.9	26.6	10.8	3.5	22.2	37.6	18.5	23.3	23.3
	CO_2 emitted (MMT/yr)	22.7	9.2	97.3	43.5	100.9	153.8	97.6	39.7	13.0	81.3	138.0	68.0	85.3	85.3
Alaska - Wildfires	Reported area burned (1000 ha)	546.5	11.7	311.3	1,950.1	98.7	217.5	26.4	1,078.3	257.4	90.1	90.9	454.7	90.8	90.8
	Forest area burned (1000 ha)	303.4	10.0	160.9	1,253.8	80.3	80.1	16.8	682.8	175.0	55.0	41.6	347.1	75.6	75.6
	C emitted (MMT/yr)	5.3	0.2	2.8	21.9	1.4	1.4	0.3	12.1	3.1	1.0	0.7	6.1	1.3	1.3
	CO_2 emitted (MMT/yr)	19.5	0.6	10.4	80.1	5.1	5.1	1.1	44.4	11.3	3.6	2.7	22.3	4.9	4.9
Prescribed Firesa (all 49 states)	Reported area burned (1000 ha)	10.3	16.0	83.1	107.1	108.5	156.5	319.3	407.9	763.9	993.7	149.6	275.8	311.5	311.5
	Forest area burned (1000 ha)	6.1	10.9	22.7	62.1	79.8	96.3	251.1	317.8	657.3	242.9	110.4	268.6	282.5	282.5
	C emitted (MMT/yr)	0.0	0.1	0.2	0.3	0.6	0.6	1.6	2.2	5.1	1.6	0.8	1.5	1.7	1.7
	CO_2 emitted (MMT/yr)	0.2	0.2	0.6	1.3	2.1	2.2	6.0	7.9	18.5	6.0	3.0	5.5	6.1	6.1
Wildfires (all 49 states)	CH_4 emitted (kt/yr)	127.1	29.8	320.3	373.8	319.7	478.8	284.4	251.4	72.7	254.7	422.6	272.4	273.7	273.7
	N_2O emitted (kt/yr)	6.9	1.6	17.8	20.5	17.7	26.3	15.9	13.8	4.0	14.2	23.3	14.9	15.0	15.0
	CO emitted (kt/yr)	2,820.2	694.4	7,264.9	8,400.6	7,168.7	10,556.4	6,418.4	5,711.1	1,664.8	5,730.1	9,612.4	6,276.2	6,220.0	6,220.0
	NO_x emitted (kt/yr)	79.7	19.5	207.4	236.6	202.9	294.4	179.6	158.0	46.2	160.3	270.0	174.3	176.3	176.3
Prescribed Firesa (all 49 states)	CH_4 emitted (kt/yr)	0.5	0.7	1.8	3.8	6.3	6.7	17.2	23.6	55.5	18.0	8.9	16.4	18.6	18.6
	N_2O emitted (kt/yr)	0.0	0.0	0.1	0.2	0.3	0.4	1.0	1.3	3.1	1.0	0.5	0.9	1.0	1.0
	CO emitted (kt/yr)	11.7	16.7	40.0	85.3	141.5	147.4	389.0	536.1	1,271.3	405.4	202.3	379.0	422.2	422.2
	NO_x emitted (kt/yr)	0.3	0.5	1.1	2.4	4.0	4.1	10.9	14.8	35.3	11.3	5.7	10.5	12.0	12.0

[a] IPCC (2006)
[b] IPCC (2007)

Table A-248: Emission Factors for Extra Tropical Forest Burning and 100-year GWP (AR4), or equivalence ratios, of CH_4 and N_2O to CO_2

Emission Factor (g per kg dry matter burned)[a]		Equivalence Ratios[b]	
CH_4	4.70	CH_4 to CO_2	25
N_2O	0.26	N_2O to CO_2	298
CO_2	1,569	CO_2 to CO_2	1

[a] IPCC (2006)
[b] IPCC (2007)

The set of fire emissions estimates using MODIS imagery and post-fire observations developed for Alaska by Veraverbeke et al. (2015a) is used here to provide a comparison with the estimates developed here (i.e., Table A-250). The spatial Alaskan Fire Emissions Database (AKFED, Veraverbeke et al. 2015b) was partitioned to forest land based on both Ruefenacht et al. (2008) and Homer et al. (2015) as well as managed/unmanaged (Ogle et al. in preparation). The estimates of annual C emitted from fire are in Table A-249, which also includes the estimates for managed forest land (both wildland and prescribed) that underlie the values provided in Table A- 247. Note that the values in the six rightmost columns effectively partition the C emissions estimates provided in Veraverbeke et al. (2015a, see Table 2). That is, Table A-249, column 2 provides the estimates developed for this Inventory while each of columns 3-5 and 6-8 sum to the emissions estimates of Veraverbeke et al. (2015a); the differences between the two sets are how they are partitioned according to forest land.

Table A-249: Estimated C emissions (MMT/yr) for fire based on the AKFED, and partitioned to managed forest land in Alaska

		Forest land based on Ruefenacht et al. (2008)			Forest land based on Homer et al. (2015)		
Year[a]	Managed forest land (Table A-14)[b]	Managed forest land	Unmanaged forest land	Non-forest land	Managed forest land	Unmanaged forest land	Non-forest land
				C emitted (MMT/year)			
2001	0.7	0.8	0.3	0.0	0.1	0.0	1.1
2002	11.2	12.7	3.3	0.8	1.5	0.4	14.8
2003	2.8	4.0	1.4	0.0	0.6	0.2	4.7
2004	34.4	51.8	16.6	1.0	7.0	2.5	59.9
2005	22.0	29.8	14.1	1.7	4.1	1.9	39.6
2006	1.4	0.7	0.1	0.0	0.1	0.0	0.7
2007	1.5	1.4	1.0	2.9	0.3	0.1	4.9
2008	0.3	0.4	0.4	0.1	0.1	0.0	0.8
2009	12.0	16.3	9.8	0.2	1.5	0.7	24.1
2010	4.7	4.6	1.1	0.3	0.7	0.1	5.1
2011	1.0	1.5	0.3	0.1	0.8	0.2	0.9
2012	0.8	0.8	0.2	0.2	0.4	0.2	0.6
2013	6.1	7.4	2.5	0.3	4.7	1.7	3.7

[a] The AKFED data include the years 2001-2013 (Veraverbeke et al. 2015b).
[b] Values include both wildland and prescribed fires in Alaska.

Non-CO_2 Emissions from Forest Fires

Emissions of non-CO_2 gases–specifically, methane (CH_4) and nitrous oxide (N_2O)–from forest fires are estimated using the same methodology described above (i.e., equation 2.27 of IPCC 2006, Volume 4, Chapter 2). The only difference in calculations is the gas-specific emission factors, which are listed in Table A-248. The summed annual estimates are provided in Table A-250. Conversion of the CH_4 and N_2O estimates to CO_2 equivalents (as provided in Chapter 6-2) is based on global warming potentials (GWPs) provided in the IPCC Fourth Assessment Report (AR4) (IPCC 2007), which are the equivalence ratios listed in Table A-248. An example application of these ratios for the current year's estimate of CH_4 emissions is: 7.34 MMT CO_2 Eq. = 293,836 MT CH_4 × (25 kg CO_2 / 1 kg CH_4) × 10^{-6}.

Uncertainty about the non-CO_2 estimates is based on assigning a probability distribution to represent the estimated precision of each factor in equation 2.27 of the *2006 IPCC Guidelines* (IPCC 2006). These probability distributions are randomly sampled with each calculation, and this is repeated a large number of times to produce a histogram, or frequency distribution of values for the calculated emissions. That is, a simple Monte Carlo ("Approach 2") method was employed to propagate uncertainty in the equation (IPCC 2006). In general, probability densities are normal and also considered marginal distributions.

Estimates of burned forest area from the MTBS data (MTBS Data Summaries 2015; Ruefenacht et al. 2008; Ogle et al. in preparation) are assigned a normal distribution with relatively low uncertainty with a standard deviation of 4 percent, and these were sampled independently by year (Homer et al. 2015; Hao and Larkin 2014; Eidenshink et al. 2007). Fuel available is based on the distribution of plot level C densities (as metric tons dry matter per hectare) as defined within the current USDA Forest Service inventory data (USDA Forest Service 2015; U.S. EPA 2015). We assume that current data adequately represent the general range of plot level C densities within a state's forest land, given the limitations of the older inventory data as discussed elsewhere in this report. The plot-level C densities are summarized as dry weight densities (metric tons per hectare) for each plot with all aboveground dry weight summed as potential fuel for wildfires and all non-living components of aboveground dry weight assigned as potential fuel for prescribed fires. Frequency distributions of the plot data indicate that densities are distributed approximately lognormally. Each state's data are fit to a lognormal distribution, and these were sampled independently by state and year. Note that each state has separate lognormal distributions for wild versus prescribed fire fuels, yet the same sampling sequence was used (i.e., jointly distributed within each state by year). Estimates for the Alaska fuel-by-combustion value as well as the combustion factor and emission factors are normal distributions with mean and standard deviations as defined in the tables (IPCC 2006 Tables 2.4, 2.5, and 2.6). These were sampled independently by year, and truncated to positive values where necessary. The equivalence ratios (Table A-248) to represent estimates as CO_2 equivalent were not considered uncertain values for these results.

Table A-250: Estimated C Released and Estimates of Non-CO_2 Emissions (MMT/year) for U.S. forests

Year	C Emitted (MMT/yr)	CH_4 Emitted (MMT/yr)	N_2O (MMT/yr)
1990	42,358	128	7
1991	48,673	145	8
1992	21,699	64	4
1993	11,978	36	2
1994	77,051	231	13
1995	10,108	31	2
1996	50,857	152	8
1997	6,518	20	1
1998	28,247	84	5
1999	64,165	192	11
2000	108,225	322	18
2001	56,252	168	9
2002	154,090	460	25
2003	87,643	262	15
2004	151,670	452	25
2005	124,903	378	21
2006	108,114	326	18
2007	161,151	486	27
2008	104,612	302	17
2009	92,011	275	15
2010	42,803	128	7
2011	90,868	273	15
2012	143,614	431	24
2013	95,743	289	16
2014	96,271	292	16
2015[a]	96,271	292	16

[a] The data for 2015 were incomplete when these estimates were summarized; therefore 2014, the most recent available estimate, is applied to 2015.

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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.[109] 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 the CH_4 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.

Methane emissions from landfills can be estimated using two primary methods. The first method uses the first order decay model as described by the *2006 IPCC Guidelines* to estimate CH_4 generation. The amount of CH_4 recovered and combusted from MSW landfills is subtracted from the CH_4 generation, and is then adjusted with an oxidation factor. The oxidation factor represents the amount of CH_4 in a landfill that is oxidized to CO_2 as it passes through the landfill cover (e.g., soil, clay, geomembrane, alternative daily cover). Annual CH_4 generation using the first order decay methodology was estimated from the integrated form of the 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 second method used to calculate CH_4 emissions from landfills, also called the back calculation method, is based off of directly measured amounts of recovered CH_4 from the landfill gas and is expressed below and by Equation HH-8 in CFR Part 98.343 of the EPA's Greenhouse Gas Reporting Program (GHGRP). The two parts of the equation consider the portion of CH_4 in the landfill gas that is not collected by the landfill gas collection system; and the portion that is collected. First, the recovered CH_4 is adjusted with the collection efficiency of the gas collection and control system and the fraction of hours the recovery system operated in the calendar year. This quantity represents the amount of CH_4 in the landfill gas that is not captured by the collection system; it is then adjusted for oxidation. The second portion of the equation adjusts the portion of CH_4 in the collected landfill gas with the efficiency of the destruction device(s), and the fraction of hours the destruction device(s) operated during the year.

$$CH_4,\text{Solid Waste} = \left[\left(\frac{R}{CE \; x \; f_{REC}} - R\right) x(1 - OX) + R \; x \; \left(1 - (DE \; x \; f_{Dest})\right)\right.$$

where,

R	= Quantity of recovered CH_4 from Equation HH-4 of the GHGRP
CE	= Collection efficiency estimated at the landfill, taking into account system coverage, operation, and cover system materials from Table HH-3 of the GHGRP. If area by soil cover type information is not available, the default value of 0.75 should be used. (percent)
fREC	= fraction of hours the recovery system was operating (percent)
OX	= oxidation factor (percent)
DE	= destruction efficiency (percent)
fDest	= fraction of hours the destruction device was operating (fraction)

The current Inventory methodology uses both methods to estimate CH_4 emissions across the time series. In previous Inventories, only the first order decay method was used. Methodological changes have been made to this Inventory to incorporate higher tier data (i.e., directly reported CH_4 emissions to the GHGRP), which cannot be directly applied to earlier years in the time series without significant bias. The overlap technique, as described in the Methodological Recalculations section of this Inventory, and in the Time Series Consistency chapter of the *2006 IPCC Guidelines*, was used to merge the higher tier data with the previously used method.

[109] 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.

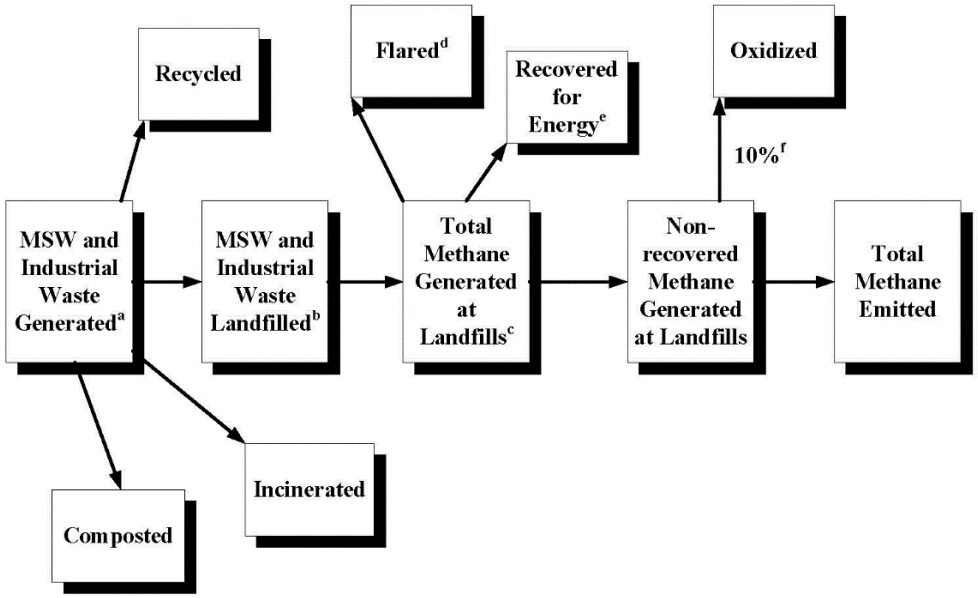
To estimate the amount of CH_4 generated in a landfill in a given year, information is needed on the quantity and composition of the waste in the landfill for multiple decades, as well as the landfill characteristics (e.g., size, aridity, waste density). Estimates and/or directly measured amounts of waste placed in municipal solid waste (MSW) and industrial waste landfills are available through various studies, surveys, and regulatory reporting programs (i.e., EPA's GHGRP). The composition of the amount of waste placed in these landfills is not readily available for most years the landfills were in operation. Consequently, and for the purposes of estimating CH_4 generation, the Inventory methodology assumes that all waste placed in MSW landfills is bulk MSW, and that all waste placed in industrial waste landfills is from either pulp and paper manufacturing facilities or food and beverage facilities.

A major methodological change was made for the current Inventory. Previous Inventories relied exclusively on the first order decay methodology. The current Inventory relies on directly reported net CH_4 emissions from EPA's GHGRP data for MSW landfills for current and a portion of historical years (from 2005 to the current Inventory year), and on the first order decay methodology for years prior to 2005. The first order decay methodology relies on the annual quantity of waste placed in landfills nationwide, parameters from an analysis of measured CH_4 generation rates for U.S. landfills, and CH_4 recovery data for landfills with gas recovery systems. The first order decay model was applied to annual waste disposal estimates for each year (up to 2004) and for three ranges of precipitation to estimate CH_4 generation rates nationwide for the years of interest. Methane emissions from industrial waste landfills were also estimated using the first order decay model. A default fraction of industrial wastes disposed in these landfills was estimated from the organic content of the wastes; facility-specific landfill disposal information is not available for all industrial waste landfills.

For years 1990 to 2004, total CH_4 emissions in a given year were estimated by adding the CH_4 generation from MSW and industrial landfills and subtracting the amounts of CH_4 recovered for energy or flaring at MSW landfills[110] and the amount oxidized in the soil at MSW and industrial landfills. As noted in the previous paragraph, directly reported net CH_4 emissions from EPA's GHGRP data for MSW landfills were used for the years 2010 to 2015. EPA's GHGRP data was also used to back-cast net CH_4 emissions for MSW landfills for 2005 to 2009. The steps taken to estimate CH_4 emissions from U.S. landfills for the years 1990 through the current Inventory year are discussed in greater detail below.

Figure A-18 presents the CH_4 emissions process—from waste generation to emissions—in graphical format. The remaining sections summarize the steps taken to estimate CH_4 emissions from MSW and industrial waste landfills. The steps and methodology are described starting from 2015 and working backwards through the time series (i.e., back to 1990).

Figure A-18: Methane Emissions Resulting from Landfilling Municipal and Industrial Waste



[a] MSW waste generation is not calculated because annual quantities of waste disposal are available through EPA 2015c; annual production data used for industrial waste (Lockwood Post's Directory and the USDA).

[110] Landfill gas recovery is only estimated for MSW landfills due to a lack of national data on industrial waste landfills. Approximately 1 percent of the industrial waste landfills reporting under the GHGRP have active landfill gas collection systems.

[b] 1940 through 1988 based on EPA 1988 and EPA 1993; 1989 through 2008 based on *BioCycle* 2010; 2009 through 2015 based on EREF 2016.
[c] *2006 IPCC Guidelines* – First Order Decay Model.
[d] EIA 2007, flare vendor database, EPA (GHGRP) 2015b.
[e] EIA 2007, EPA (LMOP) 2015a, and EPA (GHGRP) 2015b.
[f] *2006 IPCC Guidelines*; Mancinelli and McKay 1985; Czepiel et al 1996.

Step 1: Estimate Annual Quantities of Solid Waste Placed in MSW Landfills for 1940 to 2004

Historical waste data, preferably since 1940, are required for the FOD model to estimate CH_4 generation for the Inventory time series. 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. Estimates of the annual quantity of waste placed in landfills from 1960 through 1983 were developed from EPA's 1993 Report to Congress (EPA 1993) and a 1986 survey of MSW landfills (EPA 1988).

For 1989 to 2004, estimates of the annual quantity of waste placed in MSW landfills were developed from a survey of State agencies as reported in the State of Garbage (SOG) in America surveys (BioCycle 2010) and recent data from the Environmental Research & Education Foundation (EREF), adjusted to include U.S. Territories.[111] The SOG surveys and EREF (2016) provide state-specific landfill waste generation data and a national average disposal factor back to 1989. The SOG survey is no longer updated, but is available every two years for the years 2002, 2004, 2006, and 2008 (as published in BioCycle 2006; 2008, and 2010). EREF recently published a report using a similar methodology as the SOG surveys and plans to publish updated reports every three years. EREF data are available for years 2010 and 2013 (EREF 2016). A linear interpolation was used for the amount of waste generated in 2001, 2003, 2005, 2007, 2009, 2011, 2012; data were extrapolated for 2014 and 2015 based on national population growth because no data are available from these sources for those years. Upon publication of the next EREF report, the waste landfilled for 2014 to the current Inventory year will be updated.

Estimates of the quantity of waste landfilled from 1989 to the current inventory year are determined by applying a waste disposal factor to the total amount of waste generated. A waste disposal factor is determined for each year a SOG survey and EREF report is published and is the ratio of the total amount of waste landfilled to the total amount of waste generated. The waste disposal factor is interpolated for the years in-between the SOG surveys and EREF data, and extrapolated for years after the last year of data. Methodological changes have occurred over the time that the SOG survey has been published, and this has affected the fluctuating trends observed in the data.

Table A-251 shows estimates of waste quantities contributing to CH_4 emissions. The table shows SOG and EREF (EREF 2016) estimates of total waste generated and total waste landfilled (adjusted for U.S. Territories) for various years over the 1990 to 2015 timeframe even though the Inventory methodology does not use the data for 2005 onward.

Table A-251: Solid Waste in MSW and Industrial Waste Landfills Contributing to CH_4 Emissions (MMT unless otherwise noted)

	1990	2000	2005	2010	2011	2012	2013	2014	2015
Total MSW Generateda	270	377	368	315	317	319	319	320	318
Percent of MSW Landfilled	77%	61%	64%	65%	63%	63%	64%	64%	64%
Total MSW Landfilled	**205**	**226**	**234**	**202**	**199**	**200**	**201**	**202**	**203**
MSW last 30 years	4,876	5,589	5,992	6,335	6,362	6,388	6,411	6,432	6,451
MSW since 1940b	6,808	8,787	9,925	11,075	11,274	11,474	11,675	11,878	12,081
Total Industrial Waste Landfilled	**9.7**	**11.4**	**10.9**	**10.4**	**10.5**	**10.5**	**10.4**	**10.3**	**10.5**
Food and Beverage Sectorc	6.4	7.1	6.9	6.3	6.3	6.2	6.1	6.0	6.2
Pulp and Paper Sectord	3.3	4.3	4.0	4.1	4.2	4.2	4.2	4.2	4.2

[a] 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) for years 1940 to years 1988 (not presented in table), *BioCycle* 2001, 2004, 2006, and 2010 for years 1989 to 2014 (1989, 1991 to 1999, and 2006 to 2009 are not presented in table). Values for years 2010 to 2015 are based on EREF (2016) and annual population data from the U.S. Census Bureau.
[b] This estimate represents the cumulative amount of waste that has been placed in landfills since 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; *BioCycle* 2001, 2004, 2006, and 2010; and EREF 2016.
[c] Food production values for 1990 to 2015 are from ERG - inventory for Industrial Wastewater sector. USDA-NASS Agricultural Statistics 1995-2012, USDA-NASS QuickStats 2.0 (http://quickstats.nass.usda.gov/, (http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/).

[111] Since the SOG 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 2013) and the per capita rate for waste landfilled from BioCycle (2010).

[d] Production data from 1990 and 2000 are from Lockwood-Post's Directory, 2002. Production data from 2005, 2010-2014 from the FAOStat database available at: http://faostat3.fao.org/home/index.html#DOWNLOAD, Accessed on July 18, 2016. Production data form 2015 are extrapolated based on population growth and the Inventory disposal factor.

Step 2: Estimate CH_4 Generation at MSW Landfills for 1990 to 2004

The first order decay method is exclusively used for 1990 to 2004. For the first order decay method, methane generation is based on nationwide MSW generation data, to which a national average disposal factor is applied; it was not landfill-specific. Directly reported CH_4 emissions from the GHGRP are used for years they are available (i.e., 2010 to 2015), and then back-casted for years 2005 to 2009. Landfill facilities reporting to the GHGRP use a combination of the first order decay method and the back-calculation method to develop their CH_4 emissions values. Landfills reporting to the GHGRP without gas collection and control apply the first order decay method, while the landfills with gas collection and control may apply either the first order decay method or the back-calculation method, whichever is most appropriate for their site-specific landfill condition. It should be noted that the majority of landfills with gas collection report using the back-calculation method

The first order decay method is presented below, and is similar to Equation HH-5 in CFR Part 98.343 for MSW landfills, and Equation TT-6 in CFR Part 98.463 for industrial waste landfills.

$$CH_{4,\text{Solid Waste}} = [CH_{4,\text{MSW}} + CH_{4,\text{Ind}} - R] - Ox$$

where,

$CH_{4,\text{Solid Waste}}$ = Net CH_4 emissions from solid waste
$CH_{4,\text{MSW}}$ = CH_4 generation from MSW landfills
$CH_{4,\text{Ind}}$ = CH_4 generation from industrial landfills
R = CH_4 recovered and combusted (only for MSW landfills)
Ox = CH_4 oxidized from MSW and industrial waste landfills before release to the atmosphere

The input parameters needed for the FOD model equations are the mass of waste disposed each year (discussed under Step 1), degradable organic carbon (DOC), and the decay rate constant (k). The equation below provides additional detail on the activity data and emission factors used in the $CH_{4,\text{MSW}}$ equation presented above.

$$CH_{4,\text{MSW}} = \left[\sum_{x=S}^{T-1}\left\{W_x \times Lo \times \frac{16}{12} \times (e^{-k(T-x-1)} - e^{-k(T-x)})\right\}\right]$$

where,

GCH_4 = Total amount of CH_4 generated
T = Reporting year for which emissions are calculated
x = Year in which waste was disposed
S = Start year of calculation
W_x = Quantity of waste disposed of in the landfill in a given year
L_o = Methane generation potential (100 m^3 CH_4/Mg waste; EPA 1998, 2008)
16/12 = conversion factor from CH_4 to C
k = Decay rate constant (yr^{-1}, see Table A-273)

The DOC is determined from the CH_4 generation potential (L_0 in m^3 CH_4/Mg waste) as shown in 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, kt C/kt waste),
L_0 = CH_4 generation potential (100 m^3 CH_4/Mg waste; EPA 1998, 2008),
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).

DOC values can be derived for individual landfills if a good understanding of the waste composition over time is known. A default DOC value is used in the Inventory because waste composition data are not regularly collected for all landfills nationwide. When estimating CH_4 generation for the years 1990 to 2004, a default DOC value is used. This DOC value is calculated from a national CH_4 generation potential[112] of 100 m^3 CH_4/Mg waste (EPA AP-42) as described in the next few paragraphs.

The DOC value used in the CH_4 generation estimates from MSW landfills is 0.2028, and is based on the CH_4 generation potential of 100 m^3 CH_4/Mg waste (EPA 1998; EPA 2008). After EPA developed the L_o value, RTI analyzed data from a set of 52 representative landfills across the United States in different precipitation ranges to evaluate L_o, and ultimately the national 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 values for L_o were evaluated from landfill gas recovery data for this set of 52 landfills, which resulted in a best fit value for Lo 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 for years 1990 through 2004, and is the value used to derive the DOC value of 0.2028.

In 2004, the FOD model was also applied to the gas recovery data for the 52 landfills to calculate a decay rate constant (k) directly for L_0 = 100 m^3/Mg. The decay rate constant was found to increase with annual average precipitation; consequently, average values of k were developed for three precipitation ranges, shown in Table A-252 and recommended in EPA's compilation of emission factors (EPA 2008).

Table A-252: 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 (1998) 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 versus 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 2010. 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-253.

Table A-253: Percent of U.S. Population within Precipitation Ranges (%)

Precipitation Range (inches/year)	1950	1960	1970	1980	1990	2000	2010
<20	10	13	14	16	19	19	18
20-40	40	39	37	36	34	33	44
>40	50	48	48	48	48	48	38

Source: Years 1950 through 2000 are from RTI (2004) using population data from the U.S. Census Bureau and precipitation data from the National Climatic Data Center's National Oceanic and Atmospheric Administration. Year 2010 is based on the methodology from RTI (2004) and the U.S.

[112] Methane generation potential (L_o) varies with the amount of organic content of the waste material. A higher L_o occurs with a higher content of organic waste.

Bureau of Census and precipitation data from the National Climatic Data Center's National Oceanic and Atmospheric Administration where available.

The *2006 IPCC Guidelines* also require annual proportions of waste disposed of in managed landfills versus open dumps prior to 1980. 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 that was 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 (IPCC 2006) has been used for the managed landfills for the years where the first order decay methodology was used (i.e., 1990 to 2004).

Step 3: Estimate CH_4 Generation at Industrial Waste Landfills for 1990 to the Current Inventory Year

Industrial waste 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). In 2005, 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 sectors: food processing (meat, vegetables, fruits) and pulp and paper (EPA 1993). Data for annual nationwide production for the food processing and pulp and paper sectors 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 sector, production data published by the Lockwood-Post's Directory were used for years 1990 to 2001 and production data published by the U.S. Department of Agriculture were used for years 2002 through 2015. An extrapolation based on U.S. real gross domestic product was used for years 1940 through 1964. For the food processing sector, production levels were obtained or developed from the U.S. Department of Agriculture for the years 1990 through 2014 (ERG 2016). An extrapolation based on U.S. population was used for the years 1940 through 1989, and for the year 2015.

In addition to production data for the pulp and paper and food processing sectors, the following inputs are needed to use the FOD model for estimating CH_4 generation from industrial waste landfills: 1) quantity of waste that is disposed in industrial waste landfills (as a function of production), 2) CH_4 generation potential (L_0) from which a DOC value can be calculated, and 3) the decay rate constant (k).

Research into waste generation and disposal in landfills for the pulp and paper sector indicated that the quantity of waste landfilled was about 0.050 MT/MT of product compared to 0.046 MT/MT product for the food processing sector (RTI 2006). These factors were applied to estimates of annual production to estimate annual waste disposal in industrial waste landfills. Estimates for DOC were derived from available data (EPA, 2015b; Heath et al., 2010; NCASI, 2005; Kraft and Orender, 1993; NCASI 2008; Flores et al. 1999 as documented in RTI 2015). The DOC value for industrial pulp and paper waste is estimated at 0.15 (L_o of 49 m^3/MT); the DOC value for industrial food waste is estimated as 0.26 (L_o of 128 m^3/MT) (RTI 2015; RTI 2014). 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 1990 to 2010 and 1990 to 2014 Inventory years with the intent of updating values for L_o (specifically DOC) and k in the pulp and paper sector. Where pulp and paper mill wastewater treatment residuals or sludge are the primary constituents of pulp and paper waste landfilled, values for k available in the literature range from 0.01/yr to 0.1/yr, while values for L_o range from 50 m^3/MT to 200 m^3/MT.[113] Values for these factors are highly variable and are dependent on the soil moisture content, which is generally related to rainfall amounts. At this time, sufficient data were available through the GHGRP to warrant a change to the L_o (DOC) from 99 to 49 m^3/MT, but sufficient data were not obtained to warrant a change to k for the current Inventory year. EPA will consider an update to the k values for the pulp and paper sector as new data arises and will work with stakeholders to gather data and other feedback on potential changes to these values.

As with MSW landfills, a similar trend in disposal practices from open dumps to managed landfills was expected for industrial waste landfills; therefore, the same time line that was developed for MSW landfills was applied to the industrial

[113] Sources reviewed included Heath et al. 2010; Miner 2008; Skog 2008; Upton et al. 2008; Barlaz 2006; Sonne 2006; NCASI 2005; Barlaz 1998; and Skog and Nicholson 2000.

landfills to estimate the average MCF. That is, between 1940 and 1980, the fraction of waste that was 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 waste landfills.

Step 4: Estimate CH_4 Emissions Avoided from MSW Landfills for 1990 to 2004

The estimated landfill gas recovered per year (R) at MSW landfills is based on a combination of three databases that include recovery from flares and/or landfill gas-to-energy projects:

- a database developed by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007)
- a database of LFGTE projects that is primarily based on information compiled by EPA LMOP (EPA 2016a), and
- the flare vendor database (contains updated sales data collected from vendors of flaring equipment).

The fourth database, EPA's GHGRP MSW landfills database, was first introduced as a data source for the 1990 to 2013 Inventory and only the annual amounts of CH_4 recovered were used. In the current Inventory, directly reported net CH_4 emissions data are used, which includes data on the facility-specific amounts of CH_4 recovered. EPA's GHGRP MSW landfills database contains facility-reported data that undergoes rigorous verification and is considered to contain the least uncertain data of the four databases. However, this database is unique in that it only contains a portion of the landfills in the United States. (although, presumably the highest emitters since only those landfills that meet the methane generation threshold must report) and only contains data from 2010 and later.

For 1990 to 2004, a destruction efficiency of 99 percent was applied to amounts of CH_4 recovered to estimate CH_4 emissions avoided for the three databases with data available for those years. This value for destruction efficiency was selected based on the range of efficiencies (86 to 99+ percent) recommended for flares in EPA's *AP-42 Compilation of Air Pollutant Emission Factors*, Draft Chapter 2.4, Table 2.4-3 (EPA 2008). A typical value of 97.7 percent was presented for the non-methane components (i.e., volatile organic compounds and non-methane organic compounds) in test results (EPA 2008). An arithmetic average of 98.3 percent and a median value of 99 percent are derived from the test results presented in EPA 2008. Thus, a value of 99 percent for the destruction efficiency of flares has been used in Inventory methodology. Other data sources supporting a 99 percent destruction efficiency include those used to establish New Source Performance Standards (NSPS) for landfills and in recommendations for closed flares used in the EPA's LMOP.

Step 4a: Estimate CH_4 Emissions Avoided Through Landfill Gas-to-Energy (LFGTE) and Flaring Projects

The quantity of CH_4 avoided due to LFGTE systems was estimated based on information from three sources: (1) a database developed by the EIA for the voluntary reporting of greenhouse gases (EIA 2007); (2) a database compiled by LMOP and referred to as the LFGTE database for the purposes of this inventory (EPA 2016a); and (3) the GHGRP MSW landfills dataset (EPA 2016b). 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. In general, 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 LFGTE 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. EPA's GHGRP MSW landfills database contains the most detailed data on landfills that reported under the GHGRP for years 2010 through 2015, however the amount of CH_4 recovered is not specifically allocated to a flare versus a LFGTE project. The allocation into flares or LFGTE was performed by matching landfills to the EIA and LMOP databases for LFGTE projects and to the flare database for flares. Detailed information on the landfill name, owner or operator, city, and state are available for both the EIA and LFGTE databases; consequently, it was straightforward to identify landfills that were in both databases against those in EPA's GHGRP MSW landfills database.

To avoid double-counting CH_4 recovery, a hierarchical approach is applied after matching landfills in one database to the other databases. If a landfill in the EIA database was also in the LFGTE and/or the flare vendor database, the CH_4 recovery was based on the EIA data because landfill owners or operators directly reported the amount of CH_4 recovered using gas flow concentration and measurements, and because the reporting accounted for changes over time. The EIA database only includes facility-reported data through 2006; the amount of CH_4 recovered in this database for years 2007 and later were assumed to be the same as in 2006. Nearly all (93 percent) of landfills in the EIA database also report to the GHGRP.

If both the flare data and LFGTE recovery data were available for any of the remaining landfills (i.e., not in the EIA or GHGRP databases), then the CH_4 recovered were based on the LFGTE data, which provides reported landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The LFGTE database is based on the most recent EPA LMOP database (published annually). The remaining portion of avoided emissions is calculated by the flare vendor database, which estimates CH_4 combusted by flares using the midpoint of a flare's reported capacity. New flare vendor sales data were unable to be obtained for the current Inventory year. Given that each LFGTE project is likely to also have a flare, double counting reductions from flares and LFGTE projects in the LFGTE database was avoided by subtracting emission reductions associated with LFGTE projects for which a flare had not been identified from the emission reductions associated with flares (referred to as the flare correction factor).

Step 4b: Estimate CH_4 Emissions Avoided Through Flaring for the Flare Database

To avoid double counting, flares associated with landfills in EPA's GHGRP, EIA and LFGTE databases were not included in the total quantity of CH_4 recovery 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, EPA's GHGRP, or LFGTE databases). Several vendors have provided information on the size of the flare rather than the flare design gas flow rate for most years of the Inventory. Flares sales data has not been obtained for the past three Inventory years.

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. Flare sales data were not provided to the EPA for the previous and current Inventory year.

Step 4c: Reduce CH_4 Emissions Avoided Through Flaring

If comprehensive data on flares were available, each LFGTE project in EPA's GHGRP, EIA, and LFGTE databases would have an identified flare because it is assumed that most LFGTE projects have flares. However, given that the flare vendor database 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 to 2009 and 1990 to 2014 Inventory years to reduce the total number of flares in the flare vendor database that were not matched to landfills and/or LFGTE projects in the EIA and LFGTE databases. Each flare in the flare vendor database not associated with a LFGTE project in the EIA, LFGTE, or GHGRP databases was investigated to determine if it could be matched. For some unmatched flares, the location information was missing or incorrectly transferred to the flare vendor database and was corrected during the review. 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, LFGTE and EPA's GHGRP databases. The remaining flares did not have adequate information through the name, location, or owner to identify it to a landfill in any of the recovery databases or through an Internet search; it is these flares that are included in the flare correction factor for the current inventory year.

A large majority of the unmatched flares are associated with landfills in the LFGTE database 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 LFGTE database. The flare vendor database was improved in the 1990 to 2009 inventory year 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 through 2009 Inventory. The revised state-by-state flare correction factors were applied to the entire Inventory time series.

Step 5: Estimate CH_4 Oxidation from MSW and Industrial Waste Landfills

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 Guidelines for managed and covered landfills, and was therefore applied to the estimates of CH_4 generation minus recovery for both MSW and industrial waste landfills for years 1990 to 2004. For years 2005 to 2015, directly reported CH_4 emissions to the GHGRP, which include the adjustment for oxidation, are used. EPA's GHGRP allows facilities to use a range of oxidation factors: 0.0, 0.10, 0.25, 0.35.

In 2011, a literature review was conducted (RTI 2011) 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 methane down through the cover). There is considerable uncertainty and variability surrounding estimates of the rate of oxidation because oxidation is difficult to measure and varies considerably with the presence of a gas collection system, thickness and type of the cover material, size and area of the landfill, climate, and the presence of cracks and/or fissures in the cover material through which methane can escape. The *2006 IPCC Guidlines* note 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.

Sites with landfill gas collection systems are generally designed and managed better to improve gas recovery. More recent research (2006 to 2012) on landfill cover methane oxidation has relied on stable isotope techniques that may provide a more reliable measure of oxidation. Results from this recent research consistently point to higher cover soil methane oxidation rates than the *2006 IPCC Guidelines* default of 10 percent. A continued effort will be made to review the peer-reviewed literature to better understand how climate, cover type, and gas recovery influence the rate of oxidation at active and closed landfills. At this time, the IPCC recommended oxidation factor of 10 percent will continue to be used for all landfills for the years 1990 to 2004.

Step 6: Estimate Total CH_4 Emissions

For 1990 to 2004, 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-254. As stated earlier, directly reported CH_4 emissions to the GHGRP are directly used for years 2010 to 2015, and also used to back-cast emissions for 2005 to 2009. The net emissions for years 2005 to 2015 are not the sum of the rows above; data for these years include directly reported GHGRP data, whereas the other rows are outputs from the first order decay methodology.

EPA's GHGRP requires landfills meeting or exceeding a threshold of 25,000 metric tons of CH_4 generation per year to report a variety of facility-specific information, including historical and current waste disposal quantities by year, CH_4 generation, gas collection system details, CH_4 recovery, and CH_4 emissions. EPA's GHGRP provides a consistent methodology, a broader range of values for the oxidation factor, and allows for facility-specific annual waste disposal data to be used, thus these data are considered Tier 3 (highest quality data) under the *2006 IPCC Guidelines*. This is the first Inventory that incorporates directly reported GHGRP net CH_4 emissions data. Using the GHGRP data is a methodological change and required a merging of EPA's GHGRP methodology with the Inventory methodology used in previous years to ensure time series consistency.

First, and for completeness, a scale-up factor was applied to the net CH_4 emissions from EPA's GHGRP. The landfills reporting to EPA's GHGRP are considered the largest emitters, but not all landfills are required to report. For this Inventory, EPA has applied a scale-up factor of 12.5 percent to the GHGRP net CH_4 emissions to account for the non-reporting landfills. This scale-up factor may be revised in future years after a thorough review of available data for the non-reporting landfills is completed. The value of the scale-up factor was determined after plotting net CH_4 emissions across the entire time series (1990 to 2015) generated using the previous Inventory methodology against different methodological scenarios with various scale-up factors. For most years across the time series, a 12.5 percent scale-up factor resulted in an

overlapping of the net emissions data for several years where the methodology switches to the directly reported GHGRP data (2010 and later).

The EPA also investigated various back-casting approaches to estimate CH_4 emissions throughout the entire time series (back to 1990) while relying solely on the GHGRP emissions data. Back-casting CH_4 emissions back to 1990 with a limited set of data is not recommended in Volume 1: Chapter 5 of the *2006 IPCC Guidelines*, which provides best practices for time series consistency when implementing methodological changes and refinements. Plotting the back-casted emissions GHGRP against the emissions estimates from the previously used method showed an alignment of the data in 2004 and later years. The *2006 IPCC Guidelines* recommend using a splicing technique if the data overlap for a period of years as the data do with the revised methodology. Therefore, EPA decided to back-cast the GHGRP emissions from 2009 to 2005 only, while also applying the 12.5 percent scale-up factor to the back-casted GHGRP data.

Table A-254: CH_4 Emissions from Landfills (kt)

	1990	1995	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
MSW CH_4 Generation	8,214	9,140	10,270	10,477	10,669	-	-	-	-	-	-	-	-	-	-	-
Industrial CH_4 Generation	484	537	618	625	629	636	639	643	648	653	656	657	659	661	662	662
MSW CH_4 Recovered	**(718)**	**(1,935)**	**(4,894)**	**(4,995)**	**(5,304)**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
MSW CH_4 Oxidized	**(750)**	**(720)**	**(538)**	**(548)**	**(537)**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Industrial CH_4 Oxidized	**(48)**	**(54)**	**(62)**	**(63)**	**(63)**	**(64)**	**(64)**	**(64)**	**(65)**	**(65)**	**(66)**	**(66)**	**(66)**	**(66)**	**(66)**	**(66)**
MSW Net CH_4 Emissions (GHGRP)	**-**	**-**	**-**	**-**	**-**	**4,800**	**4,717**	**4,635**	**4,553**	**4,471**	**4,513**	**4,169**	**4,241**	**4,074**	**4,067**	**4,032**
Net Emissions[a]	**7,182**	**6,967**	**5,394**	**5,496**	**5,395**	**5,372**	**5,292**	**5,213**	**5,136**	**5,058**	**5,103**	**4,760**	**4,834**	**4,669**	**4,663**	**4,628**

Notes: MSW and Industrial CH_4 generation in Table A-248 represents emissions before oxidation. Totals may not sum exactly to the last significant figure due to rounding. Parentheses denote negative values.

[a] MSW Net CH_4 emissions for years 2005 to 2015 are directly reported CH_4 emissions to EPA's GHGRP for MSW landfills. The other rows are calculate by the first order decay methodology.

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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 United Nations Framework Convention on Climate Change (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. Volume 2: Energy, Chapter 6: Reference Approach of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) states, "comparability between the sectoral and reference approaches continues to allow a country to produce a second independent estimate of CO_2 emissions from fuel combustion with limited additional effort and data requirements." This reference method estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys. The basic principle is that once carbon (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 Intergovernmental Panel on Climate Change (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 Energy Information Administration (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 and Product Use 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 6). 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-255.

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-255 for 2015), 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-256. The resulting fuel type-specific energy data for 2015 are provided in Table A-257.

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 and Product Use chapter, international bunker fuels, and U.S. territory fuel consumption. Bunker fuels and feedstocks accounted for in the Industrial Processes and Product Use 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-256.

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-257).[114] The C in products from non-energy uses of fossil fuels (e.g., plastics or asphalt) was then estimated and subtracted (see Table A-259). 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). 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 *2006 IPCC 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 million metric tons (MMT). The results are contained in Table A-258.

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 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. An examination of past Common Reporting Format (CRF) table submissions during UNFCCC reviews has highlighted the need to further investigate these discrepancies. The investigation found that the most recent (two to three) inventory years tend to have larger differences in consumption and emissions estimates occurring earlier in the time series. This is a result of annual energy consumption data revisions in the EIA energy statistics, and the revisions have the greatest impact on the most recent few years of inventory estimates. As a result, the differences between the Sectoral and Reference Approach decrease and are resolved over time. For the United States, these differences are discussed below.

[114] Carbon coefficients from EIA were used wherever possible. Because EIA did not provide coefficients for coal, the IPCC-recommended emission factors were used in the top-down calculations for these fuels. See notes in Table A-258 for more specific source information.

Differences in Total Amount of Energy Consumed

Table A-261 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 consumption total that is 1.8 percent lower than the Sectoral Approach for 2015. The greatest differences lie in lower estimates for coal and petroleum consumption for the Reference Approach (1.5 percent and 3.8 percent, respectively) and higher estimates for natural gas consumption for the Reference Approach (0.3 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-262 summarizes the differences between the two methods in estimated C emissions.

As mentioned above, for 2015, the Reference Approach resulted in a 1.8 percent lower estimate of energy consumption in the United States than the Sectoral Approach. The resulting emissions estimate for the Reference Approach was 1.6 percent lower. Estimates of natural gas emissions from the Reference Approach are higher (0.4 percent), and coal and petroleum emission estimates are lower (1.6 percent and 2.8 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 (2006), 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-255: 2015 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	1,469	[a]	[a]	[a]			
	Bituminous Coal	404,919	[a]	[a]	[a]			
	Sub-bituminous Coal	425,844	[a]	[a]	[a]	367		
	Lignite	64,709	[a]	[a]	[a]	4,449		
	Coke		140	857	(90)			
	Unspecified Coal		11,318	73,958	40,704	3,031		1,653
Gas Fuels (Million Cubic Feet)	Natural Gas	26,859,772	2,718,094	1,783,512	545,792	298,148		58,713
Liquid Fuels (Thousand Barrels)	Crude Oil	3,436,515	2,687,409	169,741	92,515			
	Nat Gas Liquids and Liquefied Refinery Gases	1,219,949	56,789	352,618	21,676			3,503
	Other Liquids	0	435,714	187,576	6,055			
	Motor Gasoline	(66,055)	26,041	173,701	(2,641)	227,876		34,763
	Aviation Gasoline		30	0	(205)			
	Kerosene		1,593	4,749	450			1,262
	Jet Fuel		48,118	61,324	2,116		175,795	9,731
	Distillate Fuel		73,178	429,075	25,040	222	11,760	12,856
	Residual Fuel		69,914	119,040	8,486	14,000	64,713	23,657
	Naphtha for petrochemical feedstocks		12,021	0	(170)			
	Petroleum Coke		3,892	196,482	(1,204)	8,053		
	Other Oil for petrochemical feedstocks		2,407	0	51	1,240		
	Special Naphthas		5,532	0	(107)			
	Lubricants		12,461	26,355	1,275			172
	Waxes		2,056	1,449	130			
	Asphalt/Road Oil		11,563	6,850	3,816			
	Still Gas		0	0	0			
	Misc. Products		16	417	251			9,061

[a] Included in Unspecified Coal

Note: Parentheses indicate negative values.

Sources: Solid and Gas Fuels: EIA (2016); Liquid Fuels: EIA (1995-2015).

Table A-256: 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		22.63	25.05	22.63			
	Unspecified		25.00	25.97	20.86	194.87		25.14
Natural Gas (BTU/Cubic Foot)		1,037	1,025	1,009	1,037	1,036		1,037
Liquid Fuels (Million Btu/Barrel)	Crude Oil	5.72	6.07	5.68	5.68		5.68	5.68
	Nat Gas Liquids and Liquefied Refinery Gases	3.74	3.74	3.74	3.74		3.74	3.74
	Other Liquids	5.83	5.83	5.83	5.83		5.83	5.83
	Motor Gasoline	5.06	5.06	5.06	5.06	5.06	5.06	5.06
	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		5.80	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

Sources: Coal and lignite production: EIA (1992); Unspecified Solid Fuels, Coke, Natural Gas and Petroleum Products: EIA (1995-2015).

Table A-257: 2015 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	33.2							33.2
	Bituminous Coal	9,673.5							9,673.5
	Sub-bituminous Coal	7,299.0				10.3			7,288.6
	Lignite	832.5				57.2			775.3
	Coke		3.2	21.5	(2.0)				(16.3)
	Unspecified		283.0	1,920.8	849.1	495.2		41.6	(2,940.6)
Gas Fuels	Natural Gas	27,853.6	2,786.0	1,799.6	566.0	308.9		60.9	28,026.0
Liquid Fuels	Crude Oil	19,646.6	16,299.1	964.5	525.7				34,455.6
	Nat Gas Liquids and Liquefied Refinery Gases	4,567.5	212.6	1,320.2	81.2			13.1	3,391.9
	Other Liquids		2,538.0	1,092.6	35.3				1,410.1
	Motor Gasoline	(334.2)	131.8	878.9	(13.4)			175.9	(892.1)
	Aviation Gasoline		0.2	(1.0)	(1.0)				2.2
	Kerosene		9.0	26.9	2.6			7.2	(13.3)
	Jet Fuel		272.8	347.7	12.0		1,020.4	55.2	(1,052.1)
	Distillate Fuel		426.3	2,499.4	145.9	1.3	68.5	74.9	(2,213.9)
	Residual Oil		439.5	748.4	53.4	88.0	406.8	148.7	(708.3)
	Naphtha for petrochemical feedstocks		63.1		(0.9)				64.0
	Petroleum Coke		23.4	1,183.6	(7.3)	48.5			(1,201.4)
	Other Oil for petrochemical feedstocks		14.0		0.3	7.2			6.5
	Special Naphthas		29.0		(0.6)				29.6
	Lubricants		75.6	159.8	7.7			1.0	(91.0)
	Waxes		11.4	8.0	0.7				2.6
	Asphalt/Road Oil		76.7	45.5	25.3				6.0
	Still Gas								
	Misc. Products		0.1	2.4	1.5			52.5	48.7
Total		**69,571.6**	**23,694.9**	**13,018.8**	**2,281.3**	**1,016.7**	**1,495.7**	**631.0**	**76,084.9**

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

Table A-258: 2015 Potential CO_2 Emissions

Fuel Category	Fuel Type	Apparent Consumption (QBtu)	Carbon Coefficients (MMT Carbon/QBtu)	Potential Emissions (MMT CO_2 Eq.)
Solid Fuels	Anthracite Coal	0.03	28.28	3.4
	Bituminous Coal	9.67	25.44	902.4
	Sub-bituminous Coal	7.29	26.50	708.2
	Lignite	0.78	26.65	75.7
	Coke	(0.02)	31.00	(1.8)
	Unspecified	(2.94)	25.34	(273.2)
Gas Fuels	Natural Gas	28.03	14.46	1,485.4
Liquid Fuels	Crude Oil	34.46	20.31	2,565.3
	Nat Gas Liquids and LRGs	3.39	16.90	210.1
	Other Liquids	1.41	20.31	105.0
	Motor Gasoline	(0.89)	19.46	(63.6)
	Aviation Gasoline	0.00	18.86	0.2
	Kerosene	(0.01)	19.96	(1.0)
	Jet Fuel	(1.05)	19.70	(76.0)
	Distillate Fuel	(2.21)	20.17	(163.7)
	Residual Oil	(0.71)	20.48	(53.2)
	Naphtha for petrochemical feedstocks	0.06	18.55	4.4
	Petroleum Coke	(1.20)	27.85	(122.7)
	Other Oil for petrochemical feedstocks	0.01	20.17	0.5
	Special Naphthas	0.03	19.74	2.1
	Lubricants	(0.09)	20.20	(6.7)
	Waxes	0.00	19.80	0.2
	Asphalt/Road Oil	0.01	20.55	0.4
	Still Gas	-	18.20	-
	Misc. Products	0.05	20.31	3.6
Total				**5,305.2**

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.
Sources: C content coefficients by coal rank from USGS (1998) and SAIC (2004); Unspecified Solid Fuels, EIA (1995-2015), Natural Gas and Liquid Fuels: EPA (1995-2015).

Table A-259: 2015 Non-Energy Carbon Stored in Products

Fuel Type	Consumption for Non-Energy Use (TBtu)	Carbon Coefficients (MMT Carbon/QBtu)	Carbon Content (MMT Carbon)	Fraction Sequestered	Carbon Stored (MMT CO_2 Eq.)
Coal	121.4	31.00	3.76	0.10	2.0
Natural Gas	302.3	14.46	4.37	0.66	10.5
Asphalt & Road Oil	831.7	20.55	17.09	1.00	62.4
LPG	2,157.7	17.06	36.81	0.66	88.4
Lubricants	306.0	20.20	6.18	0.09	2.1
Pentanes Plus	78.4	19.10	1.50	0.66	3.6
Petrochemical Feedstocks	[a]	[a]	[a]	[a]	35.9
Petroleum Coke	0.0	27.85	0.00	0.30	0.0
Special Naphtha	97.0	19.74	1.92	0.66	4.6
Waxes/Misc.	[a]	[a]	[a]	[a]	0.7
Misc. U.S. Territories Petroleum	[a]	[a]	[a]	[a]	0.4
Total					**210.7**

[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-260: 2015 Reference Approach CO_2 Emissions from Fossil Fuel Consumption (MMT CO_2 Eq. unless otherwise noted)

Fuel Category	Potential Emissions	Carbon Sequestered	Net Emissions	Fraction Oxidized	Total Emissions
Coal	1,414.8	2.0	1,412.8	100.0%	1,412.8
Petroleum	2,404.9	198.2	2,206.7	100.0%	2,206.7
Natural Gas	1,485.4	10.5	1,474.9	100.0%	1,474.9
Total	**5,305.2**	**210.7**	**5,094.5**		**5,094.5**

Note: Totals may not sum due to independent rounding.

Table A-261: Fuel Consumption in the United States by Estimating Approach (TBtu)[a]

Approach	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Sectoral	**69,724**	**74,941**	**82,559**	**81,135**	**81,933**	**82,332**	**83,957**	**83,919**	**82,734**	**83,935**	**81,237**	**76,443**	**78,920**	**77,497**	**75,693**	**77,762**	**78,438**	**77,512**
Coal	18,072	19,187	21,748	21,121	21,192	21,625	21,893	22,187	21,834	22,067	21,753	19,231	20,267	19,071	16,827	17,459	17,362	15,034
Natural Gas	19,184	22,170	23,392	22,466	23,163	22,561	22,623	22,282	21,960	23,371	23,594	23,193	24,312	24,679	25,832	26,560	27,145	27,929
Petroleum	32,468	33,585	37,418	37,548	37,578	38,145	39,441	39,449	38,940	38,497	35,891	34,019	34,342	33,747	33,034	33,743	33,931	34,550
Reference (Apparent)	**68,730**	**74,018**	**81,524**	**80,676**	**81,431**	**81,724**	**83,600**	**83,498**	**82,059**	**83,905**	**80,397**	**76,464**	**77,848**	**76,524**	**75,352**	**76,046**	**76,726**	**76,085**
Coal	17,573	18,567	20,957	20,710	20,797	21,081	21,735	21,986	21,534	21,577	21,391	19,243	19,620	18,756	16,483	16,948	17,039	14,814
Natural Gas	19,276	22,274	23,484	22,535	23,238	22,630	22,690	22,349	22,029	23,441	23,666	23,277	24,409	24,778	25,924	26,637	27,228	28,026
Petroleum	31,882	33,177	37,083	37,431	37,395	38,013	39,175	39,163	38,496	38,887	35,340	33,945	33,818	32,990	32,945	32,461	32,458	33,245
Difference	**-1.4%**	**-1.2%**	**-1.3%**	**-0.6%**	**-0.6%**	**-0.7%**	**-0.4%**	**-0.5%**	**-0.8%**	**0.0%**	**-1.0%**	**0.0%**	**-1.4%**	**-1.3%**	**-0.5%**	**-2.2%**	**-2.2%**	**-1.8%**
Coal	-2.8%	-3.2%	-3.6%	-1.9%	-1.9%	-2.5%	-0.7%	-0.9%	-1.4%	-2.2%	-1.7%	0.1%	-3.2%	-1.7%	-2.0%	-2.9%	-1.9%	-1.5%
Natural Gas	0.5%	0.5%	0.4%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.4%	0.4%	0.4%	0.4%	0.3%	0.3%	0.3%
Petroleum	-1.8%	-1.2%	-0.9%	-0.3%	-0.5%	-0.3%	-0.7%	-0.7%	-1.1%	1.0%	-1.5%	-0.2%	-1.5%	-2.2%	-0.3%	-3.8%	-4.3%	-3.8%

[a] Includes U.S. Territories. Does not include international bunker fuels.

Note: Totals may not sum due to independent rounding.

Table A-262: CO_2 Emissions from Fossil Fuel Combustion by Estimating Approach (MMT CO_2 Eq.)[a]

Approach	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Sectoral	**4,858**	**5,169**	**5,734**	**5,656**	**5,695**	**5,748**	**5,856**	**5,885**	**5,800**	**5,876**	**5,691**	**5,299**	**5,472**	**5,336**	**5,130**	**5,279**	**5,319**	**5,176**
Coal	1,719	1,823	2,071	2,011	2,022	2,066	2,093	2,121	2,083	2,106	2,076	1,835	1,935	1,820	1,607	1,667	1,657	1,435
Natural Gas	1,007	1,164	1,227	1,178	1,215	1,183	1,189	1,172	1,156	1,230	1,242	1,221	1,277	1,297	1,357	1,397	1,428	1,469
Petroleum	2,133	2,182	2,435	2,467	2,459	2,500	2,574	2,592	2,560	2,539	2,373	2,243	2,260	2,219	2,166	2,216	2,234	2,271
Reference (Apparent)	**4,792**	**5,132**	**5,683**	**5,653**	**5,695**	**5,737**	**5,882**	**5,891**	**5,782**	**5,888**	**5,652**	**5,333**	**5,409**	**5,286**	**5,130**	**5,171**	**5,213**	**5,094**
Coal	1,654	1,756	1,988	1,967	1,976	2,002	2,065	2,087	2,049	2,053	2,036	1,832	1,868	1,789	1,573	1,615	1,625	1,413
Natural Gas	1,013	1,170	1,233	1,182	1,220	1,188	1,194	1,176	1,160	1,235	1,247	1,226	1,283	1,303	1,363	1,401	1,433	1,475
Petroleum	2,126	2,206	2,462	2,504	2,500	2,547	2,624	2,627	2,573	2,601	2,370	2,276	2,257	2,195	2,194	2,155	2,156	2,207
Difference	**-1.4%**	**-0.7%**	**-0.9%**	**-0.1%**	**0.0%**	**-0.2%**	**0.5%**	**0.1%**	**-0.3%**	**0.2%**	**-0.7%**	**0.6%**	**-1.2%**	**-0.9%**	**0.0%**	**-2.0%**	**-2.0%**	**-1.6%**
Coal	-3.8%	-3.7%	-4.0%	-2.2%	-2.3%	-3.1%	-1.3%	-1.6%	-1.7%	-2.5%	-1.9%	-0.2%	-3.4%	-1.8%	-2.1%	-3.1%	-2.0%	-1.6%
Natural Gas	0.6%	0.6%	0.5%	0.3%	0.4%	0.4%	0.4%	0.3%	0.3%	0.3%	0.3%	0.4%	0.5%	0.5%	0.4%	0.3%	0.3%	0.4%
Petroleum	-0.3%	1.1%	1.1%	1.5%	1.7%	1.9%	1.9%	1.4%	0.5%	2.4%	-0.1%	1.5%	-0.1%	-1.1%	1.3%	-2.7%	-3.5%	-2.8%

[a] 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[115] 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. Reporting of inventories to the UNFCCC under Decision 24/CP.19 requests "Where methodological or data gaps in inventories exist, information on these gaps should be presented in a transparent manner." Furthermore, these revised reporting guidelines allow a country to indicate that a disproportionate amount of effort would be required to collect data for a gas from a specific category that would be insignificant in terms of the overall level and trend in national emissions.[116] Specifically, where the notation key "NE" is used in the Common Reporting Format tables that accompany this Inventory report submission to the UNFCCC, countries are required to describe why such emissions or removals have not been estimated (UNFCCC 2013).

With this guidance, the United States will consider the next steps in providing transparent information on these categories in future Inventory reports.

Source Categories Not Estimated

The following section is arranged by sector and source where additional explanations are available to describe the reason the source was not estimated.

Energy

IPCC Category 1.A.3.c: CO_2 from Railways—Gaseous Fuels

It is unlikely that gaseous fuels are used by railways, but if small uses occur this fuel use is reported under the aggregated CO_2 from Fossil Fuel Combustion category.

IPCC Category 1.A.3.d: CO_2 from Domestic Navigation—Gaseous Fuels

It is unlikely that gaseous fuels are used by ships, but if small uses occur this fuel use is reported under the aggregated CO_2 from Fossil Fuel Combustion category.

[115] 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*).

[116] Paragraph 37(b) of Decision 24/CP.19 "Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention." See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

IPCC Category 1.A.5.a: CO_2 from Non-Hazardous Industrial Waste Incineration and Medical Waste Incineration

Waste incineration of the municipal waste stream and hazardous waste incineration of fossil fuel-derived materials are reported 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.

Two additional categories of waste incineration that are not directly included in our calculus are industrial non-hazardous waste and medical waste incineration. Data are not readily available for these sources.

In the calculation of emissions and storage from non-energy uses of fossil fuels there is an energy recovery component that includes emissions from waste gas; waste oils, tars, and related materials from the industrial sector. While this is not a comprehensive inclusion of non-hazardous industrial waste it does capture a subset.

Furthermore, an analysis was conducted based on a study of hospital/ medical/ infectious waste incinerator (HMIWI) facilities in the United States showing that medical waste incineration emissions could be considered insignificant. Based on that study's information of waste throughput and an analyses of fossil-based composition of the waste, it was determined that annual greenhouse gas emissions for medical waste incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of inventory reporting under the UNFCCC.[117]

IPCC Category 1.A.5.a: CO_2, CH_4 and N_2O from Stationary Fuel Combustion—Biomass in U.S. Territories

Data are currently not available to estimate emissions from this source.

IPCC Category 1.B.1.a.1.i: CO_2 and CH_4 from Fugitive Emissions from Underground Coal Mining Activities

Carbon dioxide emissions are currently not estimated for mining activities due to the minuscule emission quantities. While CH_4 recovery projects were operating at surface mines from 2006 to 2010, the avoided emissions were so small that they were not included in the Inventory estimates.

IPCC Category 1.B.1.a.1.iii: CO_2 from Fugitive Emissions from Abandoned Underground Coal Mines

Emissions from this source are not estimated due to difficulties in obtaining data. Inclusion of emissions from this source will be investigated for future Inventory reports.

IPCC Category 1.B.1.a.2.i: CO_2 and CH_4 from Fugitive Emissions from Surface Coal Mining Activities

Carbon dioxide emissions are currently not estimated for mining activities due to the minuscule emission quantities. While CH_4 recovery projects were operating at surface mines from 2006 to 2010, the avoided emissions were so small that they were not included in the Inventory estimates.

IPCC Category 1.B.2.a.3: CO_2 from Fugitive Emissions from the Transport of Oil and Natural Gas during Energy Production

Emissions from this source are not estimated due to difficulties in obtaining data. Inclusion of emissions from this source will be investigated for future Inventory reports.

IPCC Category 1.B.2.b.1: CO_2 from Fugitive Emissions from the Exploration of Oil and Natural Gas

Emissions from this source are not estimated due to difficulties in obtaining data. Inclusion of emissions from this source will be investigated for future Inventory reports.

IPCC Category 1.B.2.c.2.i: N_2O from Fugitive Emissions from Venting and Flaring from Oil Production

Data are currently not available to estimate emissions from this source.

[117] Paragraph 37(b) of Decision 24/CP.19 "Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention." See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

IPCC Category 1.B.2.c.2.ii: N_2O from Fugitive Emissions from Venting and Flaring from Natural Gas Production

Data are currently not available to estimate emissions from this source.

IPCC Category 1.B.2.c.2.iii: N_2O from Fugitive Emissions from Venting and Flaring from Combined Oil and Natural Gas Production

Data are currently not available to estimate emissions from this source.

IPCC Category 1.C: CO_2 Transport and Storage

Carbon dioxide is produced, captured, transported, and used for Enhanced Oil Recovery (EOR) as well as commercial and non-EOR industrial applications. This CO_2 is produced from both naturally-occurring CO_2 reservoirs and from industrial sources such as natural gas processing plants and ammonia plants. In the Inventory, emissions from naturally-produced CO_2 are estimated based on the specific application. In the Inventory, CO_2 that is used in non-EOR industrial and commercial applications (e.g., food processing, chemical production) is assumed to be emitted to the atmosphere during its industrial use. These emissions are discussed in the Carbon Dioxide Consumption (IPCC Category 2.B.10) section. The naturally-occurring CO_2 used in EOR operations is assumed to be fully sequestered. Additionally, all anthropogenic CO_2 emitted from natural gas processing and ammonia plants is assumed to be emitted to the atmosphere, regardless of whether the CO_2 is captured or not. These emissions are currently included in the Natural Gas Systems and the Ammonia Production sections of the Inventory report, respectively.

In the United States, facilities that produce CO_2 for various end-use applications (including capture facilities such as acid gas removal plants and ammonia plants), importers of CO_2, exporters of CO_2, facilities that conduct geologic sequestration of CO_2, and facilities that inject CO_2 underground (including facilities conducting EOR), are required to report greenhouse gas data annually to EPA through its GHGRP. EPA will continue to evaluate the availability of additional GHGRP data and other opportunities for improving the emission estimates.

Industrial Processes and Product Use

IPCC Category 2.A.4.a: CO_2 from Process Uses of Carbonates–Ceramics

Data are not currently available to estimate emissions from this source.

IPCC Category 2.A.4.c: CO_2 from Process Uses of Carbonates–Non-metallurgical Magnesium Production

Data are not currently available to estimate emissions from this source.

IPCC Category 2.B.4.a: CO_2 and 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 byproduct. EPA has identified production data for 2004 through 2015 in the American Chemistry Council's (ACC) Business of Chemistry to estimate annual emissions. EPA plans to integrate estimates for Caprolactum Production in the next Inventory.

IPCC Category 2.B.4.b: N_2O and CO_2 from Glyoxal Production

Data are currently not available to estimate emissions from this source.

IPCC Category 2.B.4.c: N_2O and CO_2 from Glyoxylic Acid Production

Data are currently not available to estimate emissions from this source.

IPCC Category 2.B.5.b: CO_2 and CH_4 from Calcium Carbide Production

Carbon dioxide 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. CH_4 may also be emitted from the production of calcium carbide because the petroleum coke used in the process contains volatile organic compounds, which form CH_4 during thermal decomposition. EPA had identified some research indicating that one facility is operating at over 100,000 tons of calcium carbide production capacity in the United

States. Pending review of this information and resources, EPA plans to integrate emission estimates to improve completeness in the next Inventory report.

IPCC Category 2.C.1.c: CH_4 from Direct Reduced Iron (DRI) Production

Emissions from this source are likely insignificant and well below the 500 kt CO_2 Eq. threshold. Additional analyses will be considered to ensure levels of insignificance for future reporting using "NE" in line with paragraph 37(b) of Decision 24/CP 19.

IPCC Category 2.C.1.e: CO_2 and CH_4 from Pellet Production

The current Inventory includes estimates for pellet production based on consumption data. The EPA has identified a potential activity data source for national-level pellet production from the U.S. Geological Survey and will update estimates based on this data in the future Inventory reports.

IPCC Category 2.E.3: C_2F_6, C_3F_8, C_4F_{10}, CF_4, NF_3, HFC-23, c-C_4F_8, and SF_6 from Photovoltaics

Along with more emissions information for semiconductor manufacturing, EPA's GHGRP requires the reporting of emissions from other types of electronics manufacturing, including micro-electro-mechanical systems (MEMs), flat panel displays, and photovoltaic cells. There currently are no flat panel display and photovoltaic cell manufacturing facilities that are reporting to EPA's GHGRP, and five reporting MEMs manufacturers. The MEMs manufacturers also report emissions from semiconductor manufacturing and do not distinguish between these two types of manufacturing in their report; thus, emissions from MEMs manufacturers are included in emissions from semiconductor manufacturing. Emissions from manufacturing of flat panel displays and photovoltaic cells may be included in future Inventory reports; however, estimation methodologies would need to be developed.

IPCC Category 2.E.4: C_2F_6, C_3F_8, CF_4, NF_3, HFC-23, c-C_4F_8, and SF_6 from Heat Transfer Fluids

Fluorinated heat transfer fluids (HTFs), of which some are liquid perfluorinated compounds, are used for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of semiconductor manufacturing production processes. Evaporation of these fluids is a source of fluorinated emissions (EPA 2006). Further research is needed to develop new emission factors for fluorinated greenhouse gas emissions from HTFs. Emissions from manufacturing of HTFs may be included in future Inventory reports; however, estimation methodologies would need to be developed based on recently available data.

Agriculture

IPCC Category 3.A.4: CH_4 from Enteric Fermentation—Camels and Llamas

Enteric fermentation emissions from camels and llamas are not estimated because there is no significant population of camels and llamas in the United States. Additional analyses will be conducted to quantitatively justify emissions reporting as "not estimated" and considered insignificant.[118]

IPCC Category 3.A.4: CH_4 and N_2O from Manure Management—Camels and Llamas

Manure management emissions from camels and llamas are not estimated because there is no significant population of camels and llamas in the United States. Additional analyses will be conducted to quantitatively justify emissions reporting as "not estimated" and considered insignificant.[119]

[118] Paragraph 37(b) of Decision 24/CP.19 "Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention." See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.
[119] Paragraph 37(b) of Decision 24/CP.19 "Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention." See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

IPCC Category 3.F.1.2: CH_4 and N_2O from Field Burning of Agricultural Residues—Barley, Oats, Rye, Potatoes

There was is no significant burning of barley, oats, rye, and potatoes in the United States, and therefore emissions from field burning of agricultural residues from these crops are not currently estimated. Additional analyses will be conducted to quantitatively justify emissions reporting as "not estimated" and considered insignificant.

ANNEX 6 Additional Information

6.1. Global Warming Potential Values

Global Warming Potential (GWP) is 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 specific period of time from the emission of a unit mass of gas relative to some reference gas (IPCC 2007). 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 kilotons (kt) of a gas and million metric tons of CO_2 equivalents (MMT CO_2 Eq.) can be expressed as follows:

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

where,

MMT CO_2 Eq.	=	Million metric tons of CO_2 equivalent
kt	=	kilotons (equivalent to a thousand metric tons)
GWP	=	Global warming potential
MMT	=	Million metric tons

GWP values allow policy makers to compare the impacts of emissions and reductions of different gases. According to the IPCC, GWP values typically have an uncertainty of ±35 percent, though some GWP values 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 GWP values from the *IPCC Fourth Assessment Report* (AR4), based upon a 100 year time horizon, although other time horizon values are available (see Table A-263). While noting the specific reporting requirements of the UNFCCC this Inventory uses agreed upon GWP values, it is also noted that unweighted gas emissions and sinks in kilotons (kt) are provided in the Trends chapter of this report (Table 2-2).

> *…the global warming potential values used by Parties included in Annex I to the Convention (Annex I Parties) to calculate the carbon dioxide equivalence of anthropogenic emissions by sources and removals by sinks of greenhouse gases shall be those listed in the column entitled "Global warming potential for given time horizon" in table 2.14 of the errata to the contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, based on the effects of greenhouse gases over a 100-year time horizon...*[120]

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, and NF_3) 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-263: IPCC AR4 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)	See footnote[b]	1	1	1
Methane (CH_4)[c]	12.4[d]	25	72	7.6
Nitrous oxide (N_2O)	121[d]	298	289	153
HFC-23	222	14,800	12,000	12,200

[120] United Nations Framework Convention on Climate Change; < http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf >; 31 January 2014; Report of the Conference of the Parties at its nineteenth session; held in Warsaw from 11 to 23 November 2013; Addendum; Part two: Action taken by the Conference of the Parties at its nineteenth session; Decision 24/CP.19; Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention; p. 2. (UNFCCC 2014)

HFC-32	5.2	675	2,330	205
HFC-125	28.2	3,500	6,350	1,100
HFC-134a	13.4	1,430	3,830	435
HFC-143a	47.1	4,470	5,890	1,590
HFC-152a	1.5	124	437	38
HFC-227ea	38.9	3,220	5,310	1,040
HFC-236fa	242	9,810	8,100	7,660
HFC-43-10mee	16.1	1,640	4,140	500
CF_4	50,000[d]	7,390	5,210	11,200
C_2F_6	10,000	12,200	8,630	18,200
C_3F_8	2,600	8,830	6,310	12,500
C_4F_{10}	2,600	8,860	6,330	12,500
c-C_4F_8	3,200	10,300	7,310	14,700
C_5F_{12}	4,100	9,160	6,510	13,300
C_6F_{14}	3,100	9,300	6,600	13,300
SF_6	3,200	22,800	16,300	32,600
NF_3	500	17,200	12,300	20,700

Source: IPCC (2007)

[a] GWP values used in this report are calculated over 100 year time horizon.

[b] For a given amount of carbon dioxide emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.

[c] 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-264 presents direct GWP values 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 GWP values 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-264). The effects of these compounds on radiative forcing are not addressed in this report.

Table A-264: 100-year Direct Global Warming Potentials for Select Ozone Depleting Substances

Gas	Direct GWP
CFC-11	4,750
CFC-12	10,900
CFC-113	6,130
HCFC-22	1,810
HCFC-123	77
HCFC-124	609
HCFC-141b	725
HCFC-142b	2,310
CH_3CCl_3	146
CCl_4	1,400
CH_3Br	5
Halon-1211	1,890
Halon-1301	7,140

Source: IPCC (2007)

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 published its *Fifth Assessment Report* (AR5) in 2013, providing the most current and comprehensive scientific assessment of climate change (IPCC 2013). Within this report, the GWP values were revised relative to the IPCC's *Second Assessment Report* (SAR) (IPCC 1996), IPCC's *Third Assessment Report* (TAR) (IPCC 2001), and the IPCC's

Fourth Assessment Report (AR4) (IPCC 2007). Although the AR4 GWP values are used throughout this report in line with UNFCCC inventory reporting guidelines, it is informative to review the changes to the GWP values and the impact they have on the total GWP-weighted emissions of the United States. All GWP values 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 GWP values are drawn from IPCC (2007), 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, and updated background concentrations were used. Table A-265 shows how the GWP values of the other gases relative to CO_2 tend to be larger in AR4 and AR5 because the revised radiative forcing of CO_2 is lower than in earlier assessments, taking into account revisions in lifetimes. Comparisons of GWP values are based on the 100-year time horizon required for UNFCCC inventory reporting. 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. 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 GWP values changing by up to 40 percent; with this change, the uncertainties associated with these well-mixed HFCs are thought to be approximately 12 percent.

It should be noted that the use of IPCC AR4 GWP values for the current Inventory applies across the entire time series of the Inventory (i.e., from 1990 to 2015). As such, GWP comparisons throughout this chapter are presented relative to AR4 GWPs.

Table A-265: Comparison of GWP values and Lifetimes Used in the SAR, AR4, and AR5

	Lifetime (years)			GWP (100 year)				Difference in GWP (Relative to AR4)					
Gas	SAR	AR4	AR5	SAR	AR4	AR5[a]	AR5 with feedbacks[b]	SAR	SAR (%)	AR5[a]	AR5 (%)	AR5 with feedbacks[b]	AR5 with feedbacks[b] (%)
Carbon dioxide (CO_2)	[c]	[d]	[d]	1	1	1	1	NC	NC	NC	NC	NC	NC
Methane (CH_4)[d]	12±3	8.7/12[e]	12.4	21	25	28	34	(4)	(16%)	3	12%	9	36%
Nitrous oxide (N_2O)	120	120/114[e]	121	310	298	265	298	12	4%	(33)	(11%)	0	0%
Hydrofluorocarbons													
HFC-23	264	270	222	11,700	14,800	12,400	13,856	(3,100)	(21%)	(2,400)	(16%)	(944)	(6)%
HFC-32	5.6	4.9	5.2	650	675	677	817	(25)	(4%)	2	+%	142	21%
HFC-125	32.6	29	28.2	2,800	3,500	3,170	3,691	(700)	(20%)	(330)	(9%)	191	5%
HFC-134a	14.6	14	13.4	1,300	1,430	1,300	1,549	(130)	(9%)	(130)	(9%)	119	8%
HFC-143a	48.3	52	47.1	3,800	4,470	4,800	5,508	(670)	(15%)	330	7%	1,038	23%
HFC-152a	1.5	1.4	1.5	140	124	138	167	16	13%	14	11%	43	35%
HFC-227ea	36.5	34.2	38.9	2,900	3,220	3,350	3,860	(320)	(10%)	130	4%	640	20%
HFC-236fa	209	240	242	6,300	9,810	8,060	8,998	(3,510)	(36%)	(1,750)	(18%)	(812)	(8)%
HFC-245fa	NA	7.6	7.7	NA	1,030	858	1032	NA	NA	(172)	(17%)	2	+%
HFC-365mfc	NA	6.6	8.7	NA	794	804	966	NA	NA	10	1%	172	22%
HFC-43-10mee	17.1	15.9	16.1	1,300	1,640	1,650	1,952	(340)	(21%)	10	1%	312	19%
Fully Fluorinated Species													
SF_6	3,200	3,200	3,200	23,900	22,800	23,500	26,087	1,100	5%	700	3%	3,287	14%
CF_4	50,000	50,000	50,000	6,500	7,390	6,630	7,349	(890)	(12%)	(760)	(10%)	(41)	(1)%
C_2F_6	10,000	10,000	10,000	9,200	12,200	11,100	12,340	(3,000)	(25%)	(1,100)	(9%)	140	1%
C_3F_8	2,600	2,600	2,600	7,000	8,830	8,900	9,878	(1,830)	(21%)	70	1%	1,048	12%
C_4F_{10}	2,600	2,600	2,600	7,000	8,860	9,200	10,213	(1,860)	(21%)	340	4%	1,353	15%
$c\text{-}C_4F_8$	3,200	3,200	3,200	8,700	10,300	9,540	10,592	(1,600)	(16%)	(760)	(7%)	292	3%
C_5F_{12}	4,100	4,100	4,100	7,500	9,160	8,550	9,484	(1,660)	(18%)	(610)	(7%)	324	4%
C_6F_{14}	3,200	3,200	3,100	7,400	9,300	7,910	8,780	(1,900)	(20%)	(1,390)	(15%)	(520)	(6)%
NF_3	NA	740	500	NA	17,200	16,100	17,885	NA	NA	(1,100)	(6%)	685	4%

+ Does not exceed 0.05 or 0.05 percent.
NC (No Change); NA (Not Applicable)
[a] The GWP values presented here are the ones most consistent with the methodology used in the AR4 report.
[b] The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime. Additionally, the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product.
[c] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.
[d] No single lifetime can be determined for CO_2. (See IPCC 2001)
[e] 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 only included in the value from AR5 that includes climate-carbon feedbacks.
[f] 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).
Note: Parentheses indicate negative values. Source: IPCC (2013), IPCC (2007), IPCC (2001), IPCC (1996).

The choice of GWP values between the SAR, AR4, and AR5 with or without climate-carbon feedbacks 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-266 shows the overall trend in U.S. greenhouse gas emissions, by gas, from 1990 through 2015 using the four GWP sets. The table also presents the impact of SAR and AR5 GWP values with or without feedbacks on the total emissions for 1990 and for 2015.

Table A-266: Effects on U.S. Greenhouse Gas Emissions Using SAR, AR4, and AR5 GWP values (MMT CO_2 Eq.)

Gas	Trend from 1990 to 2015				Revisions to Annual Emission Estimates (Relative to AR4)					
					SAR	AR5[a]	AR5[b]	SAR	AR5[a]	AR5[b]
	SAR	AR4	AR5[a]	AR5[b]	1990			2015		
CO_2	289.2	289.2	289.2	289.2	NC	NC	NC	NC	NC	NC
CH_4	(110.2)	(120.7)	(131.2)	(146.9)	(125.8)	(62.9)	94.3	(104.8)	(52.4)	78.6
N_2O	(25.5)	(24.3)	(24.5)	(21.8)	14.5	(2.4)	(39.8)	13.5	(2.2)	(37.1)
HFCs, PFCs, SF_6 and NF_3	66.4	81.0	85.9	77.9	(11.9)	(14.0)	(9.0)	(31.5)	(18.9)	(17.1)
Total	**219.9**	**225.2**	**369.6**	**198.4**	**(123.2)**	**(79.3)**	**45.5**	**(272.8)**	**(73.5)**	**24.4**
Percent Change	**3.5%**	**3.6%**	**3.4%**	**3.1%**	**(1.9)%**	**(1.2)%**	**0.7%**	**(4.1)%**	**(1.1)%**	**0.4%**

NC (No Change)

[a] The GWP values presented here are the ones most consistent with the methodology used in the AR4 report, and exclude climate-carbon feedbacks.

[b] The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime. Additionally, the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product.

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

When the GWP values from the SAR are applied to the emission estimates presented in this report, total emissions for the year 2015 are 6,463.4 MMT CO_2 Eq., as compared to the official emission estimate of 6,586.2 MMT CO_2 Eq. using AR4 GWP values (i.e., the use of SAR GWPs results in a 1.9 percent decrease relative to emissions estimated using AR4 GWPs). Table A-267 provides a detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 2015, using the GWP values from the SAR. 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-268 summarizes the resulting change in emissions from using SAR GWP values relative to emissions using AR4 values for 1990 through 2015, including the percent change for 2015.

Table A-267: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks using the SAR GWP values (MMT CO_2 Eq.)

Gas/Source	1990	2005	2011	2012	2013	2014	2015
CO_2	**5,121.4**	**6,129.7**	**5,567.5**	**5,359.5**	**5,512.1**	**5,561.8**	**5,410.6**
Fossil Fuel Combustion	4,740.7	5,747.1	5,227.7	5,024.7	5,157.6	5,202.1	5,049.2
Electricity Generation	*1,820.8*	*2,400.9*	*2,157.7*	*2,022.2*	*2,038.1*	*2,038.0*	*1,900.7*
Transportation	*1,493.8*	*1,887.0*	*1,707.6*	*1,696.8*	*1,713.0*	*1,730.4*	*1,733.2*
Industrial	*842.5*	*828.0*	*775.0*	*782.9*	*812.2*	*815.8*	*828.8*
Residential	*338.3*	*357.8*	*325.5*	*282.5*	*329.7*	*345.4*	*319.6*
Commercial	*217.4*	*223.5*	*220.4*	*196.7*	*221.0*	*231.4*	*225.7*
U.S. Territories	*27.9*	*49.9*	*41.5*	*43.6*	*43.5*	*41.2*	*41.2*
Non-Energy Use of Fuels	117.7	138.3	108.5	105.5	122.0	117.2	127.0
Iron and Steel Production & Metallurgical Coke Production	99.7	66.5	59.9	54.2	52.2	57.5	47.9
Natural Gas Systems	37.7	30.1	35.7	35.2	38.5	42.4	42.4
Cement Production	33.3	45.9	32.0	35.1	36.1	38.8	39.6
Petrochemical Production	21.3	27.0	26.3	26.5	26.4	26.5	28.1
Lime Production	11.7	14.6	14.0	13.8	14.0	14.2	13.3
Other Process Uses of Carbonates	4.9	6.3	9.3	8.0	10.4	11.8	10.8
Ammonia Production	13.0	9.2	9.3	9.4	10.0	9.6	10.8
Incineration of Waste	8.0	12.5	10.6	10.4	10.4	10.6	10.7
Urea Fertilization	2.4	3.5	4.1	4.3	4.5	4.8	5.0
Carbon Dioxide Consumption	1.5	1.4	4.1	4.0	4.2	4.5	4.3
Liming	4.7	4.3	3.9	6.0	3.9	3.6	3.8

Petroleum Systems	3.6	3.9	4.2	3.9	3.7	3.6	3.6
Soda Ash Production and Consumption	2.8	3.0	2.7	2.8	2.8	2.8	2.8
Aluminum Production	6.8	4.1	3.3	3.4	3.3	2.8	2.8
Ferroalloy Production	2.2	1.4	1.7	1.9	1.8	1.9	2.0
Titanium Dioxide Production	1.2	1.8	1.7	1.5	1.7	1.7	1.6
Glass Production	1.5	1.9	1.3	1.2	1.3	1.3	1.3
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.0	4.4	4.0	1.4	1.1
Phosphoric Acid Production	1.5	1.3	1.2	1.1	1.1	1.0	1.0
Zinc Production	0.6	1.0	1.3	1.5	1.4	1.0	0.9
Lead Production	0.5	0.6	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	0.2
Magnesium Production and Processing	+	+	+	+	+	+	+
Wood Biomass and Ethanol Consumption[a]	*219.4*	*229.8*	*268.1*	*267.7*	*286.3*	*293.7*	*277.7*
International Bunker Fuels[b]	*103.5*	*113.1*	*111.7*	*105.8*	*99.8*	*103.2*	*110.8*
CH_4	**660.3**	**575.8**	**565.6**	**560.4**	**554.1**	**553.9**	**550.1**
Enteric Fermentation	137.9	141.8	141.9	140.1	139.0	137.9	139.9
Natural Gas Systems	165.1	136.2	129.1	130.5	132.7	135.1	134.4
Landfills	150.8	112.8	100.0	101.5	98.0	97.9	97.2
Manure Management	31.2	47.3	52.9	55.1	53.1	52.8	55.7
Coal Mining	81.1	53.9	59.8	55.8	54.3	54.5	51.2
Petroleum Systems	48.9	40.3	42.1	40.6	39.1	37.7	34.9
Wastewater Treatment	13.2	13.4	12.9	12.7	12.5	12.4	12.4
Rice Cultivation	13.5	14.0	11.8	9.5	9.5	9.6	9.4
Stationary Combustion	7.1	6.2	5.9	5.6	6.7	6.8	5.8
Abandoned Underground Coal Mines	6.0	5.5	5.4	5.2	5.2	5.3	5.4
Composting	0.3	1.6	1.6	1.6	1.7	1.8	1.8
Mobile Combustion	4.7	2.4	1.9	1.8	1.8	1.7	1.7
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Petrochemical Production	0.2	0.1	+	0.1	0.1	0.1	0.2
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**374.0**	**376.2**	**378.7**	**354.4**	**349.0**	**349.0**	**348.6**
Agricultural Soil Management	266.9	270.3	281.0	264.3	260.6	260.1	261.4
Stationary Combustion	12.4	21.0	22.2	22.2	23.8	24.4	24.1
Manure Management	14.6	17.2	18.1	18.2	18.2	18.2	18.4
Mobile Combustion	42.9	37.2	23.7	21.2	19.2	17.3	16.0
Nitric Acid Production	12.6	11.8	11.3	10.9	11.1	11.4	12.0
Wastewater Treatment	3.5	4.6	4.9	5.0	5.1	5.1	5.2
Adipic Acid Production	15.8	7.4	10.7	5.8	4.1	5.7	4.4
N_2O from Product Uses	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Composting	0.4	1.7	1.7	1.8	1.9	1.9	2.0
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Semiconductor Manufacture	+	0.1	0.2	0.2	0.2	0.2	0.3
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
International Bunker Fuels[b]	*0.9*	*1.0*	*1.0*	*1.0*	*0.9*	*0.9*	*1.0*
HFCs	**36.9**	**102.3**	**129.6**	**130.4**	**132.3**	**138.3**	**143.4**
Substitution of Ozone Depleting Substances[c]	0.3	86.3	122.5	125.9	128.9	134.0	139.1
HCFC-22 Production	36.4	15.8	6.9	4.3	3.2	4.0	4.0
Semiconductor Manufacture	0.2	0.2	0.2	0.2	0.1	0.3	0.3

Magnesium Production and Processing	0.0	0.0	+	+	0.1	0.1	0.1
PFCs	**20.6**	**5.5**	**5.7**	**5.3**	**4.7**	**5.1**	**4.7**
Semiconductor Manufacture	2.2	2.6	2.8	2.5	2.3	2.6	2.6
Aluminum Production	18.4	3.0	2.9	2.8	2.5	2.5	2.1
SF_6	**30.2**	**12.3**	**9.6**	**7.2**	**6.7**	**6.9**	**6.1**
Electrical Transmission and Distribution	24.2	8.7	6.3	5.0	4.8	5.1	4.4
Magnesium Production and Processing	5.4	2.9	2.9	1.7	1.5	1.0	1.0
Semiconductor Manufacture	0.5	0.7	0.4	0.4	0.4	0.8	0.8
NF_3	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
Semiconductor Manufacture	NA	NA	NA	NA	NA	NA	NA
Total Emissions	**6,243.5**	**7,201.7**	**6,656.8**	**6,417.2**	**6,559.0**	**6,615.0**	**6,463.4**
LULUCF Emissions[d]	10.7	22.3	19.3	24.8	18.4	19.0	18.9
LULUCF Total Net Flux[e]	(460.7)	(339.3)	(395.8)	(414.5)	(390.3)	(389.2)	(386.8)
LULUCF Sector Total[f]	(450.0)	(317.0)	(376.5)	(389.7)	(371.8)	(370.3)	(367.9)
Net Emissions (Sources and Sinks)	**5,793.5**	**6,884.8**	**6,280.3**	**6,027.6**	**6,187.1**	**6,244.7**	**6,095.6**

NA (Not Applicable)
+ Does not exceed 0.05 MMT CO_2 Eq.
Note: Total emissions presented without LULUCF. Net emissions presented with LULUCF.
[a] Emissions from Wood Biomass and Ethanol Consumption are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.
[b] Emissions from International Bunker Fuels are not included in totals.
[c] Small amounts of PFC emissions also result from this source.
[d] LULUCF emissions include the CO_2, CH_4, and N_2O emissions from *Peatlands Remaining Peatlands*; CH_4 and N_2O emissions reported for Non-CO_2 Emissions from Forest Fires, Non-CO_2 Emissions from Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O Fluxes from Forest Soils and Settlement Soils.
[e] Net CO_2 flux is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements,* and *Land Converted to Settlements.*
[f] The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO_2 (i.e., sinks or negative emissions) from the atmosphere.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table A-268: Change in U.S. Greenhouse Gas Emissions Using SAR GWP values relative to AR4 GWP values (MMT CO_2 Eq.)

Gas/Source	1990	2005	2011	2012	2013	2014	2015	Percent Change in 2015
CO_2	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**
CH_4	**(125.8)**	**(109.7)**	**(107.7)**	**(106.7)**	**(105.5)**	**(105.5)**	**(104.8)**	**(16%)**
Enteric Fermentation	(26.3)	(27.0)	(27.0)	(26.7)	(26.5)	(26.3)	(26.6)	(16%)
Natural Gas Systems	(31.4)	(25.9)	(24.6)	(24.9)	(25.3)	(25.7)	(25.6)	(16%)
Landfills	(28.7)	(21.5)	(19.0)	(19.3)	(18.7)	(18.7)	(18.5)	(16%)
Manure Management	(5.9)	(9.0)	(10.1)	(10.5)	(10.1)	(10.1)	(10.6)	(16%)
Coal Mining	(15.4)	(10.3)	(11.4)	(10.6)	(10.3)	(10.4)	(9.7)	(16%)
Petroleum Systems	(9.3)	(7.7)	(8.0)	(7.7)	(7.5)	(7.2)	(6.6)	(16%)
Wastewater Treatment	(2.5)	(2.6)	(2.5)	(2.4)	(2.4)	(2.4)	(2.4)	(16%)
Rice Cultivation	(2.6)	(2.7)	(2.3)	(1.8)	(1.8)	(1.8)	(1.8)	(16%)
Stationary Combustion	(1.4)	(1.2)	(1.1)	(1.1)	(1.3)	(1.3)	(1.1)	(16%)
Abandoned Underground Coal Mines	(1.2)	(1.1)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(16%)
Composting	(0.1)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(16%)
Mobile Combustion	(0.9)	(0.5)	(0.4)	(0.3)	(0.3)	(0.3)	(0.3)	(16%)
Field Burning of Agricultural Residues	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(16%)
Petrochemical Production	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(16%)
Ferroalloy Production	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(16%)
Silicon Carbide Production and Consumption	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(16%)

Iron and Steel Production & Metallurgical Coke Production	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(16%)
Incineration of Waste	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(16%)
International Bunker Fuels[a]	*(+)*	*(+)*	*(+)*	*(+)*	*(+)*	*(+)*	*(+)*	*(16%)*
N_2O	**14.5**	**14.6**	**14.7**	**13.7**	**13.5**	**13.5**	**13.5**	**4%**
Agricultural Soil Management	10.3	10.5	10.9	10.2	10.1	10.1	10.1	4%
Stationary Combustion	0.5	0.8	0.9	0.9	0.9	0.9	0.9	4%
Manure Management	0.6	0.7	0.7	0.7	0.7	0.7	0.7	4%
Mobile Combustion	1.7	1.4	0.9	0.8	0.7	0.7	0.6	4%
Nitric Acid Production	0.5	0.5	0.4	0.4	0.4	0.4	0.5	4%
Wastewater Treatment	0.1	0.2	0.2	0.2	0.2	0.2	0.2	4%
Adipic Acid Production	0.6	0.3	0.4	0.2	0.2	0.2	0.2	4%
N_2O from Product Uses	0.2	0.2	0.2	0.2	0.2	0.2	0.2	4%
Composting	+	0.1	0.1	0.1	0.1	0.1	0.1	4%
Incineration of Waste	+	+	+	+	+	+	+	4%
Semiconductor Manufacture	+	+	+	+	+	+	+	4%
Field Burning of Agricultural Residues	+	+	+	+	+	+	+	4%
International Bunker Fuels[a]	+	+	+	+	+	+	+	*4%*
HFCs	**(11.9)**	**(18.7)**	**(26.1)**	**(26.5)**	**(27.9)**	**(29.3)**	**(31.5)**	**(18%)**
Substitution of Ozone Depleting Substances[b]	**(9.7)**	**(17.7)**	**(24.8)**	**(25.5)**	**(26.7)**	**(28.5)**	**(30.7)**	(18%)
HCFC-22 Production	+	(13.5)	(22.9)	(24.3)	(25.8)	(27.3)	(29.5)	(21%)
Semiconductor Manufacture	-9.7	(4.2)	(1.8)	(1.1)	(0.9)	(1.1)	(1.1)	(21%)
Magnesium Production and Processing	(+)	(+)	(+)	(+)	(+)	(0.1)	(0.1)	(9%)
PFCs	0.0	0.0	(+)	(+)	(+)	(+)	(+)	**(10%)**
Semiconductor Manufacture	**(3.6)**	**(1.1)**	**(1.2)**	**(0.7)**	**(1.0)**	**(0.6)**	**(0.5)**	(18%)
Aluminum Production	(+)	(0.6)	(0.7)	(0.6)	(0.5)	(0.6)	(0.6)	3%
SF_6	(3.0)	(0.5)	(0.5)	(0.1)	(0.5)	(+)	+	**5%**
Electrical Transmission and Distribution	**1.4**	**0.6**	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	5%
Magnesium Production and Processing	1.1	0.4	0.3	0.2	0.2	0.2	0.2	5%
Semiconductor Manufacture	0.3	0.1	0.1	0.1	0.1	+	+	5%
NF_3	+	+	+	+	+	+	+	**NA**
Semiconductor Manufacture	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	NA
Total Emissions	**(123.2)**	**(113.9)**	**(119.2)**	**(119.5)**	**(119.9)**	**(121.3)**	**(122.7)**	**(1.9%)**

NC (No Change)
NA (Not Applicable)
+ Absolute value does not exceed 0.05 MMT CO_2 Eq.
[a] Emissions from International Bunker Fuels are not included in totals.
[b] Small amounts of PFC emissions also result from this source.
Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table A-269 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 that result from using SAR relative to AR4 GWP values was minimal. The effect on emissions from waste was by far the greatest (10.9 percent decrease in 2015 using SAR GWP values, relative to emissions using AR4 GWP values), 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-269: Comparison of Emissions by Sector using IPCC AR4 and SAR GWP Values (MMT CO_2 Eq.)

Sector	1990	2005	2011	2012	2013	2014	2015
Energy							
AR4 GWP, Used In Inventory	5,333.8	6,279.4	5,721.8	5,506.9	5,659.3	5,703.2	5,549.4
SAR GWP	5,276.3	6,235.1	5,677.1	5,463.0	5,615.3	5,658.9	5,506.5
Difference (%)	(1.1%)	(0.7%)	(0.8%)	(0.8%)	(0.8%)	(0.8%)	(0.8%)

Industrial Processes and Product Use							
AR4 GWP, Used In Inventory	338.3	351.6	369.7	359.5	362.4	378.1	375.1
SAR GWP	327.6	333.8	344.5	333.8	335.2	349.6	344.4
Difference (%)	(3.2%)	(5.1%)	(6.8%)	(7.2%)	(7.5%)	(7.5%)	(8.2%)
Agriculture							
AR4 GWP, Used In Inventory	495.3	526.4	541.9	525.9	516.9	514.7	522.3
SAR GWP	471.4	498.8	514.0	497.8	489.2	487.3	494.0
Difference (%)	(4.8%)	(5.2%)	(5.1%)	(5.3%)	(5.4%)	(5.3%)	(5.4%)
LULUCF							
AR4 GWP, Used In Inventory	(449.1)	(315.3)	(375.1)	(387.7)	(370.4)	(368.8)	(366.4)
SAR GWP	(450.0)	(317.0)	(376.5)	(389.7)	(371.8)	(370.3)	(367.9)
Difference (%)	0.2%	0.6%	0.4%	0.5%	0.4%	0.4%	0.4%
Waste							
AR4 GWP, Used In Inventory	199.3	158.2	142.6	144.4	140.4	140.2	139.4
SAR GWP	168.2	134.1	121.1	122.6	119.3	119.1	118.5
Difference (%)	(15.6%)	(15.2%)	(15.1%)	(15.1%)	(15.0%)	(15.0%)	(15.0%)
Net Emissions							
AR4 GWP, Used In Inventory	**5,917.6**	**7,000.3**	**6,400.9**	**6,149.1**	**6,308.5**	**6,367.5**	**6,219.8**
SAR GWP	**5,793.5**	**6,884.8**	**6,280.3**	**6,027.6**	**6,187.1**	**6,244.7**	**6,095.6**
Difference (%)	**-2.1%**	**-1.7%**	**-1.9%**	**-2.0%**	**-1.9%**	**-1.9%**	**-2.0%**

+ Does not exceed 0.05 percent.

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

Further, Table A-270 and Table A-271 show the comparison of emission estimates using AR5 GWP values relative to AR4 GWP values without climate-carbon feedbacks, on an emissions and percent change basis. Table A-272 and Table A-273 show the comparison of emission estimates using AR5 GWP values with climate-carbon feedbacks. The use of AR5 GWP values without climate-carbon feedbacks[121] results in an increase in emissions of CH_4 and SF_6 relative to AR4 GWP values, but a decrease in emissions of other gases. The use of AR5 GWP values with climate-carbon feedbacks does not impact CO_2 and N_2O emissions; however, it results in an increase in emissions of NF_3, CH_4 and SF_6 relative to AR4 GWP values, and has mixed impacts on emissions of other gases. Overall, these comparisons of AR4 and AR5 GWP values do not have a significant effect on U.S. emission trends, resulting in an increase in emissions of less than 1 percent using AR5 GWP values, or 4 percent when using AR5 GWP values with climate-carbon feedbacks. As with the comparison of SAR and AR4 GWP values presented above, the percent change in emissions is equal to the percent change in the GWP for each gas; 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-270: Change in U.S. Greenhouse Gas Emissions Using AR5[a] without Climate-Carbon Feedbacks Relative to AR4 GWP Values (MMT CO_2 Eq.)

Gas	1990	2005	2011	2012	2013	2014	2015
CO_2	NC	NC	NC	NC	NC	NC	NC
CH_4	94.3	82.3	80.8	80.1	79.2	79.1	78.6
N_2O	(39.8)	(40.0)	(40.3)	(37.7)	(37.2)	(37.2)	(37.1)
HFCs	(7.5)	(13.4)	(15.0)	(14.8)	(14.9)	(15.7)	(17.1)
PFCs	(2.4)	(0.6)	(0.7)	(0.2)	(0.6)	(0.2)	(0.1)
SF_6	0.9	0.4	0.3	0.2	0.2	0.2	0.2
NF_3	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Total	**45.5**	**28.4**	**25.1**	**27.5**	**26.6**	**26.2**	**24.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

NC (No Change)

Note: Total emissions presented without LULUCF.

[a] The GWP values presented here are the ones most consistent with the methodology used in the AR4 report. The AR5 report has also calculated GWP values (shown in Table A-272) where climate-carbon feedbacks have been included for the non-CO_2 gases in order to be

[121] The IPCC AR5 report provides additional information on emission metrics. See <https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf>.

consistent with the approach used in calculating the CO_2 lifetime. Additionally, the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product.
Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table A-271: Change in U.S. Greenhouse Gas Emissions Using AR5[a] without Climate-Carbon Feedbacks Relative to AR4 GWP Values (Percent)

Gas/Source	1990	2005	2011	2012	2013	2014	2015
CO_2	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**
CH_4	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**
N_2O	**(11.0%)**	**(11.0%)**	**(11.0%)**	**(11.0%)**	**(11.0%)**	**(11.0%)**	**(11.0%)**
HFCs	**(16.0%)**	**(11.2%)**	**(9.7%)**	**(9.5%)**	**(9.4%)**	**(9.4%)**	**(9.8%)**
Substitution of Ozone Depleting Substances	11.3%	(10.2%)	(9.3%)	(9.3%)	(9.2%)	(9.2%)	(9.6%)
HCFC-22 Production[b]	(16.2%)	(16.2%)	(16.2%)	(16.2%)	(16.2%)	(16.2%)	(16.2%)
Semiconductor Manufacture[c]	(16.2%)	(16.2%)	(16.2%)	(16.2%)	(16.2%)	(16.2%)	(16.2%)
Magnesium Production and Processing[d]	0.0%	0.0%	(9.1%)	(9.1%)	(9.1%)	(9.1%)	(9.1%)
PFCs	(10.0%)	(9.6%)	(9.5%)	(3.6%)	(10.2%)	(3.5%)	(2.1%)
Semiconductor Manufacture[c]	(9.4%)	(9.1%)	(9.0%)	(9.1%)	(9.1%)	(9.2%)	(9.2%)
Aluminum Production[e]	(10.1%)	(10.1%)	(10.0%)	2.0%	(11.2%)	3.8%	9.1%
SF_6	**3.1%**	**3.1%**	**3.1%**	**3.1%**	**3.1%**	**3.1%**	**3.1%**
NF_3	**(6.4%)**	**(6.4%)**	**(6.4%)**	**(6.4%)**	**(6.4%)**	**(6.4%)**	**(6.4%)**
Total	**0.7%**	**0.4%**	**0.4%**	**0.4%**	**0.4%**	**0.4%**	**0.4%**

Note: Total emissions presented without LULUCF.
NC (No Change)
[a] The GWP values presented here are the ones most consistent with the methodology used in the AR4 report. The AR5 report has also calculated GWP values (shown in Table A-273) where climate-carbon feedbacks have been included for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime. Additionally, the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product.
[b] HFC-23 emitted
[c] Emissions from HFC-23, CF_4, C_2F_6, C_3F_8, C_4F_8, SF_6, and NF_3.
[d] Zero change in beginning of time series since emissions were zero.
[e] PFC emissions from CF_4 and C_2F_6
Note: Parentheses indicate negative values.

Table A-272: Change in U.S. Greenhouse Gas Emissions Using AR5 with Climate-Carbon Feedbacks[a] Relative to AR4 GWP Values (MMT CO_2 Eq.)

Gas	1990	2005	2011	2012	2013	2014	2015
CO_2	NC	NC	NC	NC	NC	NC	NC
CH_4	283.0	246.8	242.4	240.2	237.5	237.4	235.8
N_2O	NC	NC	NC	NC	NC	NC	NC
HFCs	(2.9)	5.0	9.2	9.7	10.0	10.3	9.9
PFCs	(+)	+	+	+	(+)	+	+
SF_6	4.2	1.7	1.3	1.0	0.9	0.9	0.8
NF_3	+	+	+	+	+	+	+
Total	**284.2**	**253.5**	**253.0**	**251.3**	**248.4**	**249.0**	**246.9**

NC (No Change)
+ Absolute value does not exceed 0.05 MMT CO_2 Eq.
[a] The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime. Additionally, the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product.
Notes: Total emissions presented without LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table A-273: Change in U.S. Greenhouse Gas Emissions Using AR5 with Climate-Carbon Feedbacks[a] Relative to AR4 GWP Values (Percent)

Gas/Source	1990	2005	2011	2012	2013	2014	2015
CO_2	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**
CH_4	**36.0%**	**36.0%**	**36.0%**	**36.0%**	**36.0%**	**36.0%**	**36.0%**

N_2O	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
HFCs	**(6.1%)**	**4.2%**	**5.9%**	**6.2%**	**6.3%**	**6.2%**	**5.7%**
Substitution of Ozone Depleting Substances	34.7%	6.3%	6.7%	6.7%	6.6%	6.6%	6.0%
HCFC-22 Production[b]	(6.4%)	(6.4%)	(6.4%)	(6.4%)	(6.4%)	(6.4%)	(6.4%)
Semiconductor Manufacture[c]	(6.4%)	(6.4%)	(6.4%)	(6.4%)	(6.4%)	(6.4%)	(6.4%)
Magnesium Production and Processing[d]	0.0%	0.0%	8.3%	8.3%	8.3%	8.3%	8.3%
PFCs	**(0.2%)**	**0.3%**	**0.5%**	**6.9%**	**(0.3%)**	**7.1%**	**8.6%**
Semiconductor Manufacture[c]	0.6%	0.9%	1.1%	0.9%	0.9%	0.8%	0.8%
Aluminum Production[e]	(0.3%)	(0.3%)	(0.2%)	13.2%	(1.5%)	15.1%	21.0%
SF_6	**14.4%**	**14.4%**	**14.4%**	**14.4%**	**14.4%**	**14.4%**	**14.4%**
NF_3	**4.0%**	**4.0%**	**4.0%**	**4.0%**	**4.0%**	**4.0%**	**4.0%**
Total	**4.5%**	**3.5%**	**3.7%**	**3.8%**	**3.7%**	**3.7%**	**3.7%**

NC (No Change)

[a] The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime. Additionally, the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product.

[b] HFC-23 emitted

[c] Emissions from HFC-23, CF_4, C_2F_6, C_3F_8, C_4F_8, SF_6, and NF_3.

[d] Zero change in beginning of time series since emissions were zero.

[e] PFC emissions from CF_4 and C_2F_6

Notes: Total emissions presented without LULUCF. Parentheses indicate negative values.Excludes Sinks.

6.2. Ozone Depleting Substance Emissions

Ozone is present in both the stratosphere,[122] where it shields the earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[123] 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, sterilization, solvent cleaning, and as an aerosol propellant.

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.[124] 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,[125] 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 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 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 GWP values and net (combined direct warming and indirect cooling) GWP ranges for some of the most common ozone depleting substances (IPCC 2007). See Annex 6.1, Global Warming Potential Values, 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-274.

[122] 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.

[123] 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.

[124] Substances with an ozone depletion potential of 0.2 or greater are designated as Class I. All other designated substances that deplete stratospheric ozone but which have an ODP of less than 0.2 are Class II.

[125] Older refrigeration and air-conditioning equipment, fire extinguishing systems, meter-dose inhalers, and foam products blown with CFCs/HCFCs may still contain ODS.

Table A-274: Emissions of Ozone Depleting Substances (kt)

Compound	1990	2005	2011	2012	2013	2014	2015
Class I							
CFC-11	29	12	24	24	24	24	25
CFC-12	128	22	5	5	5	4	4
CFC-113	59	0	0	0	0	0	0
CFC-114	4	1	+	+	+	0	0
CFC-115	8	2	+	+	+	+	+
Carbon Tetrachloride	4	0	0	0	0	0	0
Methyl Chloroform	223	0	0	0	0	0	0
Halon-1211	2	1	1	1	1	1	1
Halon-1301	2	+	+	+	+	+	+
Class II							
HCFC-22	49	82	80	76	73	69	65
HCFC-123	0	1	1	1	1	1	1
HCFC-124	0	2	1	1	1	1	+
HCFC-141b	1	4	9	9	10	10	9
HCFC-142b	1	4	2	1	1	2	2
HCFC-225ca/cb	0	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

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 Annex 3.9, Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances, 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.

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-275.

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 59.2 percent of total SO_2 emissions in 2015 (see Table A-276); coal combustion accounted for approximately 92.0 percent of that total. The second largest source was industrial fuel combustion, which produced 14.4 percent of 2015 SO_2 emissions. Overall, SO_2 emissions in the United States decreased by 83.5 percent from 1990 to 2015. 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, 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,[126] (2) New Source Performance Standards,[127] (3) the New Source Review/Prevention of Significant Deterioration Program,[128] and (4) the Sulfur Dioxide Allowance Program.[129]

Table A-275: SO_2 Emissions (kt)

Sector/Source	1990	2005	2011	2012	2013	2014	2015
Energy	**19,628**	**12,364**	**5,273**	**5,271**	**5,270**	**3,859**	**2,950**
Stationary Sources	18,407	11,541	5,008	5,006	5,005	3,640	2,756
Oil and Gas Activities	390	180	108	108	108	93	93
Mobile Sources	793	619	142	142	142	95	70
Waste Combustion	38	25	15	15	15	32	32
Industrial Processes and Product Use	**1,307**	**831**	**604**	**604**	**604**	**496**	**496**
Other Industrial Processes	362	327	171	171	171	156	156
Miscellaneous*	11	114	179	179	179	135	135
Chemical and Allied Product Manufacturing	269	228	115	115	115	104	104
Metals Processing	659	158	131	131	131	98	98
Storage and Transport	6	2	8	8	8	3	3
Solvent Use	**0**	**+**	**+**	**+**	**+**	**+**	**+**
Degreasing	0	0	0	0	0	0	0
Graphic Arts	0	0	0	0	0	0	0
Dry Cleaning	NA	0	0	0	0	0	0
Surface Coating	0	0	0	0	0	0	0
Other Industrial	0	+	+	+	+	+	+
Nonindustrial	NA	NA	NA	NA	NA	NA	NA
Agriculture	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA

[126] [42 U.S.C § 7409, CAA § 109]
[127] [42 U.S.C § 7411, CAA § 111]
[128] [42 U.S.C § 7473, CAA § 163]
[129] [42 U.S.C § 7651, CAA § 401]

Waste	**+**	**1**	**+**	**+**	**+**	**1**	**1**
Landfills	+	1	+	+	+	1	1
Wastewater Treatment	+	0	0	0	0	0	0
Miscellaneous	+	0	0	0	0	0	0
Total	**20,935**	**13,196**	**5,877**	**5,876**	**5,874**	**4,357**	**3,448**

+ Does not exceed 0.5 kt
* Miscellaneous includes other combustion and fugitive dust categories.
Note: Totals may not sum due to independent rounding.
Source: Data taken from EPA (2016) and disaggregated based on EPA (2003).

Table A-276: SO_2 Emissions from Electricity Generation (kt)

Fuel Type	1990	2005	2011	2012	2013	2014	2015
Coal	13,808	8,680	3,859	3,858	3,856	2,690	1,877
Oil	580	458	204	203	203	142	99
Gas	1	174	77	77	77	54	38
Misc. Internal Combustion	45	57	25	25	25	18	12
Other	NA	71	31	31	31	22	15
Total	**14,433**	**9,439**	**4,196**	**4,195**	**4,194**	**2,925**	**2,041**

Note: Totals may not sum due to independent rounding.
Source: Data taken from EPA (2016) and disaggregated based on EPA (2003).

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
Petroleum Systems	CH_4
Natural Gas Systems	CH_4
Incineration of Waste	CO_2, CH_4, N_2O, NO_x, CO, NMVOC
Industrial Processes and Product Use	
Titanium Dioxide Production	CO_2
Aluminum Production	CO_2, CF_4, C_2F_6
Iron and Steel Production & Metallurgical Coke Production	CO_2, CH_4
Ferroalloy Production	CO_2, CH_4
Ammonia Production	CO_2
Urea Consumption for Non-Agricultural Purposes	CO_2
Cement Production	CO_2
Lime Production	CO_2
Other Process Uses of Carbonates	CO_2
Soda Ash Production and Consumption	CO_2
Glass Production	CO_2
Carbon Dioxide Consumption	CO_2
Phosphoric Acid Production	CO_2
Petrochemical Production	CO_2, CH_4
Silicon Carbide Production and Consumption	CO_2, CH_4
Lead Production	CO_2
Zinc Production	CO_2
Adipic Acid Production	N_2O
Nitric Acid Production	N_2O
N_2O from Product Uses	N_2O
Substitution of Ozone Depleting Substances	HFCs, PFCs[a]
HCFC-22 Production	HFC-23
Semiconductor Manufacture	N_2O, HFCs, PFCs[b], SF_6, NF_3
Electrical Transmission and Distributing	SF_6
Magnesium Production and Processing	CO_2, HFCs, SF_6
Agriculture	
Enteric Fermentation	CH_4
Manure Management	CH_4, N_2O
Rice Cultivation	CH_4
Liming	CO_2
Urea Fertilization	CO_2
Field Burning of Agricultural Residues	CH_4, N_2O, NO_x, CO
Agricultural Soil Management	N_2O
Land Use, Land-Use Change, and Forestry[c]	
Forest Land Remaining Forest Land	CO_2, CH_4, N_2O, NO_x, CO
Land Converted to Forest Land	CO_2
Cropland Remaining Cropland	CO_2
Land Converted to Cropland	CO_2
Grassland Remaining Grassland	CO_2, CH_4, N_2O, NO_x, CO
Land Converted to Grassland	CO_2
Wetlands Remaining Wetlands	CO_2, CH_4, N_2O
Land Converted to Wetlands	CO_2, CH_4
Settlements Remaining Settlements	CO_2, N_2O

Land Converted to Settlements	CO_2
Waste	
Landfills	CH_4, NO_x, CO, NMVOC
Wastewater Treatment	CH_4, N_2O, NO_x, CO, NMVOC
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.

[c] The LULUCF Sector includes emissions (i.e., sources) of greenhouse gases to the atmosphere and removals of CO_2 (i.e., sinks or negative emissions) from the atmosphere. The term "flux" is used to describe the net emissions of greenhouse gases accounting for both the emissions of CO_2 to and the removals of CO_2 from the atmosphere. Removal of CO_2 from the atmosphere is also referred to as "carbon sequestration."

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-277 provides a guide for determining the magnitude of metric units.

Table A-277: 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

Degrees Celsius= (Degrees Fahrenheit – 32)*5/9
Degrees Kelvin = Degrees Celsius + 273.15

Density Conversions[130]

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 degrees 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-278 can be used as default factors, if local data are not available. See Appendix A of EIA's *Monthly Energy Review December 2016* (EIA 2016) for more detailed information on the energy content of various fuels.

[130] Reference: EIA (2007)

Table A-278: 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	23.367
Natural Gas (Btu/Cubic foot)	**1,037**
Liquid Fuels (Million Btu/Barrel)	
Motor gasoline	5.060
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, *Monthly Energy Review December 2016* (EIA 2016). For coal ranks, *State Energy Data Report 1992* (EIA 1993). All values are given in higher heating values (gross calorific values).

6.6. Abbreviations

AAPFCO	American Association of Plant Food Control Officials
ABS	Acrylonitrile butadiene styrene
AC	Air conditioner
ACC	American Chemistry Council
AEDT	FAA Aviation Environmental Design Tool
AEO	Annual Energy Outlook
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
ALU	Agriculture and Land Use National Greenhouse Gas Inventory
ANGA	American Natural Gas Alliance
ANL	Argonne National Laboratory
APC	American Plastics Council
API	American Petroleum Institute
APTA	American Public Transportation Association
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
ARI	Advanced Resources International
ARMS	Agricultural Resource Management Surveys
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
BLM	Bureau of Land Management
BoC	Bureau of Census
BOD	Biological oxygen demand
BOD5	Biochemical oxygen demand over a 5-day period
BOEM	Bureau of Ocean Energy Management
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
BOF	Basic oxygen furnace
BRS	Biennial Reporting System
BTS	Bureau of Transportation Statistics, U.S. Department of Transportation
Btu	British thermal unit
C	Carbon
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
C-CAP	Coastal Change Analysis Program
CDAP	Chemical Data Access Tool
CEAP	USDA-NRCS Conservation Effects Assessment Program
CEFM	Cattle Enteric Fermentation Model
CEMS	Continuous emission monitoring system
CFC	Chlorofluorocarbon
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CH_4	Methane
CHP	Combined heat and power
CIGRE	International Council on Large Electric Systems
CKD	Cement kiln dust
CLE	Crown Light Exposure

CMA	Chemical Manufacturer's Association
CMM	Coal mine methane
CMOP	Coalbed Methane Outreach Program
CMR	Chemical Market Reporter
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
COGCC	Colorado Oil and Gas Conservation Commission
CRF	Common Reporting Format
CRM	Component ratio method
CRP	Conservation Reserve Program
CSRA	Carbon Sequestration Rural Appraisals
CTIC	Conservation Technology Information Center
CVD	Chemical vapor deposition
CWNS	Clean Watershed Needs Survey
d.b.h	Diameter breast height
DE	Digestible energy
DESC	Defense Energy Support Center-DoD's defense logistics agency
DFAMS	Defense Fuels Automated Management System
DHS	Department of Homeland Security
DM	Dry matter
DOC	Degradable organic carbon
DOC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOT	U.S. Department of Transportation
DRI	Direct Reduced Iron
EAF	Electric arc furnace
EDB	Aircraft Engine Emissions Databank
EDF	Environmental Defense Fund
EER	Energy economy ratio
EF	Emission factor
EFMA	European Fertilizer Manufacturers Association
EJ	Exajoule
EGR	Exhaust gas recirculation
EGU	Electric generating unit
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
ETMS	Enhanced Traffic Management System
EV	Electric vehicle
EVI	Enhanced Vegetation Index
FAA	Federal Aviation Administration
FAO	Food and Agricultural Organization
FAOSTAT	Food and Agricultural Organization database
FCCC	Framework Convention on Climate Change
FEB	Fiber Economics Bureau
FERC	Federal Energy Regulatory Commission
FGD	Flue gas desulfurization
FHWA	Federal Highway Administration
FIA	Forest Inventory and Analysis
FIADB	Forest Inventory and Analysis Database
FIPR	Florida Institute of Phosphate Research

FQSV	First-quarter of silicon volume
FSA	Farm Service Agency
FTP	Federal Test Procedure
g	Gram
GCV	Gross calorific value
GDP	Gross domestic product
GHG	Greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GJ	Gigajoule
GOADS	Gulf Offshore Activity Data System
GPG	Good Practice Guidance
GRI	Gas Research Institute
GSAM	Gas Systems Analysis Model
GTI	Gas Technology Institute
GWP	Global warming potential
ha	Hectare
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
HMIWI	Hospital/medical/infectious waste incinerator
HTF	Heat Transfer Fluid
HTS	Harmonized Tariff Schedule
HWP	Harvested wood product
IBF	International bunker fuels
IC	Integrated Circuit
ICAO	International Civil Aviation Organization
ICE	Internal combustion engine
IDB	Integrated Database
IEA	International Energy Agency
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
IPPU	Industrial Processes and Product Use
ITC	U.S. International Trade Commission
ITRS	International Technology Roadmap for Semiconductors
JWR	Jim Walters Resources
KCA	Key category analysis
kg	Kilogram
kt	Kiloton
kWh	Kilowatt hour
LDDT	Light duty diesel truck
LDDV	Light duty diesel vehicle
LDGT	Light duty gas truck
LDGV	Light duty gas vehicle
LDPE	Low density polyethylene
LDT	Light-duty truck
LDV	Light-duty vehicle

LEV	Low emission vehicles
LFG	Landfill gas
LFGTE	Landfill gas-to-energy
LHV	Lower Heating Value
LKD	Lime kiln dust
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
MARPOL	International Convention for the Prevention of Pollution from Ships
MC	Motorcycle
MCF	Methane conversion factor
MCL	Maximum Contaminant Levels
MCFD	Thousand cubic feet per day
MDI	Metered dose inhalers
MECS	EIA Manufacturer's Energy Consumption Survey
MEM	Micro-electromechanical systems
MER	Monthly Energy Review
MGO	Marine gas oil
MJ	Megajoule
MLRA	Major Land Resource Area
mm	Millimeter
MMBtu	Million British thermal units
MMCF	Million cubic feet
MMCFD	Million cubic feet per day
MMS	Minerals Management Service
MMT	Million Metric Tons
MMTCE	Million metric tons carbon equivalent
MMT CO_2 Eq.	Million metric tons carbon dioxide equivalent
MODIS	Moderate Resolution Imaging Spectroradiometer
MoU	Memorandum of Understanding
MOVES	U.S. EPA's Motor Vehicle Emission Simulator model
MPG	Miles per gallon
MRLC	Multi-Resolution Land Characteristics Consortium
MRV	Monitoring, reporting, and verification
MSHA	Mine Safety and Health Administration
MSW	Municipal solid waste
MT	Metric ton
MTBE	Methyl Tertiary Butyl Ether
MTBS	Monitoring Trends in Burn Severity
MVAC	Motor vehicle air conditioning
MY	Model year
N_2O	Nitrous oxide
NA	Not available
NACWA	National Association of Clean Water Agencies
NAHMS	National Animal Health Monitoring System
NAICS	North American Industry Classification System
NAPAP	National Acid Precipitation and Assessment Program
NARR	North American Regional Reanalysis Product
NASA	National Aeronautics and Space Administration
NASF	National Association of State Foresters
NASS	USDA's National Agriculture Statistics Service
NC	No change
NCASI	National Council of Air and Stream Improvement
NCV	Net calorific value

NE	Not estimated
NEI	National Emissions Inventory
NEMA	National Electrical Manufacturers Association
NEMS	National Energy Modeling System
NESHAP	National Emission Standards for Hazardous Air Pollutants
NEU	Non-Energy Use
NEV	Neighborhood Electric Vehicle
NF_3	Nitrogen trifluoride
NGHGI	National Greenhouse Gas Inventory
NGL	Natural gas liquids
NIR	National Inventory Report
NLA	National Lime Association
NLCD	National Land Cover Dataset
NMOC	Non-methane organic compounds
NMVOC	Non-methane volatile organic compound
NO	Nitric oxide
NO	Not occuring
NO_2	Nitrogen Dioxide
NOx	Nitrogen oxides
NOAA	National Oceanic and Atmospheric Administration
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
NSPS	New source performance standards
NWS	National Weather Service
OAG	Official Airline Guide
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
OGJ	Oil & Gas Journal
OH	Hydroxyl radical
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
PET	Potential evapotranspiration
PEVM	PFC Emissions Vintage Model
PFC	Perfluorocarbon
PFPE	Perfluoropolyether
PHMSA	Pipeline and Hazardous Materials Safety Administration
PI	Productivity index
POTW	Publicly Owned Treatment Works
ppbv	Parts per billion (10^9) by volume
ppm	Parts per million
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
PV	Photovoltaic
QA/QC	Quality Assurance and Quality Control
QBtu	Quadrillion Btu
R&D	Research and Development
RECs	Reduced Emissions Completions
RCRA	Resource Conservation and Recovery Act
RMA	Rubber Manufacturers' Association
RPA	Resources Planning Act
RTO	Regression-through-the-origin
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
SCSE	South central and southeastern coastal
SEC	Securities and Exchange Commission
SEMI	Semiconductor Equipment and Materials Industry
SF_6	Sulfur hexafluoride
SICAS	Semiconductor International Capacity Statistics
SNAP	Significant New Alternative Policy Program
SNG	Synthetic natural gas
SO_2	Sulfur dioxide
SOC	Soil Organic Carbon
SOG	State of Garbage survey
SOHIO	Standard Oil Company of Ohio
SSURGO	Soil Survey Geographic Database
STMC	Scrap Tire Management Council
SULEV	Super Ultra Low Emissions Vehicle
SWANA	Solid Waste Association of North America
SWDS	Solid waste disposal sites
TA	Treated anaerobically (wastewater)
TAM	Typical animal mass
TAME	Tertiary amyl methyl ether
TAR	IPCC Third Assessment Report
TBtu	Trillion Btu
TDN	Total digestible nutrients
TEDB	Transportation Energy Data Book
TFI	The Fertilizer Institute
TIGER	Topologically Integrated Geographic Encoding and Referencing survey
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
UAN	Urea ammonium nitrate
UDI	Utility Data Institute
UFORE	U.S. Forest Service's Urban Forest Effects model
UG	Underground (coal mining)
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
USAA	U.S. Aluminum Association
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
VAM	Ventilation air methane
VKT	Vehicle kilometers traveled
VMT	Vehicle miles traveled
VOCs	Volatile organic compounds
VS	Volatile solids
WERF	Water Environment Research Federation
WFF	World Fab Forecast (previously WFW, World Fab Watch)
WGC	World Gas Conference
WIP	Waste in place
WMO	World Meteorological Organization
WMS	Waste management systems
WTE	Waste-to-energy
WW	Wastewater
WWTP	Wastewater treatment plant
ZEVs	Zero emissions vehicles

6.7. Chemical Formulas

Table A-279: 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
MgO	Magnesium oxide
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.

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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 *2006 IPCC 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 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 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

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. As noted, for all source categories, the inventory emission estimates include "Uncertainty and Time Series Consistency" that consider both quantitative and qualitative assessments of uncertainty, considering factors consistent with those noted in Volume 1, Chapter 3 of the IPCC (i.e. completeness of data, representativeness of data and models, sampling errors, measurement errors, etc.). 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 encompasses several causes such as lack of completeness, lack of data or representative data, sampling error, random or systematic measurement error, misreporting or misclassification, or missing data. 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 through 2008 National GHG Inventory* for the first time, and three other source categories (International Bunker Fuels, Energy Sources of Indirect Greenhouse Gas Emissions, and Wood Biomass and Ethanol Consumption) whose emissions are not included in the Inventory totals.

7.2. Methodology and Results

The United States has developed a quality assurance and quality control (QA/QC) and uncertainty management plan (EPA 2002). 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). For the 1990 through 2015 Inventory, EPA has used the uncertainty management plan as well as the methodology presented in the *2006 IPCC Guidelines.*

The *2006 IPCC Guidelines* recommends two methods—Approach 1 and Approach 2—for developing quantitative estimates of uncertainty in the inventory estimate of individual source categories and the overall Inventory. Of these, the Approach 2 method is both more flexible and reliable than Approach 1; both approaches 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 Approach 2. In following the UNFCCC requirement under Article 4.1, emissions from International Bunker Fuels, Energy Sources of Indirect Greenhouse Gas Emissions, and Wood Biomass and Ethanol Consumption 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.[131] Emissions from Biomass and Ethanol Consumption are accounted for implicitly in the Land Use, Land-Use Change and Forestry (LULUCF) chapter through the calculation of changes in carbon stocks. The Energy sector does provide an estimate of CO_2 emissions from Biomass and Ethanol Consumption provided as a memo item for informational purposes consistent with the UNFCCC reporting requirements.

Approach 1 and Approach 2 Methods

The Approach 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 Approach 1 method 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 Approach 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 Approach 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 Approach 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 Approach 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.

Characterization of Uncertainty in Input Variables

Both Approach 1 and Approach 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.

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-280 summarizes results based on assessments of source category-level uncertainty. The table presents base year (1990 or 1995) and current year (2015) 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

[131] 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.

the total 2015 emissions estimated for that source category. Source category trend uncertainty is described subsequently in this Appendix.

Table A-280: Summary Results of Source Category Uncertainty Analyses – TO BE UPDATED FOR FINAL INVENTORY REPORT

Source Category	Base Year Emissions[h,a]	2014 Emissions[a]	2014 Uncertainty[b]	
	MMT CO_2 Eq.	MMT CO_2 Eq.	Low	High
CO_2	**5,114.7**	**5,555.6**	**-2%**	**5%**
Fossil Fuel Combustion[c]	4,740.3	5,207.8	-2%	5%
Non-Energy Use of Fuels	118.1	114.3	-25%	42%
Iron and Steel Production & Metallurgical Coke Production	99.7	55.4	-15%	15%
Natural Gas Systems	37.7	42.4	-19%	30%
Cement Production	33.3	38.8	-6%	6%
Petrochemical Production	21.6	26.5	-5%	5%
Lime Production	11.7	14.1	-3%	3%
Other Process Uses of Carbonates	4.9	12.1	-12%	15%
Ammonia Production	13.0	9.4	-8%	8%
Incineration of Waste	8.0	9.4	-10%	14%
Carbon Dioxide Consumption	1.5	4.5	-12%	13%
Urea Consumption for Non-Agricultural Purposes	3.8	4.0	-12%	12%
Petroleum Systems	3.6	3.6	-24%	149%
Aluminum Production	6.8	2.8	-2%	2%
Soda Ash Production and Consumption	2.8	2.8	-7%	6%
Ferroalloy Production	2.2	1.9	-12%	12%
Titanium Dioxide Production	1.2	1.8	-12%	13%
Glass Production	1.5	1.3	-4%	5%
Phosphoric Acid Production	1.5	1.1	-19%	20%
Zinc Production	0.6	1.0	-19%	21%
Lead Production	0.5	0.5	-15%	16%
Silicon Carbide Production and Consumption	0.4	0.2	-9%	9%
Magnesium Production and Processing	+	+	-5%	5%
Wood Biomass and Ethanol Consumption[d]	*219.4*	*293.7*	*NE*	*NE*
International Bunker Fuels[e]	*103.5*	*103.2*	*NE*	*NE*
CH_4	**773.9**	**730.8**	**-8%**	**26%**
Natural Gas Systems	206.8	176.1	-19%	30%
Enteric Fermentation	164.2	164.3	11%	18%
Landfills	179.6	148.0	-30%	61%
Petroleum Systems	38.7	68.1	-24%	149
Coal Mining	96.5	67.6	-12%	15%
Manure Management	37.2	61.2	-18%	20%
Wastewater Treatment	15.7	14.7	-39%	2%
Rice Cultivation	13.1	11.9	-17%	17%
Stationary Combustion	8.5	8.1	-41%	155
Abandoned Underground Coal Mines	7.2	6.3	-18%	24%
Composting	0.4	2.1	-50%	50%
Mobile Combustion	5.6	2.0	-12%	18%
Field Burning of Agricultural Residues	0.2	0.3	-40%	40%
Petrochemical Production	0.2	0.1	-55%	45%
Ferroalloy Production	+	+	-12%	12%
Silicon Carbide Production and Consumption	+	+	-9%	10%
Iron and Steel Production & Metallurgical Coke Production	+	+	-19%	19%
Incineration of Waste	+	+	NE	NE
International Bunker Fuels[e]	*0.2*	*0.1*	*NE*	*NE*
N_2O	**406.2**	**403.5**	**-20%**	**11%**
Agricultural Soil Management	303.3	318.4	-18%	47%
Stationary Combustion	11.9	23.4	-24%	46%

Manure Management	14.0	17.5	-16%	24%
Mobile Combustion	41.2	16.3	-4%	27%
Nitric Acid Production	12.1	10.9	-5%	5%
Adipic Acid Production	15.2	5.4	-4%	4%
Wastewater Treatment	3.4	4.8	-76%	108%
N_2O from Product Uses	4.2	4.2	-24%	24%
Composting	0.3	1.8	-50%	50%
Incineration of Waste	0.5	0.3	-53%	163%
Semiconductor Manufacture	+	0.2	-12%	12%
Field Burning of Agricultural Residues	0.1	0.1	-29%	29%
International Bunker Fuels[e]	*1.1*	*1.0*	*NE*	*NE*
HFCs, PFCs, SF_6, and NF_3	**132.6**	**175.3**	**-4%**	**6%**
Substitution of Ozone Depleting Substances[f]	31.0	156.4	-1%	10%
Electrical Transmission and Distribution	25.4	5.6	-17%	23%
HCFC-22 Production	46.1	5.0	-7%	10%
Semiconductor Manufacture	3.6	4.5	-6%	6%
Aluminum Production	21.5	2.5	-6%	6%
Magnesium Production	5.2	1.2	-12%	15%
Total Emissions[g]	**6,427.4**	**6,865.2**	**-2%**	**5%**
LULUCF Emissions[i]	**15.0**	**24.6**	**-48%**	**58%**
LULUCF Total Net Flux[j]	**(753.0)**	**(787.0)**	**-18%**	**34%**
LULUCF Sector Total[k]	**(738.0)**	**(762.5)**	**-18%**	**35%**
Net Emissions (Sources and Sinks)[g]	**5,689.5**	**6,102.7**	**-4%**	**6%**

+ Does not exceed 0.05 MMT CO_2 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 for the current Inventory. Thus the totals reported for 2013 in this table exclude approximately 5.7 MMT 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. 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 2.5th percentile and the upper bound corresponding to 97.5th percentile.

[c] This source category's inventory estimates exclude CO_2 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] Emissions from Wood Biomass and Ethanol Consumption are not included specifically in summing energy sector totals.

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

[f] This source category's estimate for 2013 excludes 5.3 MMT of CO_2 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 and Product Use chapter of the Inventory.

[g] Totals exclude emissions for which uncertainty was not quantified.

[h] Base Year is 1990 for all sources except Substitution of Ozone Depleting Substances, for which the United States has chosen 1995.

[i] LULUCF emissions include the CO_2, CH_4, and N_2O emissions reported for Non-CO_2 Emissions from Forest Fires, N_2O Fluxes from Forest Soils, CO_2 Emissions from Agricultural Liming, CO_2 Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N_2O Fluxes from Settlement Soils.

[j] Net CO_2 flux is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements*, and *Other*.

[k] The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO_2 (i.e., sinks or negative emissions) from the atmosphere.

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

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) is presented without LULUCF. Net emissions is presented with LULUCF.

Overall (Aggregate) Inventory Level Uncertainty Estimates

The overall level uncertainty estimate for the U.S. Greenhouse Gas Emissions Inventory was developed using the IPCC Approach 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 Composting and parts of Agricultural Soil Management source categories, Approach 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), Approach 2 uncertainty results were used in the overall uncertainty estimation.

The overall uncertainty model results indicate that the 2014 U.S. greenhouse gas emissions are estimated to be within the range of approximately 6,765.4 to 7,223.9 MMT CO_2 Eq., reflecting a relative 95 percent confidence interval uncertainty range of -2 percent to 5 percent with respect to the total U.S. greenhouse gas emission estimate of approximately 6,865.2 MMT CO_2 Eq. The uncertainty interval associated with total CO_2 emissions, which constitute about 81 percent of the total U.S. greenhouse gas emissions in 2014, ranges from -2 percent to 5 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 -8 percent to 26 percent, uncertainty associated with the total inventory N_2O emission estimate ranges from -20 percent to 11 percent, and uncertainty associated with high GWP gas emissions ranges from -4 percent to 6 percent.

A summary of the overall quantitative uncertainty estimates is shown below.

Table A-281: Quantitative Uncertainty Assessment of Overall National Inventory Emissions (MMT CO_2 Eq. and Percent)

Gas	2014 Emission Estimate[a] (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[b] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[b] (%)		Mean[c] (MMT CO_2 Eq.)	Standard Deviation[c] (MMT CO_2 Eq.)
		Lower Bound[d]	Upper Bound[d]	Lower Bound	Upper Bound		
CO_2	5,555.6	5,459.4	5,830.0	-2%	5%	5,643.8	94.9
CH_4[e]	730.8	674.3	917.5	-8%	26%	785.0	60.2
N_2O[e]	403.5	322.5	447.9	-20%	11%	378.6	32.2
PFC, HFC, SF_6, and NF_3[e]	175.3	172.3	190.9	-4%	6%	181.6	4.7
Total Emissions	**6,865.2**	**6,765.4**	**7,223.9**	**-2%**	**5%**	**6,989.0**	**117.5**
LULUCF Emissions[f]	**24.6**	**12.8**	**38.9**	**-48%**	**58%**	**23.0**	**6.8**
LULUCF Total Net Flux[g]	**(787.0)**	**(1,051.4)**	**(647.8)**	**-18%**	**34%**	**(847.2)**	**102.9**
LULUCF Sector Total[h]	**(762.5)**	**(1,029.8)**	**(622.5)**	**-18%**	**35%**	**(824.2)**	**103.0**
Net Emissions (Sources and Sinks)	**6,102.7**	**5,861.6**	**6,477.6**	**-4%**	**6%**	**6,164.8**	**156.7**

[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 5.3 MMT CO_2 Eq. of emissions for which quantitative uncertainty was not assessed. Hence, these emission estimates do not match the final total U.S. greenhouse gas emission estimates presented in this Inventory.

[b] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

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

[d] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

[e] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the inventory emission calculations for 2014.

[f] LULUCF emissions include the CO_2, CH_4, and N_2O emissions reported for Non-CO_2 Emissions from Forest Fires, N_2O Fluxes from Forest Soils, CO_2 Emissions from Agricultural Liming, CO_2 Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N_2O Fluxes from Settlement Soils.

[g] Net CO_2 flux is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements*, and *Other*.

[h] The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO_2 (i.e., sinks or negative emissions) from the atmosphere.

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

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) is presented without LULUCF. Net emissions is presented with LULUCF

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 *2006 IPCC Guidelines* defines trend as the difference in emissions between the base year (i.e., 1990) and the current year (i.e., 2014) 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 Approach 1 method, 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., 2014) 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 Approach 2 method, the trend uncertainty is estimated using the 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., 2014) 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 trend uncertainty estimates present the range of likely change from base year to 2014, and are shown in Table A-282.

Table A-282: Quantitative Assessment of Trend Uncertainty (MMT CO_2 Eq. and Percent)

Gas/Source	Base Year Emissions[i,a]	2014 Emissions[a]	Emissions Trend[a]	Trend Range[a,b]	
	(MMT CO_2 Eq.)		(%)	(%)	
				Lower Bound	Upper Bound
CO_2	**5,114.7**	**5,555.6**	**9%**	**4%**	**14%**
Fossil Fuel Combustion[c]	4,740.3	5,207.8	10%	5%	15%
Non-Energy Use of Fuels	118.1	114.3	-3%	-41%	59%
Iron and Steel Production & Metallurgical Coke Production	99.7	55.4	-44%	-55%	-32%
Natural Gas Systems	37.7	42.4	12%	-21%	57%
Cement Production	33.3	38.8	16%	7%	27%
Petrochemical Production	21.6	26.5	23%	15%	31%
Lime Production	11.7	14.1	21%	16%	25%
Other Process Uses of Carbonates	4.9	12.1	-146%	104%	197%
Ammonia Production	13.0	9.4	-28%	-36%	-19%
Incineration of Waste	8.0	9.4	18%	0%	40%
Carbon Dioxide Consumption	1.5	4.5	204%	154%	264%
Urea Consumption for Non-Agricultural Purposes	3.8	4.0	6%	-10%	25%
Petroleum Systems	3.6	3.6	0%	-55%	134%
Aluminum Production	6.8	2.8	-59%	-60%	-57%
Soda Ash Production and Consumption	2.8	2.8	0%	-9%	10%
Ferroalloy Production	2.2	1.9	-11%	-25%	6%
Titanium Dioxide Production	1.2	1.8	47%	22%	76%
Glass Production	1.5	1.3	-13%	-18%	-7%
Phosphoric Acid Production	1.5	1.1	-28%	-46%	-5%
Zinc Production	0.6	1.0	51%	15%	101%
Lead Production	0.5	0.5	0%	-19%	25%
Silicon Carbide Production and Consumption	0.4	0.2	-54%	-60%	-47%
Magnesium Production and Processing	0.0	+	NA	NA	NA
Wood Biomass and Ethanol Consumption[e]	*219.4*	*293.7*	*2%*	*NE*	*NE*
International Bunker Fuels[f]	*103.5*	*103.2*	*0%*	*NE*	*NE*

CH_4	**773.9**	**730.8**	**-6%**	**-23%**	**17%**
Natural Gas Systems	206.8	176.1	-15%	-40%	20%
Enteric Fermentation	164.2	164.3	0%	-18%	23%
Landfills	179.6	148.0	-18%	-66%	105%
Petroleum Systems	38.7	68.1	76%	-23%	311%
Coal Mining	96.5	67.6	-30%	-46%	-17%
Manure Management	37.2	61.2	65%	12%	131%
Wastewater Treatment	15.7	14.7	-6%	-69%	4%
Rice Cultivation	13.1	11.9	-9%	-66%	137%
Stationary Combustion	8.5	8.1	-5%	-70%	200%
Abandoned Underground Coal Mines	7.2	6.3	-12%	-44%	26%
Composting	0.4	2.1	439%	136%	1118%
Mobile Combustion	5.6	2.0	-64%	-71%	-55%
Field Burning of Agricultural Residues	0.2	0.3	18%	-37%	123%
Petrochemical Production	0.2	0.1	-43%	-76%	38%
Ferroalloy Production	+	+	-21%	-33%	-6%
Silicon Carbide Production and Consumption	+	+	-67%	-71%	-62%
Iron and Steel Production & Metallurgical Coke Production	+	+	-44%	-67%	-42%
Incineration of Waste	+	+	NE	NE	NE
International Bunker Fuels[f]	*0.2*	*0.1*	*-52%*	*NE*	*NE*
N_2O	**406.2**	**403.5**	**-1%**	**-31%**	**44%**
Agricultural Soil Management	303.3	318.4	5%	-35%	69%
Stationary Combustion	11.9	23.4	96%	22%	213%
Manure Management	14.0	17.5	25%	-6%	64%
Mobile Combustion	41.2	16.3	-60%	-68%	-52%
Nitric Acid Production	12.1	10.9	-10%	-16%	-2%
Adipic Acid Production	15.2	5.4	-64%	-66%	-62%
Wastewater Treatment	3.4	4.8	44%	-70%	511%
N_2O from Product Uses	4.2	4.2	0%	-32%	46%
Composting	0.3	1.8	439%	135%	1111%
Incineration of Waste	0.5	0.3	-32%	-81%	143%
Field Burning of Agricultural Residues	0.1	0.1	23%	-21%	94%
International Bunker Fuels[f]	*1.1*	*1.0*	*5%*	*NE*	*NE*
HFCs, PFCs, SF_6, and NF_3	**132.6**	**175.3**	**32%**	**26%**	**45%**
Substitution of Ozone Depleting Substances[g]	31.0	156.4	405%	366%	447%
Electrical Transmission and Distribution	25.4	5.6	-78%	-83%	-71%
HCFC-22 Production	46.1	5.0	-89%	-90%	-88%
Semiconductor Manufacture	3.6	4.5	27%	17%	38%
Aluminum Production	21.5	2.5	-88%	-89%	-87%
Magnesium Production	5.2	1.2	-80%	-83%	-77%
Total Emissions[h]	**6,427.4**	**6,865.2**	**7%**	**2%**	**12%**
LULUCF Emissions[i]	**15.0**	**24.6**	**63%**	**-18%**	**229%**
LULUCF Total Net Flux[j]	**(753.0)**	**(787.0)**	**5%**	**-25%**	**46%**
LULUCF Sector Total[k]	**(738.0)**	**(762.5)**	**3%**	**-27%**	**45%**
Net Emissions (Sources and Sinks)	**5,689.5**	**6,102.7**	**7%**	**0%**	**16%**

+ Does not exceed 0.05 MMT CO_2 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 for the current Inventory. Thus the totals reported for 2014 in this table exclude approximately 5.3 MMT 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. All uncertainty estimates correspond only to the totals reported in this table.

[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 CO_2 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 Wood Biomass and Ethanol Consumption are not included specifically in summing energy sector totals.

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

[g] This source category's estimate for 2014 excludes 5.3 MMT of CO_2 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 and Product Use chapter of the Inventory.

[h] Totals exclude emissions for which uncertainty was not quantified.

[l] Base Year is 1990 for all sources except Substitution of Ozone Depleting Substances, for which the United States has chosen 1995.
[i] LULUCF emissions include the CO_2, CH_4, and N_2O emissions reported for Non-CO_2 Emissions from Forest Fires, N_2O Fluxes from Forest Soils, CO_2 Emissions from Agricultural Liming, CO_2 Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N_2O Fluxes from Settlement Soils.
[j] Net CO_2 flux is the net C stock change from the following categories*: Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements*, and *Other*.
[k] The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO_2 (i.e., sinks or negative emissions) from the atmosphere.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.
Notes: Total emissions (excluding emissions for which uncertainty was not quantified) is presented without LULUCF. Net emissions is presented with LULUCF

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 CH_4 from Incineration of Waste, and the International Bunker Fuels, Energy Sources of Indirect Greenhouse Gas Emissions, and Wood Biomass and Ethanol Consumption source categories, which are not included in the energy sector totals. Emissions from Wood Biomass and Ethanol Consumption however are accounted for implicitly in the Land Use, Land-Use Change and Forestry (LULUCF) chapter through the calculation of changes in carbon stocks. The Energy sector does provide an estimate of CO_2 emissions from Wood Biomass and Ethanol Consumption provided as a memo item for informational purposes.

Specific areas that require further research and can reduce uncertainties 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. .

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.
- *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–TO BE UPDATED FOR FINAL INVENTORY REPORT

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 2014 Inventory estimates for the 95 percent confidence interval, unless otherwise specified.

Energy

The uncertainty analysis descriptions in this section correspond to source categories included in the Energy chapter of the Inventory.

CO_2 from Fossil Fuel Combustion

For estimates of CO_2 from fossil fuel combustion, there are uncertainties in the consumption data, carbon content of fuels and products, and carbon oxidation efficiencies.

Although statistics of total fossil fuel and other energy consumption are relatively accurate, the allocation of this consumption to individual end-use sectors (i.e., residential, commercial, industrial, and transportation) is less certain. For this uncertainty estimation, the inventory estimation model for CO_2 from fossil fuel combustion was integrated with the relevant variables from the inventory estimation model for International Bunker Fuels, to realistically characterize the interaction (or endogenous correlation) between the variables of these two models.

In developing the uncertainty estimation model, uniform distributions were assumed for all activity-related input variables and emission factors, based on the SAIC/EIA (2001) report.[132] Triangular distributions were assigned for the oxidization factors (or combustion efficiencies). The uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001) and on conversations with various agency personnel.[133]

The uncertainty ranges for the activity-related input variables were typically asymmetric around their inventory estimates; the uncertainty ranges for the emissions factors were symmetric. Bias (or systematic uncertainties) associated with these variables accounted for much of the uncertainties associated with these variables (SAIC/EIA 2001).[134] For purposes of this uncertainty analysis, each input variable was simulated 10,000 times through Monte Carlo sampling.

CH_4 and N_2O from Stationary Combustion

The uncertainty estimation model for this source category was developed by integrating the CH_4 and N_2O stationary source inventory estimation models with the model for CO_2 from fossil fuel combustion to realistically characterize the interaction (or endogenous correlation) between the variables of these three models. About 55 input variables were simulated for the uncertainty analysis of this source category (about 20 from the CO_2 emissions from fossil fuel combustion inventory estimation model and about 35 from the stationary source inventory models).

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

[133] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

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

In developing the uncertainty estimation model, uniform distribution was assumed for all activity-related input variables and N_2O emission factors, based on the SAIC/EIA (2001) report.[135] For these variables, the uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[136] However, the CH_4 emission factors differ from those used by EIA. Since these factors were obtained from IPCC/UNEP/OECD/IEA (1997), uncertainty ranges were assigned based on IPCC default uncertainty estimates (IPCC 2006).

CH_4 and N_2O from Mobile Combustion

The uncertainty analysis was performed on 2014 estimates of CH_4 and N_2O emissions, incorporating probability distribution functions associated with the major input variables. For the purposes of this analysis, the uncertainty was modeled for the following four major sets of input variables: (1) VMT data, by on-road vehicle and fuel type, (2) emission factor data, by on-road vehicle, fuel, and control technology type, (3) fuel consumption, data, by non-road vehicle and equipment type, and (4) emission factor data, by non-road vehicle and equipment type.

Carbon Emitted from Non-Energy Uses of Fossil Fuels

An uncertainty analysis was conducted to quantify the uncertainty surrounding the estimates of emissions and storage factors from non-energy uses.

The non-energy use analysis is based on U.S.-specific storage factors for (1) feedstock materials (natural gas, LPG, pentanes plus, naphthas, other oils, still gas, special naphthas, and other industrial coal), (2) asphalt, (3) lubricants, and (4) waxes. To characterize uncertainty, five separate analyses were conducted, corresponding to each of the five categories. In all cases, statistical analyses or expert judgments of uncertainty were not available directly from the information sources for all the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge.

Incineration of Waste

The uncertainties in the waste incineration emission estimates arise from both the assumptions applied to the data and from the quality of the data. Key factors include MSW incineration rate; fraction oxidized; missing data on waste composition; average C content of waste components; assumptions on the synthetic/biogenic C ratio; and combustion conditions affecting N_2O emissions. The highest levels of uncertainty surround the variables that are based on assumptions (e.g., percent of clothing and footwear composed of synthetic rubber); the lowest levels of uncertainty surround variables that were determined by quantitative measurements (e.g., combustion efficiency, C content of C black).

Coal Mining

The uncertainty associated with emission estimates from underground ventilation systems can be attributed to the fact that the actual measurement data from MSHA or EPA's Greenhouse Gas Reporting Program (GHGRP) used were not continuous but rather an average of quarterly instantaneous readings. Additionally, the measurement equipment used can be expected to have resulted in an average of 10 percent overestimation of annual CH_4 emissions (Mutmansky & Wang 2000). GHGRP data was used for a number of the mines beginning in 2013, however, the equipment uncertainty is applied to both MSHA and GHGRP data.

Estimates of CH_4 recovered by degasification systems are relatively certain for utilized CH_4 because of the availability of gas sales information. Many of the recovery estimates use data on wells within 100 feet of a mined area. However, uncertainty exists concerning the radius of influence of each well. The number of wells counted, and thus the avoided emissions, may vary if the drainage area is found to be larger or smaller than estimated.

Abandoned Underground Coal Mines

The parameters for which values must be estimated for each mine in order to predict its decline curve are: 1) the coal's adsorption isotherm; 2) CH_4 flow capacity as expressed by permeability; and 3) pressure at abandonment. Because these parameters are not available for each mine, a methodological approach to estimating emissions was used that generates a probability distribution of potential outcomes based on the most likely value and the probable range of values for each

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

[136] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

parameter. The range of values is not meant to capture the extreme values, but rather values that represent the highest and lowest quartile of the cumulative probability density function of each parameter. Once the low, mid, and high values are selected, they are applied to a probability density function.

Petroleum Systems

The uncertainty analysis conducted for the 1990 through 2009 Inventory has not yet been updated for the 1990 through 2014 Inventory year; instead, the uncertainty percentage ranges calculated previously were applied to 2014 emission estimates. The majority of sources in the current Inventory were calculated using the same emission factors and activity data for which probability density functions were developed in the 1990 through 2009 uncertainty analysis.

Natural Gas Systems

The uncertainty analysis conducted for the 1990 through 2009 Inventory has not yet been updated for the 1990 through 2014 Inventory year; instead, the uncertainty percentage ranges calculated previously were applied to 2014 emissions estimates. The majority of sources in the current Inventory were calculated using the same emission factors and activity data for which probability density functions were developed in the 1990 through 2009 uncertainty analysis.

International Bunker Fuels

Emission estimates related to the consumption of international bunker fuels are subject to the same uncertainties as those from domestic aviation and marine mobile combustion emissions; however, additional uncertainties result from the difficulty in collecting accurate fuel consumption activity data for international transport activities separate from domestic transport activities. Uncertainties exist with regard to the total fuel used by military aircraft and ships, and in the activity data on military operations and training that were used to estimate percentages of total fuel use reported as bunker fuel emissions. There are also uncertainties in fuel end-uses by fuel-type, emissions factors, fuel densities, diesel fuel sulfur content, aircraft and vessel engine characteristics and fuel efficiencies, and the methodology used to back-calculate the data set to 1990 using the original set from 1995.

Wood Biomass and Ethanol Consumption

It is assumed that the combustion efficiency for woody biomass is 100 percent, which is believed to be an overestimate of the efficiency of wood combustion processes in the United States. Decreasing the combustion efficiency would decrease emission estimates. Additionally, the heat content applied to the consumption of woody biomass in the residential, commercial, and electric power sectors is unlikely to be a completely accurate representation of the heat content for all the different types of woody biomass consumed within these sectors. Emission estimates from ethanol production are more certain than estimates from woody biomass consumption due to better activity data collection methods and uniform combustion techniques.

Industrial Processes and Product Use

The uncertainty analysis descriptions in this section correspond to source categories included in the Industrial Processes and Product Use chapter of the Inventory.

Cement Production

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker and in the percentage of CKD recycled inside the cement kiln. Uncertainty is also associated with the assumption that all calcium-containing raw materials are $CaCO_3$, when a small percentage likely consists of other carbonate and non-carbonate raw materials.

Lime Production

The uncertainties contained in these estimates can be attributed to slight differences in the chemical composition of lime products and CO_2 recovery rates for on-site process use over the time series. Although the methodology accounts for various formulations of lime, it does not account for the trace impurities found in lime, such as iron oxide, alumina, and silica. In addition, a portion of the CO_2 emitted during lime production will actually be reabsorbed when the lime is consumed, especially at captive lime production facilities. Another uncertainty is the assumption that calcination emissions for LKD are around 2 percent. There is limited data publicly available on LKD generation rates and also quantities, types of other byproducts/wastes produced at lime facilities.

Glass Production

The uncertainty levels presented in this section arise in part due to variations in the chemical composition of limestone used in glass production. The uncertainty estimates also account for uncertainty associated with activity data. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The

accuracy of distribution by end use is also uncertain because this value is reported by the manufacturer of the input carbonates (limestone, dolomite & soda ash) and not the end user. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. Lastly, much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses.

Other Process Uses of Carbonates

The uncertainty levels presented in this section account for uncertainty associated with activity data. Data on limestone and dolomite consumption are collected by USGS through voluntary national surveys. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The accuracy of distribution by end-use is also uncertain because this value is reported by the producer/mines and not the end-user. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end-uses of limestone and dolomite. Lastly, much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses. Uncertainty in the estimates also arises in part due to variations in the chemical composition of limestone.

Ammonia Production

The uncertainties presented in this section are primarily due to how accurately the emission factor used represents an average across all ammonia plants using natural gas feedstock. Uncertainties are also associated with ammonia production estimates and the assumption that all ammonia production and subsequent urea production was from the same process. Uncertainty is also associated with the representativeness of the emission factor used for the petroleum coke-based ammonia process. It is also assumed that ammonia and urea are produced at collocated plants from the same natural gas raw material.

Urea Consumption for Non-Agricultural Purposes

The primary uncertainties associated with this source category are associated with the accuracy of the estimates of urea production, urea imports, urea exports, and the amount of urea used as fertilizer as well as the fact that each estimate is obtained from a different data source. Because urea production estimates are no longer available from the USGS, there is additional uncertainty associated with urea produced beginning in 2011. There is also uncertainty associated with the assumption that all of the carbon in urea is released into the environment as CO_2 during use.

Nitric Acid Production

Uncertainty associated with the parameters used to estimate N_2O emissions includes that of production data, the share of U.S. nitric acid production attributable to each emission abatement technology over the time series (especially prior to 2010), and the associated emission factors applied to each abatement technology type.

Adipic Acid Production

Uncertainty associated with N_2O emission estimates includes the methods used by companies to monitor and estimate emissions.

Silicon Carbide Production and Consumption

There is uncertainty associated with the emission factors used because they are based on stoichiometry as opposed to monitoring of actual SiC production plants. For CH_4, there is also uncertainty associated with the hydrogen-containing volatile compounds in the petroleum coke (IPCC 2006). There is also uncertainty associated with the use or destruction of methane generated from the process in addition to uncertainty associated with levels of production, net imports, consumption levels, and the percent of total consumption that is attributed to metallurgical and other non-abrasive uses.

Titanium Dioxide Production

As of 2004, the last remaining sulfate-process plant in the United States closed. Since annual TiO_2 production was not reported by USGS by the type of production process used (chloride or sulfate) prior to 2004 and only the percentage of total production capacity by process was reported, the percent of total TiO_2 production capacity that was attributed to the chloride process was multiplied by total TiO_2 production to estimate the amount of TiO_2 produced using the chloride process. Finally, the emission factor was applied uniformly to all chloride-process production, and no data were available to account for differences in production efficiency among chloride-process plants.

Soda Ash Production and Consumption

Emission estimates from soda ash production have relatively low associated uncertainty levels in that reliable and accurate data sources are available for the emission factor and activity data. Soda ash production data was collected by the USGS from voluntary surveys. One source of uncertainty is the purity of the trona ore used for manufacturing soda ash. The

primary source of uncertainty, however, results from the fact that emissions from soda ash consumption are dependent upon the type of processing employed by each end-use.

Petrochemical Production

Sources of uncertainty on the CH_4 and CO_2 emission factors used for acrylonitrile and methanol production are derived from the use of default or average factors from a limited number of studies. There is some uncertainty in the applicability of the average emission factors for each petrochemical type across all prior years. While petrochemical production processes in the United States have not changed significantly since 1990, some operational efficiencies have been implemented at facilities over the time series.

HCFC-22 Production

The uncertainty analysis presented in this section was based on a plant-level Monte Carlo Stochastic Simulation for 2006. A normal probability density function was assumed for all measurements and biases except the equipment leak estimates for one plant; a log-normal probability density function was used for this plant's equipment leak estimates. The simulation for 2006 yielded a 95-percent confidence interval for U.S. emissions of 6.8 percent below to 9.6 percent above the reported total.

The relative errors yielded by the Monte Carlo Stochastic Simulation for 2006 were applied to the U.S. emission estimate for 2014. The resulting estimates of absolute uncertainty are likely to be reasonably accurate because (1) the methods used by the three plants to estimate their emissions are not believed to have changed significantly since 2006, and (2) although the distribution of emissions among the plants may have changed between 2006 and 2014, the two plants that contribute significantly to emissions were estimated to have similar relative uncertainties in their 2006 (as well as 2005) emission estimates.

Carbon Dioxide Production

Uncertainty is associated with the data reported through EPA's GHGRP, specifically the amount of CO_2 consumed for food and beverage applications given a threshold for reporting under GHGRP applicable to those reporting under Subpart PP, in addition to the exclusion of the amount of CO_2 transferred to all other end-use categories. Uncertainty is also associated with the exclusion of imports/exports data for CO_2 suppliers.

Phosphoric Acid Production

Regional production for 2014 was estimated based on regional production data from previous years and multiplied by regionally-specific emission factors. There is uncertainty associated with the degree to which the estimated 2014 regional production data represents actual production in those regions.

An additional source of uncertainty is the carbonate composition of phosphate rock; the composition of phosphate rock varies depending upon where the material is mined, and may also vary over time. A third source of uncertainty is the assumption that all domestically-produced phosphate rock is used in phosphoric acid production and used without first being calcined.

Iron and Steel Production and Metallurgical Coke Production

Uncertainty is associated with the total U.S. coking coal consumption, total U.S. coke production, and materials consumed during this process. Therefore, for the purpose of this analysis, uncertainty parameters are applied to primary data inputs to the calculation (i.e., coking coal consumption and metallurgical coke production) only.

There is uncertainty associated with the assumption that direct reduced iron and sinter consumption are equal to production. There is uncertainty associated with the assumption that all coal used for purposes other than coking coal is for direct injection coal; some of this coal may be used for electricity generation. There is also uncertainty associated with the C contents for pellets, sinter, and natural ore. For electric arc furnace (EAF) steel production, there is uncertainty associated with the amount of EAF anode and charge C consumed due to inconsistent data throughout the time series. Also for EAF steel production, there is uncertainty associated with the assumption that 100 percent of the natural gas attributed to "steelmaking furnaces" by AISI is process-related and nothing is combusted for energy purposes. Uncertainty is also associated with the use of process gases such as blast furnace gas and coke oven gas.

Ferroalloy Production

Uncertainty for this source is associated with the type and availability of annual ferroalloy production data, which have varied over the time series. Such production data may or may not include details such as ferroalloy content, production practices (e.g., biomass used as primary or secondary carbon source), amount of reducing agent used, and furnace specifics (e.g., type, operation technique, control technology).

Aluminum Production

Uncertainty was assigned to the CO_2, CF_4, and C_2F_6 emission values reported by each individual facility to EPA's GHGRP. Uncertainty surrounding the reported CO_2, CF_4, and C_2F_6 emission values were determined to have a normal distribution with uncertainty ranges of ±6, ±16, and ±20 percent, respectively.

Magnesium Production

Uncertainty surrounding the total estimated emissions in 2014 is attributed to the uncertainties around SF_6, HFC-134a and CO_2 emission estimates. To estimate the uncertainty surrounding the estimated 2014 SF_6 emissions from magnesium production and processing, the uncertainties associated with three variables were estimated: (1) emissions reported by magnesium producers and processors for 2014 through EPA's GHGRP, (2) emissions estimated for magnesium producers and processors that reported via the Partnership in prior years but did not report 2014 emissions through EPA's GHGRP, and (3) emissions estimated for magnesium producers and processors that did not participate in the Partnership or report through EPA's GHGRP. Additional uncertainties exist in these estimates that are not addressed in this methodology, such as the basic assumption that SF_6 neither reacts nor decomposes during use.

Lead Production

Uncertainty associated with lead production relates to the applicability of emission factors and the accuracy of primary and secondary production data provided by the USGS.

Zinc Production

There is uncertainty associated with the amount of EAF dust consumed in the United States to produce secondary zinc using emission-intensive Waelz kilns.

There are also uncertainties associated with the accuracy of the emission factors used to estimate CO_2 emissions from secondary zinc production processes.

Semiconductor Manufacture

The equation used to estimate uncertainty is:

$$\text{Total Emissions } (E_T) = \text{GHGRP Reported F-GHG Emissions } (E_{R,\text{F-GHG}}) + \text{Non-Reporters' Estimated F-GHG Emissions } (E_{NR,\text{F-GHG}}) + \text{GHGRP Reported } N_2O \text{ Emissions } (E_{R,N2O}) + \text{Non-Reporters' Estimated } N_2O \text{ Emissions } (E_{NR,N2O})$$

where E_R and E_{NR} denote totals for the indicated subcategories of emissions for F-GHG and N_2O, respectively.

The uncertainty estimate of $E_{R,\text{ F-GHG}}$, or GHGRP reported F-GHG emissions, is developed based on gas-specific uncertainty estimates of emissions for two industry segments, one processing 200 mm wafers and one processing 300 mm wafers. These gas and wafer-specific uncertainty estimates are applied to the total emissions of the facilities that did not abate emissions as reported under EPA's GHGRP.

For those facilities reporting abatement of emissions under EPA's GHGRP, estimates of uncertainties for the no abatement industry segments are modified to reflect the use of full and partial abatement. For all facilities reporting gas abatement, a triangular distribution of destruction or removal efficiency is assumed for each gas. For facilities reporting partial abatement, the distribution of fraction of the gas fed through the abatement device, for each gas, is assumed to be triangularly distributed as well. Gas-specific emission uncertainties were estimated by convolving the distributions of unabated emissions with the appropriate distribution of abatement efficiency for fully and partially abated facilities using a Montel Carlo simulation.

The uncertainty in $E_{R,\text{F-GHG}}$ is obtained by allocating the estimates of uncertainties to the total GHGRP-reported emissions from each of the six industry segments. The uncertainty in $E_{R,N2O}$ is obtained by assuming that the uncertainty in the emissions reported by each of the GHGRP reporting facilities results from the uncertainty in quantity of N_2O consumed and the N_2O emission factor (or utilization). The quantity of N_2O utilized (the complement of the emission factor) was assumed to have a triangular distribution with a minimum value of 0 percent, mode of 20 percent and maximum value of 84 percent. The uncertainty for the total reported N_2O emissions was then estimated by combining the uncertainties of each of the facilities reported emissions using Monte Carlo simulation. The estimate of uncertainty in $E_{NR,\text{F-GHG}}$ and $E_{NR,N2O}$ entailed developing estimates of uncertainties for the proportion of total emissions attributed to non-reporters for 2011 and 2012, which are subsequently dependent on the emissions factors for each non-reporting sub-category and the corresponding estimates of Total Manufactured Layer Area (TMLA) for the years 2011 and 2012.

The uncertainty in TMLA depends on the uncertainty of two variables – an estimate of the uncertainty in the average annual capacity utilization for each level of production of fabs (e.g., full scale or R&D production) and a corresponding estimate of the uncertainty in the number of layers manufactured. For both variables, the distributions of capacity utilizations and number of manufactured layers are assumed triangular for all categories of non-reporting fabs. For production fabs and for facilities that manufacture discrete devices, the most probable utilization is assumed to be 79 percent for 2011 and 65 percent for 2012, with the highest and lowest utilization assumed to be 84 percent for 2011 and 70 percent for 2012, and 62 percent for 2011 and 51 percent for 2012, respectively. The most probable values for utilization for R&D facilities are assumed to be 79 percent for 2011 and 65 percent for 2012, with the highest utilization also at 79 percent for 2011 and 65 percent for 2012, and the lowest utilization at 40 percent for 2011 and 33 percent for 2012. For the triangular distributions that govern the number of possible layers manufactured, it is assumed the most probable value is one layer less than reported in the ITRS.

The uncertainty bounds for the average capacity utilization and the number of layers manufactured are used as inputs in a separate Monte Carlo simulation to estimate the uncertainty around the TMLA of both individual facilities as well as the total non-reporting TMLA of each sub-population for both 2011 and 2012. The uncertainty around the emission factors for each non-reporting category of facilities (for both 2011 and 2012) is dependent on the uncertainty of the total emissions (MMT CO_2 Eq. units) and the TMLA of each reporting facility in that category. For simplicity, the results of the Monte Carlo simulations on the bounds of the gas- and wafer size-specific emissions as well as the TMLA and emission factors are assumed to be normally distributed and the uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean. The departures from normality were observed to be small. The final step in estimating the uncertainty in emissions of non-reporting facilities is convolving the distribution of emission factors with the distribution of TMLA individually for 2011 and 2012, along with the distributions of GHGRP-reported emissions for 2011 and 2012 to estimate the uncertainty around the proportion of total emissions attributed to non-reporters for 2011 and 2012 using Monte Carlo simulation.

Substitution of Ozone Depleting Substances

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, significant uncertainties exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

The Vintaging Model estimates emissions from 66 end-uses. The uncertainty analysis quantifies the level of uncertainty associated with the aggregate emissions resulting from the top 21 end-uses, comprising over 95 percent of the total emissions, and 6 other end-uses. These 27 end-uses comprise 97 percent of the total emissions, equivalent to 156.4 MMT CO_2 Eq.

In order to calculate uncertainty, functional forms were developed to simplify some of the complex "vintaging" aspects of some end-use sectors, especially with respect to refrigeration and air-conditioning, and to a lesser degree, fire extinguishing. The functional forms used variables that included. Uncertainty was estimated around each variable within the functional forms (e.g., growth rates, emission factors, transition from ODSs, change in charge size as a result of the transition, disposal quantities, disposal emission rates, and either stock for the current year or original ODS consumption) based on expert judgment. The most significant sources of uncertainty for this source category include the emission factors for residential unitary AC, as well as the percent of non-MDI aerosol propellant that is HFC-152a.

Electrical Transmission and Distribution

To estimate the uncertainty associated with emissions of SF_6 from Electrical Transmission and Distribution, uncertainties associated with four quantities were estimated: (1) emissions from Partners, (2) emissions from GHGRP-Only Reporters, (3) emissions from Non-Reporters, and (4) emissions from manufacturers of electrical equipment. Uncertainties were also estimated regarding (1) the quantity of SF_6 supplied with equipment by equipment manufacturers, which is projected from Partner provided nameplate capacity data and industry SF_6 nameplate capacity estimates, and (2) the manufacturers' SF_6 emissions rate.

Nitrous Oxide from Product Uses

The overall uncertainty associated with the 2014 N_2O emission estimate from N_2O product usage was calculated using the *2006 IPCC Guidelines* (IPCC 2006) Approach 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions include production data, total market share of each end use, and the emission factors applied to each end use, respectively.

Agriculture

The uncertainty analysis descriptions in this section correspond to some source categories included in the Agriculture chapter of the Inventory.

Enteric Fermentation

Uncertainty estimates were developed for the 1990 through 2001 Inventory report (i.e., 2003 submission to the UNFCCC). There have been no significant changes to the methodology since that time; consequently, these uncertainty estimates were directly applied to the 2014 emission estimates in this Inventory report.

A total of 185 primary input variables were identified as key input variables for the uncertainty analysis. A normal distribution was assumed for almost all activity- and emission factor-related input variables. Triangular distributions were assigned to three input variables to ensure only positive values would be simulated.

Manure Management

An analysis (ERG 2003a) was conducted for the manure management emission estimates presented in the 1990 through 2001 Inventory report (i.e., 2003 submission to the UNFCCC) to determine the uncertainty associated with estimating CH_4 and N_2O emissions from livestock manure management. These uncertainty estimates were directly applied to the 2014 emission estimates as there have not been significant changes in the methodology since that time.

Rice Cultivation

Sources of uncertainty in the Tier 3 method include management practices, uncertainties in model structure (i.e., algorithms and parameterization), and variance associated with the NRI sample. Sources of uncertainty in the IPCC (2006) Tier 1 method include the emission factors, management practices, and variance associated with the NRI sample. A Monte Carlo analysis was used to propagate uncertainties in the Tier 1 and 3 methods, and the uncertainties from each approach are combined to produce the final CH_4 emissions estimate using simple error propagation (IPCC 2006).

Agricultural Soil Management

Uncertainty was estimated for each of the following five components of N_2O emissions from agricultural soil management: (1) direct emissions simulated by DAYCENT; (2) the components of indirect emissions (N volatilized and leached or runoff) simulated by DAYCENT; (3) direct emissions approximated with the IPCC (2006) Approach 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) approximated with the IPCC (2006) Approach 1 method; and (5) indirect emissions estimated with the IPCC (2006) Approach 1 method.

Field Burning of Agricultural Residues

Due to data limitations, uncertainty resulting from the fact that emissions from burning of Kentucky bluegrass and "other crop" residues are not included in the emissions estimates was not incorporated into the uncertainty analysis.

Land Use, Land-Use Change, and Forestry

The uncertainty analysis descriptions in this section correspond to source categories included in the Land Use, Land-Use Change, and Forestry chapter of the Inventory.

Forest Land Remaining Forest Land

The uncertainty analysis descriptions in this section correspond to source categories included in the *Forest Land Remaining Forest Land* sub-chapter of Land Use, Land-Use Change, and Forestry chapter of the Inventory.

Changes in Forest Carbon Stocks

A quantitative uncertainty analysis placed bounds on current flux for forest ecosystems as well as C in harvested wood products through Monte Carlo Stochastic Simulation of the Methods and probabilistic sampling of C conversion factors and inventory data.

Non-CO_2 Emissions from Forest Fires

In order to quantify the uncertainties for emissions from forest fires calculated as described above, a Monte Carlo (IPCC Approach 2) sampling approach was employed to propagate uncertainty in the equation as it was applied for U.S. forest land. See IPCC (2006) and Annex 3.13 for the quantities and assumptions employed to define and propagate uncertainty.

Direct N_2O fluxes from Forest Soils

The amount of N_2O emitted from forests depends not only on N inputs and fertilized area, but also on a large number of variables, including organic C availability, oxygen gas partial pressure, soil moisture content, pH, temperature,

and tree planting/harvesting cycles. The effect of the combined interaction of these variables on N_2O flux is complex and highly uncertain.

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. The uncertainty ranges around the 2005 activity data and emission factor input variables were directly applied to the 2014 emissions estimates. IPCC (2006) provided estimates for the uncertainty associated with direct and indirect N_2O emission factor for synthetic N fertilizer application to soils.

Cropland Remaining Cropland

The uncertainty analysis descriptions in this section correspond to source categories included in the *Cropland Remaining Cropland* sub-chapter of Land Use, Land-Use Change, and Forestry chapter of the Inventory.

Agricultural Soil Carbon Stock Change

Uncertainty associated with the *Cropland Remaining Cropland* land-use category was addressed for changes in agricultural soil C stocks (including both mineral and organic soils).

CO_2 Emissions from Liming

Uncertainty regarding the amount of limestone and dolomite applied to soils was estimated at ±15 percent with normal densities (Tepordei 2003; Willett 2013b). Analysis of the uncertainty associated with the emission factors included the fraction of lime dissolved by nitric acid versus the fraction that reacts with carbonic acid, and the portion of bicarbonate that leaches through the soil and is transported to the ocean. The probability distribution functions for the fraction of lime dissolved by nitric acid and the portion of bicarbonate that leaches through the soil were represented as smoothed triangular distributions between ranges of zero and 100 percent of the estimates.

CO_2 Emissions from Urea Fertilization

The largest source of uncertainty was the default emission factor, which assumes that 100 percent of the C in $CO(NH_2)_2$ applied to soils is ultimately emitted into the environment as CO_2. In addition, each urea consumption data point has an associated uncertainty.

Land Converted to Cropland

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 methodologies are based on the same method described for *Cropland Remaining Cropland*.

Uncertainty was estimated for each subsource (i.e., biomass C stocks, mineral soil C stocks and organic soil C stocks) and method that was used in the Inventory analysis (i.e., Tier 2 and Tier 3).

Grassland Remaining Grassland

Uncertainty was estimated for each subsource (i.e., mineral soil C stocks and organic soil C stocks) and disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3).

Land Converted to Grassland

Uncertainty was estimated for each subsource (i.e., biomass C stocks, mineral soil C stocks and organic soil C stocks) and disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3).

Wetlands Remaining Wetlands

The uncertainty analysis descriptions in this section correspond to source categories included in the *Wetlands Remaining Wetlands* sub-chapter of Land Use, Land-Use Change, and Forestry chapter of the Inventory.

Peatlands Remaining Peatlands

The uncertainty associated with peat production data was estimated to be ± 25 percent (Apodaca 2008), assumed to be normally distributed, and is attributed to the USGS receives data from the smaller peat producers but estimates production from some larger peat distributors. The uncertainty associated with the reported production data for Alaska was assumed to be the same as for the lower 48 states, or ± 25 percent with a normal distribution. The uncertainty associated with the average bulk density values was estimated to be ± 25 percent with a normal distribution (Apodaca 2008). The uncertainty associated with the emission factors was assumed to be triangularly distributed. The uncertainty values surrounding the C fractions were based on IPCC (2006) and the uncertainty was assumed to be uniformly distributed. The uncertainty values associated with the fraction of peatland covered by ditches was assumed to be ± 100 percent with a normal distribution based on the assumption that greater than 10 percent coverage, the upper uncertainty bound, is not typical of drained organic soils outside of The Netherlands (IPCC 2013).

Settlements Remaining Settlements

The uncertainty analysis descriptions in this section correspond to source categories included in the *Settlements Remaining Settlements* sub-chapter of the Land Use, Land-Use Change, and Forestry chapter of the Inventory.

Changes in Carbon Stocks in Urban Trees

Uncertainty associated with changes in C stocks in urban trees includes the uncertainty associated with urban area, percent urban tree coverage, and estimates of gross and net C sequestration for each of the 50 states and the District of Columbia. Additional uncertainty is associated with the biomass equations, conversion factors, and decomposition assumptions used to calculate C sequestration and emission estimates (Nowak et al. 2002).

N_2O Fluxes from Settlement Soils

The amount of N_2O emitted from settlements depends not only on N inputs and fertilized area, but also on a large number of variables, including organic C availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and irrigation/watering practices. The effect of the combined interaction of these variables on N_2O flux is complex and highly uncertain.

Uncertainties exist in both the fertilizer N and sewage sludge application rates in addition to the emission factors. Uncertainty in the amounts of sewage sludge applied to non-agricultural lands and used in surface disposal was derived from variability in several factors. The uncertainty ranges around 2005 activity data and emission factor input variables were directly applied to the 2014 emission estimates.

Other

The uncertainty analysis descriptions in this section correspond to source categories included in the Other sub-chapter of Land Use, Land-Use Change, and Forestry chapter of the Inventory.

Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills

The uncertainty analysis for landfilled yard trimmings and food scraps includes an evaluation of the effects of uncertainty for the following data and factors: disposal in landfills per year (tons of C), initial C content, moisture content, decay rate, and proportion of C stored. The C storage landfill estimates are also a function of the composition of the yard trimmings (i.e., the proportions of grass, leaves and branches in the yard trimmings mixture). There are respective uncertainties associated with each of these factors.

Waste

The uncertainty analysis descriptions in this section correspond to source categories included in the Waste chapter of the Inventory.

Landfills

The primary uncertainty associated with the estimates of CH_4 emissions from MSW and industrial waste landfills concerns the characterization of landfills. There is also a high degree of uncertainty and variability associated with the first order decay model, particularly when a homogeneous waste composition and hypothetical decomposition rates are applied to heterogeneous landfills (IPCC 2006).

The lack of landfill-specific information regarding the number and type of industrial waste landfills in the United States is a primary uncertainty with respect to the industrial waste generation and emissions estimates. Uncertainty also exists in the estimates of the landfill gas oxidized. Another significant source of uncertainty lies with the estimates of CH_4 recovered by flaring and gas-to-energy projects at MSW landfills. Industrial waste landfills are shown with a lower range of uncertainty due to the smaller number of data sources and associated uncertainty involved.

Wastewater Treatment

Uncertainty associated with the parameters used to estimate CH_4 emissions from wastewater treatment include that of numerous input variables used to model emissions from domestic wastewater, and wastewater from pulp and paper manufacture, meat and poultry processing, fruits and vegetable processing, ethanol production, and petroleum refining. Uncertainty associated with the parameters used to estimate N_2O emissions include that of sewage sludge disposal, total U.S. population, average protein consumed per person, fraction of N in protein, non-consumption nitrogen factor, emission factors per capita and per mass of sewage-N, and for the percentage of total population using centralized wastewater treatment plants.

Composting

The estimated uncertainty from the *2006 IPCC Guidelines* is ±50 percent for the Approach 1 methodology.

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.

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

ANNEX 8 QA/QC Procedures

8.1. Background

The purpose of this annex is to describe the Quality Assurance/Quality Control (QA/QC) procedures and information quality considerations that are used throughout the process of creating and compiling the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. This includes the evaluation of the quality and relevance of data and models used as inputs into the Inventory; proper management, incorporation, and aggregation of data; and review of the numbers and estimates to ensure that they are as accurate and transparent as possible. Quality control—in the form of both good practices (such as documentation procedures) and checks on whether good practices and procedures are being followed—is applied at every stage of inventory development and document preparation. In addition, quality assurance occurs at two stages—an expert review and a public review. While both phases can significantly contribute to the quality of the Inventory, the public review phase is also essential for promoting the openness of the Inventory development process and the transparency of the inventory data and methods. As described in respective source category text, comments received from these reviews may also result in updates or changes to continue to improve inventory quality.

8.2. Purpose

The *Quality Assurance/Quality Control and Uncertainty Management Plan* for the Inventory (QA/QC Management Plan) guides the process of ensuring the quality of the Inventory. The QA/QC Management Plan describes data and methodology checks, develops processes governing peer review and public comments, and provides guidance on conducting an analysis of the uncertainty surrounding the emission estimates. The QA/QC Management Plan procedures also stress continual improvement, providing for corrective actions that are designed to improve the inventory estimates over time.

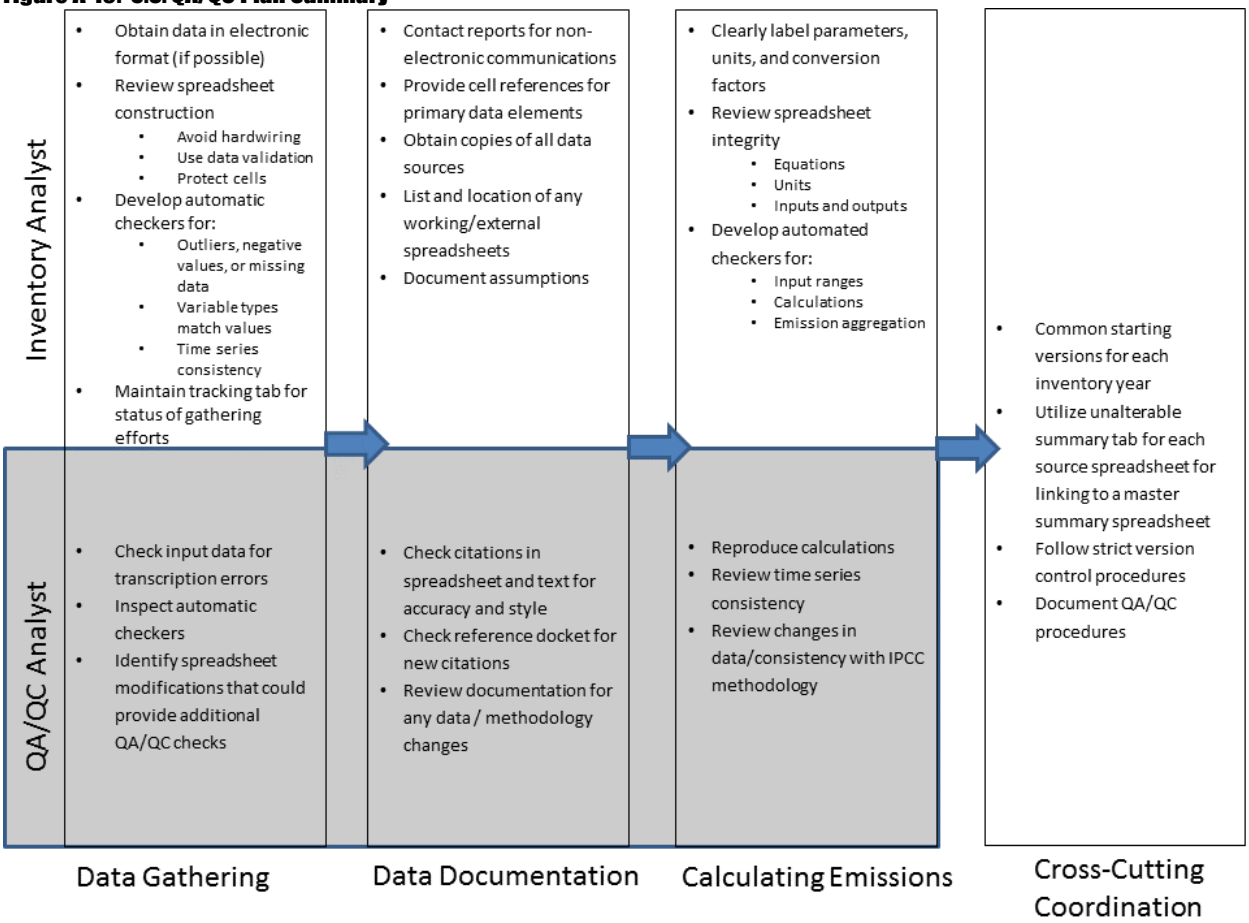
Key attributes of the QA/QC Management Plan are summarized in Figure A-19. These attributes include:

- *Procedures and Forms:* detailed and specific systems that serve to standardize the process of documenting and archiving information, as well as to guide the implementation of QA/QC and the analysis of uncertainty.
- *Implementation of Procedures:* application of QA/QC procedures throughout the whole Inventory development process from initial data collection, through preparation of the emission estimates, to publication of the Inventory.
- *Quality Assurance:* expert and public reviews for both the Inventory estimates and the report (which is the primary vehicle for disseminating the results of the Inventory development process). The expert technical review conducted by the UNFCCC supplements these QA processes, consistent with the *2006 IPCC Guidelines* (IPCC 2006).
- *Quality Control*: consideration of secondary data and category-specific checks (Tier 2 QC) in parallel, and coordination with the uncertainty assessment; the development of protocols and templates, which provide for more structured communication and integration with the suppliers of secondary information.
- *Tier 1 (general) and Tier 2 (category-specific) Checks:* quality controls and checks, as recommended by the *IPCC Good Practice Guidance and 2006 IPCC Guidelines* (IPCC 2006).
- *Record Keeping:* provisions to track which procedures have been followed, the results of the QA/QC process, uncertainty analysis, and feedback mechanisms for corrective action based on the results of the investigations, which provide for continual data quality improvement and guided research efforts.
- *Multi-Year Implementation*: a schedule for coordinating the application of QA/QC procedures across multiple years, especially for category-specific QC.
- *Interaction and Coordination:* promoting communication within the EPA, across Federal agencies and departments, state government programs, and research institutions and consulting firms involved in supplying data or preparing estimates for the Inventory. The QA/QC Management Plan itself is intended to be revised to

reflect new information that becomes available as the program develops, methods are improved, or additional supporting documents become necessary.

In addition, based on the national QA/QC Management Plan for the Inventory, source-specific QA/QC plans have been developed for a number of sources. These plans follow the procedures outlined in the national QA/QC plan, tailoring the procedures to the specific text and spreadsheets of the individual sources. For each greenhouse gas emissions source or sink included in this Inventory, a minimum of a Tier 1 QA/QC analysis has been undertaken. Where QA/QC activities for a particular source go beyond the minimum Tier 1 level, and include Tier 2 or category-specific checks further explanation is provided within the respective source category text. Similarly, responses or updates based on comments from the expert, public and the international technical expert reviews (e.g. UNFCCC) are also addressed within the respective source category text.

Figure A-19: U.S. QA/QC Plan Summary



8.3. Assessment Factors

The *Inventory of U.S. Greenhouse Gas Emissions and Sinks* development process follows guidance outlined in EPA's *Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity, of Information Disseminated by the Environmental Protection Agency* [137] and *A Summary of General Assessment Factors for Evaluating*

[137] EPA report #260R-02-008, October 2002, Available online at <http://www.epa.gov/quality/guidelines-ensuring-and-maximizing-quality-objectivity-utility-and-integrity-information>.

the Quality of Scientific and Technical Information.[138] This includes evaluating the data and models used as inputs into the Inventory against the five general assessment factors: soundness, applicability and utility, clarity and completeness, uncertainty and variability, evaluation and review. Table A-283 defines each factor and explains how it was considered during the process of creating the current Inventory.

Table A-283: Assessment Factors and Definitions

General Assessment Factor	Definition	How the Factor was Considered
Soundness (AF1)	The extent to which the scientific and technical procedures, measures, methods or models employed to generate the information are reasonable for, and consistent with their intended application.	The underlying data, methodologies, and models used to generate the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* are reasonable for and consistent with their intended application, to provide information regarding all sources and sinks of greenhouse gases in the United States for the Inventory year, as required per UNFCCC Annex I country reporting requirements. The U.S. emissions calculations follow the *2006 IPCC Guidelines* developed specifically for UNFCCC inventory reporting. They are based on the best available, peer-reviewed scientific information, and have been used by the international community for over 20 years. When possible, Tier 2 and Tier 3 methodologies from the *2006 IPCC Guidelines* are applied to calculate U.S. emissions more accurately.
Applicability and Utility (AF2)	The extent to which the information is relevant for the Agency's intended use.	The Inventory's underlying data, methodology, and models are relevant for their intended application because they generate the sector-specific greenhouse gas emissions trends necessary for assessing and understanding all sources and sinks of greenhouse gases in the United States for the Inventory year. They are relevant for communicating U.S. emissions information to domestic audiences, and they are consistent with the *2006 IPCC Guidelines* developed specifically for UNFCCC reporting purposes of international greenhouse gas inventories.
Clarity and Completeness (AF3)	The degree of clarity and completeness with which the data, assumptions, methods, quality assurance, sponsoring organizations and analyses employed to generate the information are documented.	The methodological and calculation approaches applied to generate the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* are extensively documented in the *2006 IPCC Guidelines*. The Inventory report describes its adherence to the *2006 IPCC Guidelines*, and the U.S. Government agencies provide data to implement the *2006 IPCC Guidelines* approaches. Any changes made to calculations, due to updated data and methods, are explained and

[138] EPA report #100/B-03/001, June 2003, Available online at <http://www.epa.gov/risk/guidance-evaluating-and-documenting-quality-existing-scientific-and-technical-information>, and Addendum to: A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information, December 2012, Available online at <http://www.epa.gov/risk/summary-general-assessment-factors-evaluating-quality-scientific-and-technical-information>.

		documented in the report consistent with UNFCCC reporting guidelines.
Uncertainty and Variability (AF4)	The extent to which the variability and uncertainty (quantitative and qualitative) in the information or in the procedures, measures, methods or models are evaluated and characterized.	The evaluation of uncertainties for underlying data is documented in the Uncertainty section of the Annex to the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. In accordance with the *2006 IPCC Guidelines*, the uncertainty associated with the Inventory's underlying data, methodology, and models was evaluated by running a Monte-Carlo uncertainty analysis on source category emissions data to produce a 95 percent confidence interval for the annual greenhouse gas emissions for that source. To develop 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.
Evaluation and Review (AF5)	The extent of independent verification, validation and peer review of the information or of the procedures, measures, methods or models.	The majority of the underlying methodology, calculations, and models used to generate the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* have been independently verified and peer reviewed as part of their publication in the *2006 IPCC Guidelines*. In cases where the methodology differs slightly from the *2006 IPCC Guidelines*, these were independently verified and validated by technical experts during the annual expert review phase of the Inventory development process. For the data used in calculating greenhouse gas emissions for each source, multiple levels of evaluation and review occur. Data are compared to results from previous years, and calculations and equations are continually evaluated and updated as appropriate. Throughout the process, inventory data and methodological improvements are planned and incorporated. The Inventory undergoes annual cycles of expert and public review before publication. This process ensures that both experts and the general public can review each source of emissions and sinks, and have an extended opportunity to provide feedback on the methodologies used, calculations, data sources, and presentation of information.