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

The following nine 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 2014). 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 or sink 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. Annex 8 provides information on the QA/QC methods and procedures used in the development of the Inventory, including responses to UNFCCC reviews. Finally, Annex 9 provides an overview of GHGRP data use in the Inventory.

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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. A qualitative review of key categories, along with non-key categories has not identified additional categories to consider as key.

The methodology for conducting a key category analysis, as defined by Volume 1, Chapter 4 of 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 used to identify key categories for the United States; provides level and trend assessment equations; and provides a brief evaluation of IPCC's quantitative methodologies for defining key categories. The United States key category analysis generally follows the IPCC suggested aggregation level of analysis, but in some cases does differ by avoiding disaggregating into many smaller categories (i.e., separating pools and subcategories within LULUCF source categories). The UNFCCC common reporting format reporting software generates Table A-7, which also identifies key categories using an Approach 1 analysis based on the default disaggregation approach provided in Volume 1, Chapter 4 of the *2006 IPCC Guidelines*.

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 CO_2 Eq. emissions in 2019. 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 Categories for the United States (1990 and 2019)

CRF Source/Sink Category	Greenhouse Gas	Approach 1				Approach 2				2019 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										
1.A.3.b CO_2 Emissions from Mobile Combustion: Road	CO_2	•	•	•	•	•	•	•	•	1,535.3
1.A.1 CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	•	•	•	•	•	•	•	•	973.5
1.A.1 CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	•	•	•	•	•	•	•	•	616.0
1.A.2 CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	•	•	•	•	•	•	•	•	524.3
1.A.4.b CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	•	•	•	•	•	•	•		275.3
1.A.2 CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	•	•	•	•	•	•	•	•	264.0
1.A.4.a CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	•	•	•	•	•	•	•	•	192.8
1.A.3.a CO_2 Emissions from Mobile Combustion: Aviation	CO_2	•	•	•	•	•		•		178.4
1.A.5 CO_2 Emissions from Non-Energy Use of Fuels	CO_2	•		•		•	•	•		110.1
1.A.4.b CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	•	•	•	•		•			63.5

CRF Source/Sink Category	Greenhouse Gas	Approach 1				Approach 2				2019 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	
1.A.3.e CO_2 Emissions from Mobile Combustion: Other	CO_2	•	•	•	•					53.7
1.A.2 CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	•	•	•	•	•	•	•	•	49.2
1.A.4.a CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	•	•	•	•					43.9
1.B.2 CO_2 Emissions from Petroleum Systems	CO_2	•	•	•	•	•	•	•	•	43.3
1.B.2 CO_2 Emissions from Natural Gas Systems	CO_2	•		•						36.9
1.A.3.c CO_2 Emissions from Mobile Combustion: Railways	CO_2	•		•						36.7
1.A.3.d CO_2 Emissions from Mobile Combustion: Marine	CO_2	•		•						33.8
5.C.1 CO_2 Emissions from Incineration of Waste	CO_2	•	•	•	•		•			20.2
1.A.5 CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	•		•						19.5
1.A.1 CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	•	•	•	•	•	•		•	16.2
1.A.5.b CO_2 Emissions from Mobile Combustion: Military	CO_2				•					5.3
1.A.5 CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2						•			2.5
1.A.4.a CO_2 Emissions from Stationary	CO_2		•		•					1.6

CRF Source/Sink Category	Greenhouse Gas	Approach 1				Approach 2				2019 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	
Combustion - Coal - Commercial										
1.A.4.b CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2						•		•	0.0
1.B.2 CH_4 Emissions from Natural Gas Systems	CH_4	•	•	•	•	•	•	•	•	156.4
1.B.1 Fugitive Emissions from Coal Mining	CH_4	•	•	•	•	•	•	•	•	47.4
1.B.2 CH_4 Emissions from Petroleum Systems	CH_4	•	•	•	•	•	•	•	•	40.2
1.B.2 CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4					•		•		7.0
1.A.4.b CH_4 Emissions from Stationary Combustion - Residential	CH_4					•		•		4.6
1.A.1 N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O					•				16.7
1.A.3.b N_2O Emissions from Mobile Combustion: Road	N_2O	•	•	•	•		•		•	9.6
1.A.2 N_2O Emissions from Stationary Combustion - Industrial	N_2O					•				2.5
Industrial Processes and Product Use										
2.C.1 CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	•	•	•	•	•	•	•	•	41.3
2.A.1 CO_2 Emissions from Cement Production	CO_2	•		•						40.9
2.B.8 CO_2 Emissions from Petrochemical Production	CO_2	•	•	•	•					30.8

CRF Source/Sink Category	Greenhouse Gas	Approach 1				Approach 2				2019 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	
2.B.3 N_2O Emissions from Adipic Acid Production	N_2O		•		•					5.3
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air Conditioning	HFCs, PFCs	•	•	•	•	•	•	•	•	132.6
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs		•		•	•	•	•	•	16.3
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs		•		•					16.1
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs						•			2.8
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs						•			2.0
2.G SF_6 Emissions from Electrical Transmission and Distribution	SF_6	•	•	•	•		•		•	4.2
2.B.9 HFC-23 Emissions from HCFC-22 Production	HFCs	•	•	•	•		•		•	3.7
2.C.3 PFC Emissions from Aluminum Production	PFCs	•	•	•	•					1.8
Agriculture										
3.G CO_2 Emissions from Liming	CO_2						•			2.4
3.A.1 CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	•	•	•	•	•		•		172.3

CRF Source/Sink Category	Greenhouse Gas	Approach 1				Approach 2				2019 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	
3.B.1 CH_4 Emissions from Manure Management: Cattle	CH_4	•	•	•	•		•		•	35.4
3.B.4 CH_4 Emissions from Manure Management: Other Livestock	CH_4	•		•						26.9
3.C CH_4 Emissions from Rice Cultivation	CH_4					•		•		15.1
3.D.1 Direct N_2O Emissions from Agricultural Soil Management	N_2O	•	•	•	•	•	•	•	•	290.4
3.D.2 Indirect N_2O Emissions from Applied Nitrogen	N_2O	•	•	•	•	•	•	•	•	54.2
Waste										
5.A CH_4 Emissions from Landfills	CH_4	•	•	•	•	•	•	•	•	114.5
5.D CH_4 Emissions from Wastewater Treatment	CH_4	•				•				18.4
5.D N_2O Emissions from Wastewater Treatment	N_2O	•		•		•	•	•	•	26.4
Land Use, Land-Use Change, and Forestry										
4.E.2 Net CO_2 Emissions from Land Converted to Settlements	CO_2			•	•			•	•	79.2
4.B.2 Net CO_2 Emissions from Land Converted to Cropland	CO_2			•				•		54.2
4.C.1 Net CO_2 Emissions from Grassland Remaining Grassland	CO_2							•	•	14.5
4.B.1 Net CO_2 Emissions from Cropland Remaining Cropland	CO_2			•	•			•	•	(14.5)
4.C.2 Net CO_2 Emissions from Land Converted to Grassland	CO_2			•	•			•	•	(23.2)

CRF Source/Sink Category	Greenhouse Gas	Approach 1				Approach 2				2019 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	
4.A.2 Net CO_2 Emissions from Land Converted to Forest Land	CO_2			•				•		(99.1)
4.E.1 Net CO_2 Emissions from Settlements Remaining Settlements	CO_2			•	•			•	•	(124.1)
4.A.1 Net CO_2 Emissions from Forest Land Remaining Forest Land	CO_2			•	•			•	•	(691.8)
4.A.1 CH_4 Emissions from Forest Fires	CH_4				•					9.5
Subtotal Without LULUCF										**6,428.9**
Total Emissions Without LULUCF										**6,577.2**
Percent of Total Without LULUCF										**98%**
Subtotal With LULUCF										**5,591.6**
Total Emissions With LULUCF										**5,788.3**
Percent of Total With LULUCF										**97%**

Note: Parentheses indicate negative values (or sequestration).

Table A-2 provides a complete listing of source categories by IPCC sector, along with notations on the criteria used in identifying key categories, without LULUCF sources and sinks. Similarly, Table A-3 provides a complete listing of source and sink categories by IPCC sector, along with notations on the criteria used in identifying key categories, including LULUCF sources and sinks. The notations refer specifically to the year(s) in the Inventory time series (i.e., 1990 to 2019) in which each source or sink category reached the threshold for being a key category based on either a Tier 1 or Tier 2 level assessment.

In addition to conducting Approach 1 and 2 level and trend assessments, a qualitative assessment of 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 either quantitative method. For this Inventory, no additional categories were identified using criteria recommend by IPCC, but EPA continues to update its qualitative assessment on an annual basis.

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

CRF Source/Sink Category	Greenhouse Gas	2019 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
Energy					
1.A.3.b CO_2 Emissions from Mobile Combustion: Road	CO_2	1,535.3	•	L_1 T_1 L_2 T_2	1990, 2019
1.A.1 CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	973.5	•	L_1 T_1 L_2 T_2	1990, 2019
1.A.1 CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	616.0	•	L_1 T_1 L_2 T_2	1990, 2019
1.A.2 CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	524.3	•	L_1 T_1 L_2 T_2	1990, 2019
1.A.4.b CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	275.3	•	L_1 T_1 L_2 T_2	1990, 2019
1.A.2 CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	264.0	•	L_1 T_1 L_2 T_2	1990, 2019
1.A.4.a CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	192.8	•	L_1 T_1 L_2 T_2	1990, 2019
1.A.3.a CO_2 Emissions from Mobile Combustion: Aviation	CO_2	178.4	•	L_1 T_1 L_2	1990, 2019
1.A.5 CO_2 Emissions from Non-Energy Use of Fuels	CO_2	110.1	•	L_1 L_2 T_2	1990, 2019
1.A.4.b CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	63.5	•	L_1 T_1 T_2	1990_1, 2019_1
1.A.3.e CO_2 Emissions from Mobile Combustion: Other	CO_2	53.7	•	L_1 T_1	1990_1, 2019_1
1.A.2 CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	49.2	•	L_1 T_1 L_2 T_2	1990, 2019
1.A.4.a CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	43.9	•	L_1 T_1	1990_1, 2019_1
1.B.2 CO_2 Emissions from Petroleum Systems	CO_2	43.3	•	L_1 T_1 L_2 T_2	2019
1.B.2 CO_2 Emissions from Natural Gas Systems	CO_2	36.9	•	L_1	1990_1, 2019_1

CRF Source/Sink Category	Greenhouse Gas	2019 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
1.A.3.c CO_2 Emissions from Mobile Combustion: Railways	CO_2	36.7	•	L_1	1990_1, 2019_1
1.A.3.d CO_2 Emissions from Mobile Combustion: Marine	CO_2	33.8	•	L_1	1990_1, 2019_1
5.C.1 CO_2 Emissions from Incineration of Waste	CO_2	20.2	•	L_1 T_1 T_2	2019_1
1.A.5 CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	19.5	•	L_1	1990_1, 2019_1
1.A.1 CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	16.2	•	L_1 T_1 L_2 T_2	1990
1.A.5.b CO_2 Emissions from Mobile Combustion: Military	CO_2	5.3			
1.A.5 CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	2.5	•	T_2	
1.A.5 CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	2.5			
1.A.4.a CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	1.6	•	T_1	
1.A.1 CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4			
1.B.2 CO_2 Emissions from Abandoned Oil and Gas Wells	CO_2	+			
1.A.4.b CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	0.0	•	T_2	
1.B.2 CH_4 Emissions from Natural Gas Systems	CH_4	156.4	•	L_1 T_1 L_2 T_2	1990, 2019
1.B.1 Fugitive Emissions from Coal Mining	CH_4	47.4	•	L_1 T_1 L_2 T_2	1990, 2019
1.B.2 CH_4 Emissions from Petroleum Systems	CH_4	40.2	•	L_1 T_1 L_2 T_2	1990, 2019
1.B.2 CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4	7.0	•	L_2	1990_2, 2019_2
1.B.1 Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	5.9			
1.A.4.b CH_4 Emissions from Stationary Combustion - Residential	CH_4	4.6	•	L_2	1990_2, 2019_2
1.A.2 CH_4 Emissions from Stationary Combustion - Industrial	CH_4	1.5			
1.A.4.a CH_4 Emissions from Stationary Combustion - Commercial	CH_4	1.2			

CRF Source/Sink Category	Greenhouse Gas	2019 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
1.A.1 CH_4 Emissions from Stationary Combustion - Gas - Electricity Generation	CH_4	1.1			
1.A.3.b CH_4 Emissions from Mobile Combustion: Road	CH_4	0.9			
1.A.3.e CH_4 Emissions from Mobile Combustion: Other	CH_4	0.9			
1.A.3.d CH_4 Emissions from Mobile Combustion: Marine	CH_4	0.4			
5.B.2 CH_4 Emissions from Anaerobic Digestion at Biogas Facilities	CH_4	0.2			
1.A.1 CH_4 Emissions from Stationary Combustion - Coal - Electricity Generation	CH_4	0.2			
1.A.3.c CH_4 Emissions from Mobile Combustion: Railways	CH_4	0.1			
1.A.5 CH_4 Emissions from Stationary Combustion - U.S. Territories	CH_4	+			
1.A.3.a CH_4 Emissions from Mobile Combustion: Aviation	CH_4	+			
1.A.1 CH_4 Emissions from Stationary Combustion - Wood - Electricity Generation	CH_4	+			
1.A.1 CH_4 Emissions from Stationary Combustion - Oil - Electricity Generation	CH_4	+			
1.A.5.b CH_4 Emissions from Mobile Combustion: Military	CH_4	+			
5.C.1 CH_4 Emissions from Incineration of Waste	CH_4	+			
1.A.1 N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O	16.7	•	L_2	1990_2, 2019_2
1.A.3.b N_2O Emissions from Mobile Combustion: Road	N_2O	9.6	•	L_1 T_1 T_2	1990_1
1.A.3.e N_2O Emissions from Mobile Combustion: Other	N_2O	6.5			
1.A.1 N_2O Emissions from Stationary Combustion - Gas - Electricity Generation	N_2O	4.4			
1.A.2 N_2O Emissions from Stationary Combustion - Industrial	N_2O	2.5	•	L_2	1990_2
1.A.3.a N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.6			
1.A.4.b N_2O Emissions from Stationary Combustion - Residential	N_2O	0.9			
1.A.3.d N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6			

CRF Source/Sink Category	Greenhouse Gas	2019 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
5.C.1 N_2O Emissions from Incineration of Waste	N_2O	0.4			
1.A.4.a N_2O Emissions from Stationary Combustion - Commercial	N_2O	0.3			
1.A.3.c N_2O Emissions from Mobile Combustion: Railways	N_2O	0.3			
1.A.5 N_2O Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1			
1.B.2 N_2O Emissions from Petroleum Systems	N_2O	+			
1.A.1 N_2O Emissions from Stationary Combustion - Wood - Electricity Generation	N_2O	+			
1.B.2 N_2O Emissions from Natural Gas Systems	N_2O	+			
1.A.1 N_2O Emissions from Stationary Combustion - Oil - Electricity Generation	N_2O	+			
1.A.5.b N_2O Emissions from Mobile Combustion: Military	N_2O	+			
Industrial Processes and Product Use					
2.C.1 CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	41.3	•	L_1 T_1 L_2 T_2	1990, 2019
2.A.1 CO_2 Emissions from Cement Production	CO_2	40.9	•	L_1	1990_1, 2019_1
2.B.8 CO_2 Emissions from Petrochemical Production	CO_2	30.8	•	L_1 T_1	1990_1, 2019_1
2.A.2 CO_2 Emissions from Lime Production	CO_2	13.0			
2.B.1 CO_2 Emissions from Ammonia Production	CO_2	12.3			
2.A.4 CO_2 Emissions from Other Process Uses of Carbonates	CO_2	7.5			
2.B.10 CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	6.6			
2.B.10 CO_2 Emissions from Carbon Dioxide Consumption	CO_2	4.9			
2.C.3 CO_2 Emissions from Aluminum Production	CO_2	1.9			
2.B.7 CO_2 Emissions from Soda Ash Production	CO_2	1.8			
2.C.2 CO_2 Emissions from Ferroalloy Production	CO_2	1.6			
2.B.6 CO_2 Emissions from Titanium Dioxide Production	CO_2	1.5			
2.A.3 CO_2 Emissions from Glass Production	CO_2	1.3			
2.C.6 CO_2 Emissions from Zinc Production	CO_2	1.0			

CRF Source/Sink Category	Greenhouse Gas	2019 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
2.B.10 CO_2 Emissions from Phosphoric Acid Production	CO_2	0.9			
2.C.5 CO_2 Emissions from Lead Production	CO_2	0.5			
2.B.5 CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.2			
2.C.4 CO_2 Emissions from Magnesium Production and Processing	CO_2	+			
2.B.8 CH_4 Emissions from Petrochemical Production	CH_4	0.3			
2.C.2 CH_4 Emissions from Ferroalloy Production	CH_4	+			
2.B.5 CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+			
2.C.1 CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+			
2.B.2 N_2O Emissions from Nitric Acid Production	N_2O	10.0			
2.B.3 N_2O Emissions from Adipic Acid Production	N_2O	5.3	•	T_1	
2.G N_2O Emissions from Product Uses	N_2O	4.2			
2.B.4 N_2O Emissions from Caprolactam, Glyoxal, and Glyoxylic Acid Production	N_2O	1.4			
2.E N_2O Emissions from Electronics Industry	N_2O	0.2			
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air Conditioning	HFCs, PFCs	132.6	•	L_1 T_1 L_2 T_2	2019
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	16.3	•	T_1 L_2 T_2	2019_2
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs	16.1	•	T_1	
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs	2.8	•	T_2	
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs	2.0	•	T_2	
2.E PFC, HFC, SF_6, and NF_3 Emissions from Electronics Industry	HiGWP	4.4			
2.G SF_6 Emissions from Electrical Transmission and Distribution	SF_6	4.2	•	L_1 T_1 T_2	1990_1

CRF Source/Sink Category	Greenhouse Gas	2019 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
2.B.9 HFC-23 Emissions from HCFC-22 Production	HFCs	3.7	•	L_1 T_1 T_2	1990_1
2.C.3 PFC Emissions from Aluminum Production	PFCs	1.8	•	L_1 T_1	1990_1
2.C.4 SF_6 Emissions from Magnesium Production and Processing	SF_6	1.0			
2.C.4 HFC-134a Emissions from Magnesium Production and Processing	HFCs	0.1			
Agriculture					
3.H CO_2 Emissions from Urea Fertilization	CO_2	5.3			
3.G CO_2 Emissions from Liming	CO_2	2.4	•	T_2	
3.A.1 CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	172.3	•	L_1 T_1 L_2	1990, 2019
3.B.1 CH_4 Emissions from Manure Management: Cattle	CH_4	35.4	•	L_1 T_1 T_2	2019_1
3.B.4 CH_4 Emissions from Manure Management: Other Livestock	CH_4	26.9	•	L_1	2019_1
3.C CH_4 Emissions from Rice Cultivation	CH_4	15.1	•	L_2	1990_2, 2019_2
3.A.4 CH_4 Emissions from Enteric Fermentation: Other Livestock	CH_4	6.3			
3.F CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.4			
3.D.1 Direct N_2O Emissions from Agricultural Soil Management	N_2O	290.4	•	L_1 T_1 L_2 T_2	1990, 2019
3.D.2 Indirect N_2O Emissions from Applied Nitrogen	N_2O	54.2	•	L_1 T_1 L_2 T_2	1990, 2019
3.B.1 N_2O Emissions from Manure Management: Cattle	N_2O	15.4			
3.B.4 N_2O Emissions from Manure Management: Other Livestock	N_2O	4.2			
3.F N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.2			
Waste					
5.A CH_4 Emissions from Landfills	CH_4	114.5	•	L_1 T_1 L_2 T_2	1990, 2019
5.D CH_4 Emissions from Wastewater Treatment	CH_4	18.4	•	L_1 L_2	1990
5.B CH_4 Emissions from Composting	CH_4	2.3			
5.D N_2O Emissions from Wastewater Treatment	N_2O	26.4	•	L_1 L_2 T_2	1990_2, 2019
5.B N_2O Emissions from Composting	N_2O	2.0			

Note: LULUCF sources and sinks are not included in this analysis.
+ Does not exceed 0.05 MMT CO_2 Eq.
[a] 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).
[b] Emissions from these sources not included in emission totals.

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

CRF Source/Sink Category	Greenhouse Gas	2019 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
Energy					
1.A.3.b CO_2 Emissions from Mobile Combustion: Road	CO_2	1,535.3	•	L_1 T_1 L_2 T_2	1990, 2019
1.A.1 CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	973.5	•	L_1 T_1 L_2 T_2	1990, 2019
1.A.1 CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	616.0	•	L_1 T_1 L_2 T_2	1990_1, 2019
1.A.2 CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	524.3	•	L_1 T_1 L_2 T_2	1990, 2019
1.A.4.b CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	275.3	•	L_1 T_1 L_2	1990, 2019
1.A.2 CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	264.0	•	L_1 T_1 L_2 T_2	1990, 2019
1.A.4.a CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	192.8	•	L_1 T_1 L_2 T_2	1990_1, 2019
1.A.3.a CO_2 Emissions from Mobile Combustion: Aviation	CO_2	178.4	•	L_1 T_1 L_2	1990, 2019
1.A.5 CO_2 Emissions from Non-Energy Use of Fuels	CO_2	110.1	•	L_1 L_2	1990, 2019
1.A.4.b CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	63.5	•	L_1 T_1	1990_1, 2019_1
1.A.3.e CO_2 Emissions from Mobile Combustion: Other	CO_2	53.7	•	L_1 T_1	1990_1, 2019_1
1.A.2 CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	49.2	•	L_1 T_1 L_2 T_2	1990, 2019_1
1.A.4.a CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	43.9	•	L_1 T_1	1990_1, 2019_1
1.B.2 CO_2 Emissions from Petroleum Systems	CO_2	43.3	•	L_1 T_1 L_2 T_2	2019
1.B.2 CO_2 Emissions from Natural Gas Systems	CO_2	36.9	•	L_1	1990_1, 2019_1
1.A.3.c CO_2 Emissions from Mobile Combustion: Railways	CO_2	36.7	•	L_1	1990_1, 2019_1
1.A.3.d CO_2 Emissions from Mobile Combustion: Marine	CO_2	33.8	•	L_1	1990_1, 2019_1
5.C.1 CO_2 Emissions from Incineration of Waste	CO_2	20.2	•	L_1 T_1	2019_1
1.A.5 CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	19.5	•	L_1	1990_1, 2019_1
1.A.1 CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	16.2	•	L_1 T_1 T_2	1990_1
1.A.5.b CO_2 Emissions from Mobile Combustion: Military	CO_2	5.3	•	T_1	
1.A.5 CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	2.5			
1.A.5 CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	2.5			
1.A.4.a CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	1.6	•	T_1	
1.A.1 CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4			
1.B.2 CO_2 Emissions from Abandoned Oil and Gas Wells	CO_2	+			

CRF Source/Sink Category	Greenhouse Gas	2019 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
1.A.4.b CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	0.0	•	T_2	
1.B.2 CH_4 Emissions from Natural Gas Systems	CH_4	156.4	•	L_1 T_1 L_2 T_2	1990, 2019
1.B.1 Fugitive Emissions from Coal Mining	CH_4	47.4	•	L_1 T_1 L_2 T_2	1990, 2019_1
1.B.2 CH_4 Emissions from Petroleum Systems	CH_4	40.2	•	L_1 T_1 L_2 T_2	1990, 2019
1.B.2 CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4	7.0	•	L_2	1990_2, 2019_2
1.B.1 Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	5.9			
1.A.4.b CH_4 Emissions from Stationary Combustion - Residential	CH_4	4.6	•	L_2	1990_2
1.A.2 CH_4 Emissions from Stationary Combustion - Industrial	CH_4	1.5			
1.A.4.a CH_4 Emissions from Stationary Combustion - Commercial	CH_4	1.2			
1.A.1 CH_4 Emissions from Stationary Combustion - Gas - Electricity Generation	CH_4	1.1			
1.A.3.b CH_4 Emissions from Mobile Combustion: Road	CH_4	0.9			
1.A.3.e CH_4 Emissions from Mobile Combustion: Other	CH_4	0.9			
1.A.3.d CH_4 Emissions from Mobile Combustion: Marine	CH_4	0.4			
5.B.2 CH_4 Emissions from Anaerobic Digestion at Biogas Facilities	CH_4	0.2			
1.A.1 CH_4 Emissions from Stationary Combustion - Coal - Electricity Generation	CH_4	0.2			
1.A.3.c CH_4 Emissions from Mobile Combustion: Railways	CH_4	0.1			
1.A.5 CH_4 Emissions from Stationary Combustion - U.S. Territories	CH_4	+			
1.A.3.a CH_4 Emissions from Mobile Combustion: Aviation	CH_4	+			
1.A.1 CH_4 Emissions from Stationary Combustion - Wood - Electricity Generation	CH_4	+			
1.A.1 CH_4 Emissions from Stationary Combustion - Oil - Electricity Generation	CH_4	+			
1.A.5.b CH_4 Emissions from Mobile Combustion: Military	CH_4	+			
5.C.1 CH_4 Emissions from Incineration of Waste	CH_4	+			
1.A.1 N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O	16.7			
1.A.3.b N_2O Emissions from Mobile Combustion: Road	N_2O	9.6	•	L_1 T_1 T_2	1990_1
1.A.3.e N_2O Emissions from Mobile Combustion: Other	N_2O	6.5			
1.A.1 N_2O Emissions from Stationary Combustion - Gas - Electricity Generation	N_2O	4.4			

CRF Source/Sink Category	Greenhouse Gas	2019 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
1.A.2 N_2O Emissions from Stationary Combustion - Industrial	N_2O	2.5			
1.A.3.a N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.6			
1.A.4.b N_2O Emissions from Stationary Combustion - Residential	N_2O	0.9			
1.A.3.d N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6			
5.C.1 N_2O Emissions from Incineration of Waste	N_2O	0.4			
1.A.4.a N_2O Emissions from Stationary Combustion - Commercial	N_2O	0.3			
1.A.3.c N_2O Emissions from Mobile Combustion: Railways	N_2O	0.3			
1.A.5 N_2O Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1			
1.B.2 N_2O Emissions from Petroleum Systems	N_2O	+			
1.A.1 N_2O Emissions from Stationary Combustion - Wood - Electricity Generation	N_2O	+			
1.B.2 N_2O Emissions from Natural Gas Systems	N_2O	+			
1.A.1 N_2O Emissions from Stationary Combustion - Oil - Electricity Generation	N_2O	+			
1.A.5.b N_2O Emissions from Mobile Combustion: Military	N_2O	+			
Industrial Processes and Product Use					
2.C.1 CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	41.3	•	L_1 T_1 L_2 T_2	1990, 2019_1
2.A.1 CO_2 Emissions from Cement Production	CO_2	40.9	•	L_1	1990_1, 2019_1
2.B.8 CO_2 Emissions from Petrochemical Production	CO_2	30.8	•	L_1 T_1	1990_1, 2019_1
2.A.2 CO_2 Emissions from Lime Production	CO_2	13.0			
2.B.1 CO_2 Emissions from Ammonia Production	CO_2	12.3			
2.A.4 CO_2 Emissions from Other Process Uses of Carbonates	CO_2	7.5			
2.B.10 CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	6.6			
2.B.10 CO_2 Emissions from Carbon Dioxide Consumption	CO_2	4.9			
2.C.3 CO_2 Emissions from Aluminum Production	CO_2	1.9			
2.B.7 CO_2 Emissions from Soda Ash Production	CO_2	1.8			
2.C.2 CO_2 Emissions from Ferroalloy Production	CO_2	1.6			
2.B.6 CO_2 Emissions from Titanium Dioxide Production	CO_2	1.5			
2.A.3 CO_2 Emissions from Glass Production	CO_2	1.3			
2.C.6 CO_2 Emissions from Zinc Production	CO_2	1.0			

CRF Source/Sink Category	Greenhouse Gas	2019 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
2.B.10 CO_2 Emissions from Phosphoric Acid Production	CO_2	0.9			
2.C.5 CO_2 Emissions from Lead Production	CO_2	0.5			
2.B.5 CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.2			
2.C.4 CO_2 Emissions from Magnesium Production and Processing	CO_2	+			
2.B.8 CH_4 Emissions from Petrochemical Production	CH_4	0.3			
2.C.2 CH_4 Emissions from Ferroalloy Production	CH_4	+			
2.B.5 CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+			
2.C.1 CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+			
2.B.2 N_2O Emissions from Nitric Acid Production	N_2O	10.0			
2.B.3 N_2O Emissions from Adipic Acid Production	N_2O	5.3	•	T_1	
2.G N_2O Emissions from Product Uses	N_2O	4.2			
2.B.4 N_2O Emissions from Caprolactam, Glyoxal, and Glyoxylic Acid Production	N_2O	1.4			
2.E N_2O Emissions from Electronics Industry	N_2O	0.2			
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air Conditioning	HFCs, PFCs	132.6	•	L_1 T_1 L_2 T_2	2019
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	16.3	•	T_1 L_2 T_2	2019_2
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs	16.1	•	T_1	
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs	2.8			
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs	2.0			
2.E PFC, HFC, SF_6, and NF_3 Emissions from Electronics Industry	HiGWP	4.4			
2.G SF_6 Emissions from Electrical Transmission and Distribution	SF_6	4.2	•	L_1 T_1 T_2	1990_1
2.B.9 HFC-23 Emissions from HCFC-22 Production	HFCs	3.7	•	L_1 T_1 T_2	1990_1
2.C.3 PFC Emissions from Aluminum Production	PFCs	1.8	•	L_1 T_1	1990_1
2.C.4 SF_6 Emissions from Magnesium Production and Processing	SF_6	1.0			
2.C.4 HFC-134a Emissions from Magnesium Production and Processing	HFCs	0.1			
Agriculture					
3.H CO_2 Emissions from Urea Fertilization	CO_2	5.3			
3.G CO_2 Emissions from Liming	CO_2	2.4			
3.A.1 CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	172.3	•	L_1 T_1 L_2	1990, 2019

CRF Source/Sink Category	Greenhouse Gas	2019 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
3.B.1 CH_4 Emissions from Manure Management: Cattle	CH_4	35.4	•	L_1 T_1 T_2	2019_1
3.B.4 CH_4 Emissions from Manure Management: Other Livestock	CH_4	26.9	•	L_1	2019_1
3.C CH_4 Emissions from Rice Cultivation	CH_4	15.1	•	L_2	1990_2, 2019_2
3.A.4 CH_4 Emissions from Enteric Fermentation: Other Livestock	CH_4	6.3			
3.F CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.4			
3.D.1 Direct N_2O Emissions from Agricultural Soil Management	N_2O	290.4	•	L_1 T_1 L_2 T_2	1990, 2019
3.D.2 Indirect N_2O Emissions from Applied Nitrogen	N_2O	54.2	•	L_1 T_1 L_2 T_2	1990, 2019
3.B.1 N_2O Emissions from Manure Management: Cattle	N_2O	15.4			
3.B.4 N_2O Emissions from Manure Management: Other Livestock	N_2O	4.2			
3.F N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.2			
Waste					
5.A CH_4 Emissions from Landfills	CH_4	114.5	•	L_1 T_1 L_2 T_2	1990, 2019
5.D CH_4 Emissions from Wastewater Treatment	CH_4	18.4			
5.B CH_4 Emissions from Composting	CH_4	2.3			
5.D N_2O Emissions from Wastewater Treatment	N_2O	26.4	•	L_1 L_2 T_2	1990_2, 2019
5.B N_2O Emissions from Composting	N_2O	2.0			
Land Use, Land-Use Change, and Forestry					
4.E.2 Net CO_2 Emissions from Land Converted to Settlements	CO_2	79.2	•	L_1 T_1 L_2 T_2	1990, 2019
4.B.2 Net CO_2 Emissions from Land Converted to Cropland	CO_2	54.2	•	L_1 L_2	1990, 2019
4.C.1 Net CO_2 Emissions from Grassland Remaining Grassland	CO_2	14.5	•	L_2 T_2	1990_2, 2019_2
4.D.2 Net CO_2 Emissions from Land Converted to Wetlands	CO_2	(+)			
4.D.1 Net CO_2 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CO_2	(+)			
4.B.1 Net CO_2 Emissions from Cropland Remaining Cropland	CO_2	(+)	•	L_1 T_1 L_2 T_2	1990, 2019_2
4.C.2 Net CO_2 Emissions from Land Converted to Grassland	CO_2	(+)	•	L_1 T_1 L_2 T_2	2019
4.A.2 Net CO_2 Emissions from Land Converted to Forest Land	CO_2	(+)	•	L_1 L_2	1990, 2019_1
4.E.1 Net CO_2 Emissions from Settlements Remaining Settlements	CO_2	(+)	•	L_1 T_1 L_2 T_2	1990, 2019
4.A.1 Net CO_2 Emissions from Forest Land Remaining Forest Land	CO_2	(+)	•	L_1 T_1 L_2 T_2	1990, 2019
4.A.1 CH_4 Emissions from Forest Fires	CH_4	9.5	•	T_1	
4.D.1 CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CH_4	3.8			
4.C.1 CH_4 Emissions from Grass Fires	CH_4	0.3			
4.D.2 CH_4 Emissions from Land Converted to Coastal Wetlands	CH_4	0.2			

CRF Source/Sink Category	Greenhouse Gas	2019 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
4.A.4 CH_4 Emissions from Drained Organic Soils	CH_4	+			
4.D.1 CH_4 Emissions from Peatlands Remaining Peatlands	CH_4	+			
4.A.1 N_2O Emissions from Forest Fires	N_2O	6.2			
4.E.1 N_2O Emissions from Settlement Soils	N_2O	2.4			
4.A.1 N_2O Emissions from Forest Soils	N_2O	0.5			
4.C.1 N_2O Emissions from Grass Fires	N_2O	0.3			
4.D.1 N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	N_2O	0.1			
4.A.4 N_2O Emissions from Drained Organic Soils	N_2O	0.1			
4.D.1 N_2O Emissions from Peatlands Remaining Peatlands	N_2O	+			

Note: Parentheses indicate negative values (or sequestration).
+ Does not exceed 0.05 MMT CO_2 Eq.
[a] 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).
[b] Emissions from these sources not included in emission totals.

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 90 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. 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. The uncertainty associated with CO_2 from mobile combustion is applied to each mode's emission estimate. No uncertainty was associated with CH_4 emissions from waste incineration nor certain F-GHGs, photovoltaics (PV), micro-electro-mechanical systems (MEMS) devices (MEMs), and Heat Transfer Fluids (HTFs) from the Electronics Industry because an uncertainty analysis was not conducted.

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 or sink 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 or sink category. The United States has attempted to define source and sink categories by the conventions that 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 2019 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 2019 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 Category Approach 1 and Approach 2 Analysis—Level Assessment, without LULUCF

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
1.A.1 CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,546.5	0.24	0.24	10%	0.023
1.A.3.b CO_2 Emissions from Mobile Combustion: Road	CO_2	1,157.4	0.18	0.42	6%	0.012
1.A.2 CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	408.8	0.06	0.48	7%	0.005
1.A.2 CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	287.2	0.04	0.53	21%	0.009
3.D.1 Direct N_2O Emissions from Agricultural Soil Management	N_2O	272.5	0.04	0.57	31%	0.013
1.A.4.b CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	237.8	0.04	0.61	7%	0.003
1.B.2 CH_4 Emissions from Natural Gas Systems	CH_4	187.7	0.03	0.64	15%	0.004
1.A.3.a CO_2 Emissions from Mobile Combustion: Aviation	CO_2	187.4	0.03	0.66	6%	0.002
5.A CH_4 Emissions from Landfills	CH_4	179.6	0.03	0.69	23%	0.006
1.A.1 CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	175.4	0.03	0.72	5%	0.001
3.A.1 CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	158.4	0.02	0.74	18%	0.004
1.A.2 CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	157.8	0.02	0.77	16%	0.004

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
1.A.4.a CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	142.0	0.02	0.79	7%	0.002
1.A.5 CO_2 Emissions from Non-Energy Use of Fuels	CO_2	112.8	0.02	0.81	50%	0.009
2.C.1 CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	104.7	0.02	0.82	18%	0.003
1.A.4.b CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	97.8	0.02	0.84	6%	0.001
1.A.1 CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	97.5	0.02	0.85	8%	0.001
1.B.1 Fugitive Emissions from Coal Mining	CH_4	96.5	0.01	0.87	17%	0.002
1.A.4.a CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	74.3	0.01	0.88	5%	0.001
1.B.2 CH_4 Emissions from Petroleum Systems	CH_4	48.5	0.01	0.89	34%	0.003
2.B.9 HFC-23 Emissions from HCFC-22 Production	HFCs	46.1	0.01	0.90	10%	0.001
3.D.2 Indirect N_2O Emissions from Applied Nitrogen	N_2O	43.4	0.01	0.90	154%	0.010
1.A.3.d CO_2 Emissions from Mobile Combustion: Marine	CO_2	39.3	0.01	0.91	6%	<0.001
1.A.3.b N_2O Emissions from Mobile Combustion: Road	N_2O	37.7	0.01	0.91	14%	0.001
1.A.3.e CO_2 Emissions from Mobile Combustion: Other	CO_2	36.0	0.01	0.92	6%	<0.001
1.A.3.c CO_2 Emissions from Mobile Combustion: Railways	CO_2	35.5	0.01	0.93	6%	<0.001
2.A.1 CO_2 Emissions from Cement Production	CO_2	33.5	0.01	0.93	6%	<0.001
1.B.2 CO_2 Emissions from Natural Gas Systems	CO_2	32.0	<0.01	0.94	15%	0.001
2.G SF_6 Emissions from Electrical Transmission and Distribution	SF_6	23.2	<0.01	0.94	18%	0.001
2.B.8 CO_2 Emissions from Petrochemical Production	CO_2	21.6	<0.01	0.94	6%	<0.001
2.C.3 PFC Emissions from Aluminum Production	PFCs	21.5	<0.01	0.95	7%	<0.001
1.A.5 CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	21.2	<0.01	0.95	11%	<0.001
5.D CH_4 Emissions from Wastewater Treatment	CH_4	20.2	<0.01	0.95	38%	0.001
1.A.1 N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O	20.1	<0.01	0.96	48%	0.001
3.B.4 CH_4 Emissions from Manure Management: Other Livestock	CH_4	19.3	<0.01	0.96	20%	0.001
5.D N_2O Emissions from Wastewater Treatment	N_2O	18.7	<0.01	0.96	209%	0.006
3.B.1 CH_4 Emissions from Manure Management: Cattle	CH_4	17.9	<0.01	0.96	20%	0.001
3.C CH_4 Emissions from Rice Cultivation	CH_4	16.0	<0.01	0.97	149%	0.004

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
2.B.3 N_2O Emissions from Adipic Acid Production	N_2O	15.2	<0.01	0.97	5%	<0.001
1.A.5.b CO_2 Emissions from Mobile Combustion: Military	CO_2	13.6	<0.01	0.97	6%	<0.001
2.B.1 CO_2 Emissions from Ammonia Production	CO_2	13.0	<0.01	0.97	5%	<0.001
2.B.2 N_2O Emissions from Nitric Acid Production	N_2O	12.1	<0.01	0.97	5%	<0.001
1.A.4.a CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	12.0	<0.01	0.98	15%	<0.001
2.A.2 CO_2 Emissions from Lime Production	CO_2	11.7	<0.01	0.98	2%	<0.001
5.C.1 CO_2 Emissions from Incineration of Waste	CO_2	11.2	<0.01	0.98	29%	0.001
3.B.1 N_2O Emissions from Manure Management: Cattle	N_2O	11.2	<0.01	0.98	24%	<0.001
1.B.2 CO_2 Emissions from Petroleum Systems	CO_2	9.7	<0.01	0.98	34%	0.001
1.B.1 Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	7.2	<0.01	0.98	23%	<0.001
2.C.3 CO_2 Emissions from Aluminum Production	CO_2	6.8	<0.01	0.99	2%	<0.001
1.B.2 CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4	6.6	<0.01	0.99	219%	0.002
2.A.4 CO_2 Emissions from Other Process Uses of Carbonates	CO_2	6.3	<0.01	0.99	14%	<0.001
3.A.4 CH_4 Emissions from Enteric Fermentation: Other Livestock	CH_4	6.3	<0.01	0.99	18%	<0.001
1.A.4.b CH_4 Emissions from Stationary Combustion - Residential	CH_4	5.2	<0.01	0.99	233%	0.002
1.A.3.b CH_4 Emissions from Mobile Combustion: Road	CH_4	5.2	<0.01	0.99	26%	<0.001
2.C.4 SF_6 Emissions from Magnesium Production and Processing	SF_6	5.2	<0.01	0.99	8%	<0.001
1.A.3.e N_2O Emissions from Mobile Combustion: Other	N_2O	4.8	<0.01	0.99	61%	<0.001
3.G CO_2 Emissions from Liming	CO_2	4.7	<0.01	0.99	111%	0.001
2.G N_2O Emissions from Product Uses	N_2O	4.2	<0.01	0.99	24%	<0.001
2.B.10 CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	3.8	<0.01	0.99	16%	<0.001
2.E PFC, HFC, SF_6, and NF_3 Emissions from Electronics Industry	HiGWP	3.6	<0.01	0.99	6%	<0.001
1.A.2 N_2O Emissions from Stationary Combustion - Industrial	N_2O	3.1	<0.01	0.99	201%	0.001
1.A.4.b CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	3.0	<0.01	1.00	NE	<0.001
3.B.4 N_2O Emissions from Manure Management: Other Livestock	N_2O	2.8	<0.01	1.00	24%	<0.001
3.H CO_2 Emissions from Urea Fertilization	CO_2	2.4	<0.01	1.00	43%	<0.001
2.C.2 CO_2 Emissions from Ferroalloy Production	CO_2	2.2	<0.01	1.00	12%	<0.001
1.A.2 CH_4 Emissions from Stationary Combustion - Industrial	CH_4	1.8	<0.01	1.00	49%	<0.001

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
1.A.3.a N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.7	<0.01	1.00	67%	<0.001
2.B.4 N_2O Emissions from Caprolactam, Glyoxal, and Glyoxylic Acid Production	N_2O	1.7	<0.01	1.00	32%	<0.001
2.A.3 CO_2 Emissions from Glass Production	CO_2	1.5	<0.01	1.00	5%	<0.001
2.B.10 CO_2 Emissions from Phosphoric Acid Production	CO_2	1.5	<0.01	1.00	20%	<0.001
2.B.10 CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.5	<0.01	1.00	5%	<0.001
2.B.7 CO_2 Emissions from Soda Ash Production	CO_2	1.4	<0.01	1.00	9%	<0.001
2.B.6 CO_2 Emissions from Titanium Dioxide Production	CO_2	1.2	<0.01	1.00	13%	<0.001
1.A.4.a CH_4 Emissions from Stationary Combustion - Commercial	CH_4	1.1	<0.01	1.00	147%	<0.001
1.A.4.b N_2O Emissions from Stationary Combustion - Residential	N_2O	1.0	<0.01	1.00	215%	<0.001
1.A.3.d N_2O Emissions from Mobile Combustion: Marine	N_2O	0.8	<0.01	1.00	44%	<0.001
1.A.3.e CH_4 Emissions from Mobile Combustion: Other	CH_4	0.7	<0.01	1.00	52%	<0.001
2.C.6 CO_2 Emissions from Zinc Production	CO_2	0.6	<0.01	1.00	16%	<0.001
1.A.1 CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.5	<0.01	1.00	NA	<0.001
2.C.5 CO_2 Emissions from Lead Production	CO_2	0.5	<0.01	1.00	15%	<0.001
1.A.5 CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	0.5	<0.01	1.00	19%	<0.001
5.C.1 N_2O Emissions from Incineration of Waste	N_2O	0.5	<0.01	1.00	328%	<0.001
1.A.4.a N_2O Emissions from Stationary Combustion - Commercial	N_2O	0.4	<0.01	1.00	179%	<0.001
5.B CH_4 Emissions from Composting	CH_4	0.4	<0.01	1.00	50%	<0.001
3.F CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.4	<0.01	1.00	18%	<0.001
2.B.5 CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.4	<0.01	1.00	10%	<0.001
5.B N_2O Emissions from Composting	N_2O	0.3	<0.01	1.00	50%	<0.001
1.A.1 N_2O Emissions from Stationary Combustion - Gas - Electricity Generation	N_2O	0.3	<0.01	1.00	48%	<0.001
1.A.3.d CH_4 Emissions from Mobile Combustion: Marine	CH_4	0.3	<0.01	1.00	86%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Coal - Electricity Generation	CH_4	0.3	<0.01	1.00	10%	<0.001
1.A.3.c N_2O Emissions from Mobile Combustion: Railways	N_2O	0.3	<0.01	1.00	69%	<0.001
2.B.8 CH_4 Emissions from Petrochemical Production	CH_4	0.2	<0.01	1.00	57%	<0.001
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	0.2	<0.01	1.00	72%	<0.001

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
3.F N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.2	<0.01	1.00	17%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Gas - Electricity Generation	CH_4	0.1	<0.01	1.00	2%	<0.001
1.A.1 N_2O Emissions from Stationary Combustion - Oil - Electricity Generation	N_2O	0.1	<0.01	1.00	10%	<0.001
1.A.3.c CH_4 Emissions from Mobile Combustion: Railways	CH_4	0.1	<0.01	1.00	26%	<0.001
1.A.3.a CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.1	<0.01	1.00	87%	<0.001
1.A.5 N_2O Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1	<0.01	1.00	199%	<0.001
1.A.5 CH_4 Emissions from Stationary Combustion - U.S. Territories	CH_4	+	<0.01	1.00	55%	<0.001
2.E N_2O Emissions from Electronics Industry	N_2O	+	<0.01	1.00	9%	<0.001
2.B.5 CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+	<0.01	1.00	9%	<0.001
2.C.1 CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+	<0.01	1.00	20%	<0.001
2.C.2 CH_4 Emissions from Ferroalloy Production	CH_4	+	<0.01	1.00	12%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Oil - Electricity Generation	CH_4	+	<0.01	1.00	9%	<0.001
1.B.2 N_2O Emissions from Petroleum Systems	N_2O	+	<0.01	1.00	34%	<0.001
5.B.2 CH_4 Emissions from Anaerobic Digestion at Biogas Facilities	CH_4	+	<0.01	1.00	50%	<0.001
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air Conditioning	HFCs, PFCs	+	<0.01	1.00	14%	<0.001
1.B.2 CO_2 Emissions from Abandoned Oil and Gas Wells	CO_2	+	<0.01	1.00	219%	<0.001
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs	+	<0.01	1.00	9%	<0.001
1.B.2 N_2O Emissions from Natural Gas Systems	N_2O	+	<0.01	1.00	15%	<0.001
1.A.1 N_2O Emissions from Stationary Combustion - Wood - Electricity Generation	N_2O	+	<0.01	1.00	2%	<0.001
2.C.4 CO_2 Emissions from Magnesium Production and Processing	CO_2	+	<0.01	1.00	3%	<0.001
1.A.5.b CH_4 Emissions from Mobile Combustion: Military	CH_4	+	<0.01	1.00	26%	<0.001
1.A.5.b N_2O Emissions from Mobile Combustion: Military	N_2O	+	<0.01	1.00	14%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Wood - Electricity Generation	CH_4	+	<0.01	1.00	2%	<0.001

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
5.C.1 CH_4 Emissions from Incineration of Waste	CH_4	+	<0.01	1.00	NE	<0.001
1.A.5 CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	0.0	<0.01	1.00	17%	<0.001
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs	0.0	<0.01	1.00	17%	<0.001
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs	0.0	<0.01	1.00	24%	<0.001
2.C.4 HFC-134a Emissions from Magnesium Production and Processing	HFCs	0.0	<0.01	1.00	25%	<0.001

Note: LULUCF sources and sinks are not included in this analysis.
+ Does not exceed 0.05 MMT CO_2 Eq.
NE (Not Estimated)
NA (Not Available)
[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.

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

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
1.A.1 CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,546.5	0.20	0.20	10%	0.020
1.A.3.b CO_2 Emissions from Mobile Combustion: Road	CO_2	1,157.4	0.15	0.36	6%	0.010
4.A.1 Net CO_2 Emissions from Forest Land Remaining Forest Land	CO_2	787.6	0.10	0.46	27%	0.028
1.A.2 CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	408.8	0.05	0.51	7%	0.004
1.A.2 CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	287.2	0.04	0.55	21%	0.008
3.D.1 Direct N_2O Emissions from Agricultural Soil Management	N_2O	272.5	0.04	0.59	31%	0.011
1.A.4.b CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	237.8	0.03	0.62	7%	0.002
1.B.2 CH_4 Emissions from Natural Gas Systems	CH_4	187.7	0.02	0.64	15%	0.004
1.A.3.a CO_2 Emissions from Mobile Combustion: Aviation	CO_2	187.4	0.02	0.67	6%	0.002
5.A CH_4 Emissions from Landfills	CH_4	179.6	0.02	0.69	23%	0.005
1.A.1 CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	175.4	0.02	0.71	5%	0.001
3.A.1 CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	158.4	0.02	0.73	18%	0.004
1.A.2 CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	157.8	0.02	0.75	16%	0.003
1.A.4.a CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	142.0	0.02	0.77	7%	0.001
1.A.5 CO_2 Emissions from Non-Energy Use of Fuels	CO_2	112.8	0.01	0.79	50%	0.007
4.E.1 Net CO_2 Emissions from Settlements Remaining Settlements	CO_2	109.6	0.01	0.80	96%	0.014

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
2.C.1 CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	104.7	0.01	0.82	18%	0.003
4.A.2 Net CO_2 Emissions from Land Converted to Forest Land	CO_2	98.2	0.01	0.83	11%	0.001
1.A.4.b CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	97.8	0.01	0.84	6%	0.001
1.A.1 CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	97.5	0.01	0.85	8%	0.001
1.B.1 Fugitive Emissions from Coal Mining	CH_4	96.5	0.01	0.87	17%	0.002
1.A.4.a CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	74.3	0.01	0.88	5%	<0.001
4.E.2 Net CO_2 Emissions from Land Converted to Settlements	CO_2	62.9	0.01	0.89	34%	0.003
4.B.2 Net CO_2 Emissions from Land Converted to Cropland	CO_2	51.8	0.01	0.89	103%	0.007
1.B.2 CH_4 Emissions from Petroleum Systems	CH_4	48.5	0.01	0.90	34%	0.002
2.B.9 HFC-23 Emissions from HCFC-22 Production	HFCs	46.1	0.01	0.90	10%	0.001
3.D.2 Indirect N_2O Emissions from Applied Nitrogen	N_2O	43.4	0.01	0.91	154%	0.009
1.A.3.d CO_2 Emissions from Mobile Combustion: Marine	CO_2	39.3	0.01	0.92	6%	<0.001
1.A.3.b N_2O Emissions from Mobile Combustion: Road	N_2O	37.7	<0.01	0.92	14%	0.001
1.A.3.e CO_2 Emissions from Mobile Combustion: Other	CO_2	36.0	<0.01	0.93	6%	<0.001
1.A.3.c CO_2 Emissions from Mobile Combustion: Railways	CO_2	35.5	<0.01	0.93	6%	<0.001
2.A.1 CO_2 Emissions from Cement Production	CO_2	33.5	<0.01	0.93	6%	<0.001
1.B.2 CO_2 Emissions from Natural Gas Systems	CO_2	32.0	<0.01	0.94	15%	0.001
4.B.1 Net CO_2 Emissions from Cropland Remaining Cropland	CO_2	23.2	<0.01	0.94	601%	0.018
2.G SF_6 Emissions from Electrical Transmission and Distribution	SF_6	23.2	<0.01	0.94	18%	0.001
2.B.8 CO_2 Emissions from Petrochemical Production	CO_2	21.6	<0.01	0.95	6%	<0.001
2.C.3 PFC Emissions from Aluminum Production	PFCs	21.5	<0.01	0.95	7%	<0.001
1.A.5 CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	21.2	<0.01	0.95	11%	<0.001
5.D CH_4 Emissions from Wastewater Treatment	CH_4	20.2	<0.01	0.96	38%	0.001
1.A.1 N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O	20.1	<0.01	0.96	48%	0.001
3.B.4 CH_4 Emissions from Manure Management: Other Livestock	CH_4	19.3	<0.01	0.96	20%	0.001
5.D N_2O Emissions from Wastewater Treatment	N_2O	18.7	<0.01	0.96	209%	0.005

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
3.B.1 CH_4 Emissions from Manure Management: Cattle	CH_4	17.9	<0.01	0.97	20%	<0.001
3.C CH_4 Emissions from Rice Cultivation	CH_4	16.0	<0.01	0.97	149%	0.003
2.B.3 N_2O Emissions from Adipic Acid Production	N_2O	15.2	<0.01	0.97	5%	<0.001
1.A.5.b CO_2 Emissions from Mobile Combustion: Military	CO_2	13.6	<0.01	0.97	6%	<0.001
2.B.1 CO_2 Emissions from Ammonia Production	CO_2	13.0	<0.01	0.97	5%	<0.001
2.B.2 N_2O Emissions from Nitric Acid Production	N_2O	12.1	<0.01	0.97	5%	<0.001
1.A.4.a CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	12.0	<0.01	0.98	15%	<0.001
2.A.2 CO_2 Emissions from Lime Production	CO_2	11.7	<0.01	0.98	2%	<0.001
5.C.1 CO_2 Emissions from Incineration of Waste	CO_2	11.2	<0.01	0.98	29%	<0.001
3.B.1 N_2O Emissions from Manure Management: Cattle	N_2O	11.2	<0.01	0.98	24%	<0.001
1.B.2 CO_2 Emissions from Petroleum Systems	CO_2	9.7	<0.01	0.98	34%	<0.001
4.C.1 Net CO_2 Emissions from Grassland Remaining Grassland	CO_2	8.3	<0.01	0.98	1066%	0.012
4.D.1 Net CO_2 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CO_2	7.4	<0.01	0.98	64%	0.001
1.B.1 Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	7.2	<0.01	0.99	23%	<0.001
2.C.3 CO_2 Emissions from Aluminum Production	CO_2	6.8	<0.01	0.99	2%	<0.001
1.B.2 CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4	6.6	<0.01	0.99	219%	0.002
2.A.4 CO_2 Emissions from Other Process Uses of Carbonates	CO_2	6.3	<0.01	0.99	14%	<0.001
3.A.4 CH_4 Emissions from Enteric Fermentation: Other Livestock	CH_4	6.3	<0.01	0.99	18%	<0.001
4.C.2 Net CO_2 Emissions from Land Converted to Grassland	CO_2	6.2	<0.01	0.99	148%	0.001
1.A.4.b CH_4 Emissions from Stationary Combustion - Residential	CH_4	5.2	<0.01	0.99	233%	0.002
1.A.3.b CH_4 Emissions from Mobile Combustion: Road	CH_4	5.2	<0.01	0.99	26%	<0.001
2.C.4 SF_6 Emissions from Magnesium Production and Processing	SF_6	5.2	<0.01	0.99	8%	<0.001
1.A.3.e N_2O Emissions from Mobile Combustion: Other	N_2O	4.8	<0.01	0.99	61%	<0.001
3.G CO_2 Emissions from Liming	CO_2	4.7	<0.01	0.99	111%	0.001
2.G N_2O Emissions from Product Uses	N_2O	4.2	<0.01	0.99	24%	<0.001
2.B.10 CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	3.8	<0.01	0.99	16%	<0.001
4.D.1 CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CH_4	3.7	<0.01	0.99	30%	<0.001

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
2.E PFC, HFC, SF_6, and NF_3 Emissions from Electronics Industry	HiGWP	3.6	<0.01	0.99	6%	<0.001
1.A.2 N_2O Emissions from Stationary Combustion - Industrial	N_2O	3.1	<0.01	1.00	201%	0.001
1.A.4.b CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	3.0	<0.01	1.00	NE	<0.001
3.B.4 N_2O Emissions from Manure Management: Other Livestock	N_2O	2.8	<0.01	1.00	24%	<0.001
3.H CO_2 Emissions from Urea Fertilization	CO_2	2.4	<0.01	1.00	43%	<0.001
2.C.2 CO_2 Emissions from Ferroalloy Production	CO_2	2.2	<0.01	1.00	12%	<0.001
4.E.1 N_2O Emissions from Settlement Soils	N_2O	2.0	<0.01	1.00	56%	<0.001
1.A.2 CH_4 Emissions from Stationary Combustion - Industrial	CH_4	1.8	<0.01	1.00	49%	<0.001
1.A.3.a N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.7	<0.01	1.00	67%	<0.001
2.B.4 N_2O Emissions from Caprolactam, Glyoxal, and Glyoxylic Acid Production	N_2O	1.7	<0.01	1.00	32%	<0.001
2.A.3 CO_2 Emissions from Glass Production	CO_2	1.5	<0.01	1.00	5%	<0.001
2.B.10 CO_2 Emissions from Phosphoric Acid Production	CO_2	1.5	<0.01	1.00	20%	<0.001
2.B.10 CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.5	<0.01	1.00	5%	<0.001
2.B.7 CO_2 Emissions from Soda Ash Production	CO_2	1.4	<0.01	1.00	9%	<0.001
2.B.6 CO_2 Emissions from Titanium Dioxide Production	CO_2	1.2	<0.01	1.00	13%	<0.001
1.A.4.a CH_4 Emissions from Stationary Combustion - Commercial	CH_4	1.1	<0.01	1.00	147%	<0.001
1.A.4.b N_2O Emissions from Stationary Combustion - Residential	N_2O	1.0	<0.01	1.00	215%	<0.001
4.A.1 CH_4 Emissions from Forest Fires	CH_4	0.9	<0.01	1.00	18%	<0.001
1.A.3.d N_2O Emissions from Mobile Combustion: Marine	N_2O	0.8	<0.01	1.00	44%	<0.001
1.A.3.e CH_4 Emissions from Mobile Combustion: Other	CH_4	0.7	<0.01	1.00	52%	<0.001
2.C.6 CO_2 Emissions from Zinc Production	CO_2	0.6	<0.01	1.00	16%	<0.001
4.A.1 N_2O Emissions from Forest Fires	N_2O	0.6	<0.01	1.00	14%	<0.001
1.A.1 CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.5	<0.01	1.00	NA	<0.001
2.C.5 CO_2 Emissions from Lead Production	CO_2	0.5	<0.01	1.00	15%	<0.001
1.A.5 CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	0.5	<0.01	1.00	19%	<0.001
5.C.1 N_2O Emissions from Incineration of Waste	N_2O	0.5	<0.01	1.00	328%	<0.001
4.D.2 Net CO_2 Emissions from Land Converted to Wetlands	CO_2	0.4	<0.01	1.00	37%	<0.001
1.A.4.a N_2O Emissions from Stationary Combustion - Commercial	N_2O	0.4	<0.01	1.00	179%	<0.001

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
5.B CH_4 Emissions from Composting	CH_4	0.4	<0.01	1.00	50%	<0.001
3.F CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.4	<0.01	1.00	18%	<0.001
2.B.5 CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.4	<0.01	1.00	10%	<0.001
5.B N_2O Emissions from Composting	N_2O	0.3	<0.01	1.00	50%	<0.001
1.A.1 N_2O Emissions from Stationary Combustion - Gas - Electricity Generation	N_2O	0.3	<0.01	1.00	48%	<0.001
1.A.3.d CH_4 Emissions from Mobile Combustion: Marine	CH_4	0.3	<0.01	1.00	86%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Coal - Electricity Generation	CH_4	0.3	<0.01	1.00	10%	<0.001
1.A.3.c N_2O Emissions from Mobile Combustion: Railways	N_2O	0.3	<0.01	1.00	69%	<0.001
4.D.2 CH_4 Emissions from Land Converted to Coastal Wetlands	CH_4	0.2	<0.01	1.00	30%	<0.001
2.B.8 CH_4 Emissions from Petrochemical Production	CH_4	0.2	<0.01	1.00	57%	<0.001
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	0.2	<0.01	1.00	72%	<0.001
3.F N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.2	<0.01	1.00	17%	<0.001
4.D.1 N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	N_2O	0.1	<0.01	1.00	116%	<0.001
4.A.4 N_2O Emissions from Drained Organic Soils	N_2O	0.1	<0.01	1.00	128%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Gas - Electricity Generation	CH_4	0.1	<0.01	1.00	2%	<0.001
4.A.1 N_2O Emissions from Forest Soils	N_2O	0.1	<0.01	1.00	318%	<0.001
4.C.1 N_2O Emissions from Grass Fires	N_2O	0.1	<0.01	1.00	146%	<0.001
1.A.1 N_2O Emissions from Stationary Combustion - Oil - Electricity Generation	N_2O	0.1	<0.01	1.00	10%	<0.001
4.C.1 CH_4 Emissions from Grass Fires	CH_4	0.1	<0.01	1.00	146%	<0.001
1.A.3.c CH_4 Emissions from Mobile Combustion: Railways	CH_4	0.1	<0.01	1.00	26%	<0.001
1.A.3.a CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.1	<0.01	1.00	87%	<0.001
1.A.5 N_2O Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1	<0.01	1.00	199%	<0.001
1.A.5 CH_4 Emissions from Stationary Combustion - U.S. Territories	CH_4	+	<0.01	1.00	55%	<0.001
2.E N_2O Emissions from Electronics Industry	N_2O	+	<0.01	1.00	9%	<0.001
2.B.5 CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+	<0.01	1.00	9%	<0.001

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
2.C.1 CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+	<0.01	1.00	20%	<0.001
2.C.2 CH_4 Emissions from Ferroalloy Production	CH_4	+	<0.01	1.00	12%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Oil - Electricity Generation	CH_4	+	<0.01	1.00	9%	<0.001
1.B.2 N_2O Emissions from Petroleum Systems	N_2O	+	<0.01	1.00	34%	<0.001
5.B.2 CH_4 Emissions from Anaerobic Digestion at Biogas Facilities	CH_4	+	<0.01	1.00	50%	<0.001
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air Conditioning	HFCs, PFCs	+	<0.01	1.00	14%	<0.001
4.A.4 CH_4 Emissions from Drained Organic Soils	CH_4	+	<0.01	1.00	80%	<0.001
1.B.2 CO_2 Emissions from Abandoned Oil and Gas Wells	CO_2	+	<0.01	1.00	219%	<0.001
4.D.1 CH_4 Emissions from Peatlands Remaining Peatlands	CH_4	+	<0.01	1.00	78%	<0.001
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs	+	<0.01	1.00	9%	<0.001
1.B.2 N_2O Emissions from Natural Gas Systems	N_2O	+	<0.01	1.00	15%	<0.001
1.A.1 N_2O Emissions from Stationary Combustion - Wood - Electricity Generation	N_2O	+	<0.01	1.00	2%	<0.001
2.C.4 CO_2 Emissions from Magnesium Production and Processing	CO_2	+	<0.01	1.00	3%	<0.001
1.A.5.b CH_4 Emissions from Mobile Combustion: Military	CH_4	+	<0.01	1.00	26%	<0.001
4.D.1 N_2O Emissions from Peatlands Remaining Peatlands	N_2O	+	<0.01	1.00	53%	<0.001
1.A.5.b N_2O Emissions from Mobile Combustion: Military	N_2O	+	<0.01	1.00	14%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Wood - Electricity Generation	CH_4	+	<0.01	1.00	2%	<0.001
5.C.1 CH_4 Emissions from Incineration of Waste	CH_4	+	<0.01	1.00	NE	<0.001
2.C.4 HFC-134a Emissions from Magnesium Production and Processing	HFCs	0.0	<0.01	1.00	25%	<0.001
1.A.5 CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	0.0	<0.01	1.00	17%	<0.001
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs	0.0	<0.01	1.00	17%	<0.001
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs	0.0	<0.01	1.00	24%	<0.001

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

NA (Not Available)
[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.

Table A-6: 2019 Key Category Approach 1 and Approach 2 Analysis—Level Assessment, without LULUCF

CRF Source/Sink Category	Greenhouse Gas	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
1.A.3.b CO_2 Emissions from Mobile Combustion: Road	CO_2	1,535.3	0.23	0.23	6%	0.015
1.A.1 CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	973.5	0.15	0.38	10%	0.014
1.A.1 CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	616.0	0.09	0.48	5%	0.005
1.A.2 CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	524.3	0.08	0.55	7%	0.006
3.D.1 Direct N_2O Emissions from Agricultural Soil Management	N_2O	290.4	0.04	0.60	31%	0.014
1.A.4.b CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	275.3	0.04	0.64	7%	0.003
1.A.2 CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	264.0	0.04	0.68	21%	0.008
1.A.4.a CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	192.8	0.03	0.71	7%	0.002
1.A.3.a CO_2 Emissions from Mobile Combustion: Aviation	CO_2	178.4	0.03	0.74	6%	0.002
3.A.1 CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	172.3	0.03	0.76	18%	0.005
1.B.2 CH_4 Emissions from Natural Gas Systems	CH_4	156.4	0.02	0.79	15%	0.004
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air Conditioning	HFCs, PFCs	132.6	0.02	0.81	14%	0.003
5.A CH_4 Emissions from Landfills	CH_4	114.5	0.02	0.82	23%	0.004
1.A.5 CO_2 Emissions from Non-Energy Use of Fuels	CO_2	110.1	0.02	0.84	50%	0.008
1.A.4.b CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	63.5	0.01	0.85	6%	0.001
3.D.2 Indirect N_2O Emissions from Applied Nitrogen	N_2O	54.2	0.01	0.86	154%	0.013
1.A.3.e CO_2 Emissions from Mobile Combustion: Other	CO_2	53.7	0.01	0.87	6%	0.001
1.A.2 CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	49.2	0.01	0.88	16%	0.001
1.B.1 Fugitive Emissions from Coal Mining	CH_4	47.4	0.01	0.88	17%	0.001
1.A.4.a CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	43.9	0.01	0.89	5%	<0.001

CRF Source/Sink Category	Greenhouse Gas	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
1.B.2 CO_2 Emissions from Petroleum Systems	CO_2	43.3	0.01	0.90	34%	0.002
2.C.1 CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	41.3	0.01	0.90	18%	0.001
2.A.1 CO_2 Emissions from Cement Production	CO_2	40.9	0.01	0.91	6%	<0.001
1.B.2 CH_4 Emissions from Petroleum Systems	CH_4	40.2	0.01	0.91	34%	0.002
1.B.2 CO_2 Emissions from Natural Gas Systems	CO_2	36.9	0.01	0.92	15%	0.001
1.A.3.c CO_2 Emissions from Mobile Combustion: Railways	CO_2	36.7	0.01	0.93	6%	<0.001
3.B.1 CH_4 Emissions from Manure Management: Cattle	CH_4	35.4	0.01	0.93	20%	0.001
1.A.3.d CO_2 Emissions from Mobile Combustion: Marine	CO_2	33.8	0.01	0.94	6%	<0.001
2.B.8 CO_2 Emissions from Petrochemical Production	CO_2	30.8	<0.01	0.94	6%	<0.001
3.B.4 CH_4 Emissions from Manure Management: Other Livestock	CH_4	26.9	<0.01	0.94	20%	0.001
5.D N_2O Emissions from Wastewater Treatment	N_2O	26.4	<0.01	0.95	209%	0.008
5.C.1 CO_2 Emissions from Incineration of Waste	CO_2	20.2	<0.01	0.95	29%	0.001
1.A.5 CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	19.5	<0.01	0.95	11%	<0.001
5.D CH_4 Emissions from Wastewater Treatment	CH_4	18.4	<0.01	0.96	38%	0.001
1.A.1 N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O	16.7	<0.01	0.96	48%	0.001
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	16.3	<0.01	0.96	72%	0.002
1.A.1 CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	16.2	<0.01	0.97	8%	<0.001
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs	16.1	<0.01	0.97	9%	<0.001
3.B.1 N_2O Emissions from Manure Management: Cattle	N_2O	15.4	<0.01	0.97	24%	0.001
3.C CH_4 Emissions from Rice Cultivation	CH_4	15.1	<0.01	0.97	149%	0.003
2.A.2 CO_2 Emissions from Lime Production	CO_2	13.0	<0.01	0.97	2%	<0.001
2.B.1 CO_2 Emissions from Ammonia Production	CO_2	12.3	<0.01	0.98	5%	<0.001
2.B.2 N_2O Emissions from Nitric Acid Production	N_2O	10.0	<0.01	0.98	5%	<0.001
1.A.3.b N_2O Emissions from Mobile Combustion: Road	N_2O	9.6	<0.01	0.98	14%	<0.001

CRF Source/Sink Category	Greenhouse Gas	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
2.A.4 CO_2 Emissions from Other Process Uses of Carbonates	CO_2	7.5	<0.01	0.98	14%	<0.001
1.B.2 CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4	7.0	<0.01	0.98	219%	0.002
2.B.10 CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	6.6	<0.01	0.98	16%	<0.001
1.A.3.e N_2O Emissions from Mobile Combustion: Other	N_2O	6.5	<0.01	0.98	61%	0.001
3.A.4 CH_4 Emissions from Enteric Fermentation: Other Livestock	CH_4	6.3	<0.01	0.98	18%	<0.001
1.B.1 Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	5.9	<0.01	0.99	23%	<0.001
3.H CO_2 Emissions from Urea Fertilization	CO_2	5.3	<0.01	0.99	43%	<0.001
1.A.5.b CO_2 Emissions from Mobile Combustion: Military	CO_2	5.3	<0.01	0.99	6%	<0.001
2.B.3 N_2O Emissions from Adipic Acid Production	N_2O	5.3	<0.01	0.99	5%	<0.001
2.B.10 CO_2 Emissions from Carbon Dioxide Consumption	CO_2	4.9	<0.01	0.99	5%	<0.001
1.A.4.b CH_4 Emissions from Stationary Combustion - Residential	CH_4	4.6	<0.01	0.99	233%	0.002
2.E PFC, HFC, SF_6, and NF_3 Emissions from Electronics Industry	HiGWP	4.4	<0.01	0.99	6%	<0.001
1.A.1 N_2O Emissions from Stationary Combustion - Gas - Electricity Generation	N_2O	4.4	<0.01	0.99	48%	<0.001
2.G SF_6 Emissions from Electrical Transmission and Distribution	SF_6	4.2	<0.01	0.99	18%	<0.001
2.G N_2O Emissions from Product Uses	N_2O	4.2	<0.01	0.99	24%	<0.001
3.B.4 N_2O Emissions from Manure Management: Other Livestock	N_2O	4.2	<0.01	0.99	24%	<0.001
2.B.9 HFC-23 Emissions from HCFC-22 Production	HFCs	3.7	<0.01	0.99	10%	<0.001
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs	2.8	<0.01	0.99	17%	<0.001
1.A.5 CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	2.5	<0.01	0.99	17%	<0.001
1.A.5 CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	2.5	<0.01	0.99	19%	<0.001
1.A.2 N_2O Emissions from Stationary Combustion - Industrial	N_2O	2.5	<0.01	0.99	201%	0.001
3.G CO_2 Emissions from Liming	CO_2	2.4	<0.01	0.99	111%	<0.001
5.B CH_4 Emissions from Composting	CH_4	2.3	<0.01	1.00	50%	<0.001

CRF Source/Sink Category	Greenhouse Gas	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
5.B N_2O Emissions from Composting	N_2O	2.0	<0.01	1.00	50%	<0.001
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs	2.0	<0.01	1.00	24%	<0.001
2.C.3 CO_2 Emissions from Aluminum Production	CO_2	1.9	<0.01	1.00	2%	<0.001
2.B.7 CO_2 Emissions from Soda Ash Production	CO_2	1.8	<0.01	1.00	9%	<0.001
2.C.3 PFC Emissions from Aluminum Production	PFCs	1.8	<0.01	1.00	7%	<0.001
1.A.3.a N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.6	<0.01	1.00	67%	<0.001
1.A.4.a CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	1.6	<0.01	1.00	15%	<0.001
2.C.2 CO_2 Emissions from Ferroalloy Production	CO_2	1.6	<0.01	1.00	12%	<0.001
1.A.2 CH_4 Emissions from Stationary Combustion - Industrial	CH_4	1.5	<0.01	1.00	49%	<0.001
2.B.6 CO_2 Emissions from Titanium Dioxide Production	CO_2	1.5	<0.01	1.00	13%	<0.001
2.B.4 N_2O Emissions from Caprolactam, Glyoxal, and Glyoxylic Acid Production	N_2O	1.4	<0.01	1.00	32%	<0.001
2.A.3 CO_2 Emissions from Glass Production	CO_2	1.3	<0.01	1.00	5%	<0.001
1.A.4.a CH_4 Emissions from Stationary Combustion - Commercial	CH_4	1.2	<0.01	1.00	147%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Gas - Electricity Generation	CH_4	1.1	<0.01	1.00	2%	<0.001
2.C.4 SF_6 Emissions from Magnesium Production and Processing	SF_6	1.0	<0.01	1.00	8%	<0.001
2.C.6 CO_2 Emissions from Zinc Production	CO_2	1.0	<0.01	1.00	16%	<0.001
1.A.3.b CH_4 Emissions from Mobile Combustion: Road	CH_4	0.9	<0.01	1.00	26%	<0.001
1.A.3.e CH_4 Emissions from Mobile Combustion: Other	CH_4	0.9	<0.01	1.00	52%	<0.001
1.A.4.b N_2O Emissions from Stationary Combustion - Residential	N_2O	0.9	<0.01	1.00	215%	<0.001
2.B.10 CO_2 Emissions from Phosphoric Acid Production	CO_2	0.9	<0.01	1.00	20%	<0.001
1.A.3.d N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6	<0.01	1.00	44%	<0.001
2.C.5 CO_2 Emissions from Lead Production	CO_2	0.5	<0.01	1.00	15%	<0.001
3.F CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.4	<0.01	1.00	18%	<0.001

CRF Source/Sink Category	Greenhouse Gas	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
5.C.1 N_2O Emissions from Incineration of Waste	N_2O	0.4	<0.01	1.00	328%	<0.001
1.A.3.d CH_4 Emissions from Mobile Combustion: Marine	CH_4	0.4	<0.01	1.00	86%	<0.001
1.A.1 CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4	<0.01	1.00	NA	<0.001
2.B.8 CH_4 Emissions from Petrochemical Production	CH_4	0.3	<0.01	1.00	57%	<0.001
1.A.4.a N_2O Emissions from Stationary Combustion - Commercial	N_2O	0.3	<0.01	1.00	179%	<0.001
1.A.3.c N_2O Emissions from Mobile Combustion: Railways	N_2O	0.3	<0.01	1.00	69%	<0.001
2.E N_2O Emissions from Electronics Industry	N_2O	0.2	<0.01	1.00	9%	<0.001
5.B.2 CH_4 Emissions from Anaerobic Digestion at Biogas Facilities	CH_4	0.2	<0.01	1.00	50%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Coal - Electricity Generation	CH_4	0.2	<0.01	1.00	10%	<0.001
3.F N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.2	<0.01	1.00	17%	<0.001
2.B.5 CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.2	<0.01	1.00	10%	<0.001
1.A.3.c CH_4 Emissions from Mobile Combustion: Railways	CH_4	0.1	<0.01	1.00	26%	<0.001
2.C.4 HFC-134a Emissions from Magnesium Production and Processing	HFCs	0.1	<0.01	1.00	25%	<0.001
1.A.5 N_2O Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1	<0.01	1.00	199%	<0.001
1.B.2 N_2O Emissions from Petroleum Systems	N_2O	+	<0.01	1.00	34%	<0.001
1.A.5 CH_4 Emissions from Stationary Combustion - U.S. Territories	CH_4	+	<0.01	1.00	55%	<0.001
1.A.3.a CH_4 Emissions from Mobile Combustion: Aviation	CH_4	+	<0.01	1.00	87%	<0.001
1.A.1 N_2O Emissions from Stationary Combustion - Wood - Electricity Generation	N_2O	+	<0.01	1.00	2%	<0.001
2.C.2 CH_4 Emissions from Ferroalloy Production	CH_4	+	<0.01	1.00	12%	<0.001
1.B.2 N_2O Emissions from Natural Gas Systems	N_2O	+	<0.01	1.00	15%	<0.001
2.B.5 CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+	<0.01	1.00	9%	<0.001
2.C.1 CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+	<0.01	1.00	20%	<0.001

CRF Source/Sink Category	Greenhouse Gas	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
1.B.2 CO_2 Emissions from Abandoned Oil and Gas Wells	CO_2	+	<0.01	1.00	219%	<0.001
1.A.1 N_2O Emissions from Stationary Combustion - Oil - Electricity Generation	N_2O	+	<0.01	1.00	10%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Wood - Electricity Generation	CH_4	+	<0.01	1.00	2%	<0.001
2.C.4 CO_2 Emissions from Magnesium Production and Processing	CO_2	+	<0.01	1.00	3%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Oil - Electricity Generation	CH_4	+	<0.01	1.00	9%	<0.001
1.A.5.b CH_4 Emissions from Mobile Combustion: Military	CH_4	+	<0.01	1.00	26%	<0.001
1.A.5.b N_2O Emissions from Mobile Combustion: Military	N_2O	+	<0.01	1.00	14%	<0.001
5.C.1 CH_4 Emissions from Incineration of Waste	CH_4	+	<0.01	1.00	NE	<0.001
1.A.4.b CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	0.0	<0.01	1.00	NE	<0.001

Note: LULUCF sources and sinks are not included in this analysis.
+ Does not exceed 0.05 MMT CO_2 Eq.
NE (Not Estimated)
NA (Not Available)
[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.

Table A-7: 2019 Key Category Approach 1 and Approach 2 Analysis—Level Assessment with LULUCF

CRF Source/Sink Category	Greenhouse Gas	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
1.A.3.b CO_2 Emissions from Mobile Combustion: Road	CO_2	1,535.3	0.20	0.20	6%	0.013
1.A.1 CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	973.5	0.13	0.33	10%	0.012
4.A.1 Net CO_2 Emissions from Forest Land Remaining Forest Land	CO_2	691.8	0.09	0.42	27%	0.024
1.A.1 CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	616.0	0.08	0.50	5%	0.004
1.A.2 CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	524.3	0.07	0.56	7%	0.005
3.D.1 Direct N_2O Emissions from Agricultural Soil Management	N_2O	290.4	0.04	0.60	31%	0.012
1.A.4.b CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	275.3	0.04	0.64	7%	0.002

CRF Source/Sink Category	Greenhouse Gas	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
1.A.2 CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	264.0	0.03	0.67	21%	0.007
1.A.4.a CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	192.8	0.03	0.70	7%	0.002
1.A.3.a CO_2 Emissions from Mobile Combustion: Aviation	CO_2	178.4	0.02	0.72	6%	0.001
3.A.1 CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	172.3	0.02	0.74	18%	0.004
1.B.2 CH_4 Emissions from Natural Gas Systems	CH_4	156.4	0.02	0.76	15%	0.003
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air Conditioning	HFCs, PFCs	132.6	0.02	0.78	14%	0.002
4.E.1 Net CO_2 Emissions from Settlements Remaining Settlements	CO_2	124.1	0.02	0.79	96%	0.015
5.A CH_4 Emissions from Landfills	CH_4	114.5	0.01	0.81	23%	0.003
1.A.5 CO_2 Emissions from Non-Energy Use of Fuels	CO_2	110.1	0.01	0.82	50%	0.007
4.A.2 Net CO_2 Emissions from Land Converted to Forest Land	CO_2	99.1	0.01	0.84	11%	0.001
4.E.2 Net CO_2 Emissions from Land Converted to Settlements	CO_2	79.2	0.01	0.85	34%	0.003
1.A.4.b CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	63.5	0.01	0.86	6%	<0.001
4.B.2 Net CO_2 Emissions from Land Converted to Cropland	CO_2	54.2	0.01	0.86	103%	0.007
3.D.2 Indirect N_2O Emissions from Applied Nitrogen	N_2O	54.2	0.01	0.87	154%	0.011
1.A.3.e CO_2 Emissions from Mobile Combustion: Other	CO_2	53.7	0.01	0.88	6%	<0.001
1.A.2 CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	49.2	0.01	0.88	16%	0.001
1.B.1 Fugitive Emissions from Coal Mining	CH_4	47.4	0.01	0.89	17%	0.001
1.A.4.a CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	43.9	0.01	0.89	5%	<0.001
1.B.2 CO_2 Emissions from Petroleum Systems	CO_2	43.3	0.01	0.90	34%	0.002
2.C.1 CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	41.3	0.01	0.91	18%	0.001
2.A.1 CO_2 Emissions from Cement Production	CO_2	40.9	0.01	0.91	6%	<0.001
1.B.2 CH_4 Emissions from Petroleum Systems	CH_4	40.2	0.01	0.92	34%	0.002
1.B.2 CO_2 Emissions from Natural Gas Systems	CO_2	36.9	<0.01	0.92	15%	0.001

CRF Source/Sink Category	Greenhouse Gas	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
1.A.3.c CO_2 Emissions from Mobile Combustion: Railways	CO_2	36.7	<0.01	0.93	6%	<0.001
3.B.1 CH_4 Emissions from Manure Management: Cattle	CH_4	35.4	<0.01	0.93	20%	0.001
1.A.3.d CO_2 Emissions from Mobile Combustion: Marine	CO_2	33.8	<0.01	0.93	6%	<0.001
2.B.8 CO_2 Emissions from Petrochemical Production	CO_2	30.8	<0.01	0.94	6%	<0.001
3.B.4 CH_4 Emissions from Manure Management: Other Livestock	CH_4	26.9	<0.01	0.94	20%	0.001
5.D N_2O Emissions from Wastewater Treatment	N_2O	26.4	<0.01	0.95	209%	0.007
4.C.2 Net CO_2 Emissions from Land Converted to Grassland	CO_2	23.2	<0.01	0.95	148%	0.004
5.C.1 CO_2 Emissions from Incineration of Waste	CO_2	20.2	<0.01	0.95	29%	0.001
1.A.5 CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	19.5	<0.01	0.95	11%	<0.001
5.D CH_4 Emissions from Wastewater Treatment	CH_4	18.4	<0.01	0.96	38%	0.001
1.A.1 N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O	16.7	<0.01	0.96	48%	0.001
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	16.3	<0.01	0.96	72%	0.002
1.A.1 CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	16.2	<0.01	0.96	8%	<0.001
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs	16.1	<0.01	0.96	9%	<0.001
3.B.1 N_2O Emissions from Manure Management: Cattle	N_2O	15.4	<0.01	0.97	24%	<0.001
3.C CH_4 Emissions from Rice Cultivation	CH_4	15.1	<0.01	0.97	149%	0.003
4.B.1 Net CO_2 Emissions from Cropland Remaining Cropland	CO_2	14.5	<0.01	0.97	601%	0.011
4.C.1 Net CO_2 Emissions from Grassland Remaining Grassland	CO_2	14.5	<0.01	0.97	1066%	0.020
2.A.2 CO_2 Emissions from Lime Production	CO_2	13.0	<0.01	0.97	2%	<0.001
2.B.1 CO_2 Emissions from Ammonia Production	CO_2	12.3	<0.01	0.98	5%	<0.001
2.B.2 N_2O Emissions from Nitric Acid Production	N_2O	10.0	<0.01	0.98	5%	<0.001
1.A.3.b N_2O Emissions from Mobile Combustion: Road	N_2O	9.6	<0.01	0.98	14%	<0.001
4.A.1 CH_4 Emissions from Forest Fires	CH_4	9.5	<0.01	0.98	18%	<0.001
4.D.1 Net CO_2 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CO_2	7.7	<0.01	0.98	64%	0.001

CRF Source/Sink Category	Greenhouse Gas	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
2.A.4 CO_2 Emissions from Other Process Uses of Carbonates	CO_2	7.5	<0.01	0.98	14%	<0.001
1.B.2 CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4	7.0	<0.01	0.98	219%	0.002
2.B.10 CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	6.6	<0.01	0.98	16%	<0.001
1.A.3.e N_2O Emissions from Mobile Combustion: Other	N_2O	6.5	<0.01	0.98	61%	0.001
3.A.4 CH_4 Emissions from Enteric Fermentation: Other Livestock	CH_4	6.3	<0.01	0.98	18%	<0.001
4.A.1 N_2O Emissions from Forest Fires	N_2O	6.2	<0.01	0.99	14%	<0.001
1.B.1 Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	5.9	<0.01	0.99	23%	<0.001
3.H CO_2 Emissions from Urea Fertilization	CO_2	5.3	<0.01	0.99	43%	<0.001
1.A.5.b CO_2 Emissions from Mobile Combustion: Military	CO_2	5.3	<0.01	0.99	6%	<0.001
2.B.3 N_2O Emissions from Adipic Acid Production	N_2O	5.3	<0.01	0.99	5%	<0.001
2.B.10 CO_2 Emissions from Carbon Dioxide Consumption	CO_2	4.9	<0.01	0.99	5%	<0.001
1.A.4.b CH_4 Emissions from Stationary Combustion - Residential	CH_4	4.6	<0.01	0.99	233%	0.001
2.E PFC, HFC, SF_6, and NF_3 Emissions from Electronics Industry	HiGWP	4.4	<0.01	0.99	6%	<0.001
1.A.1 N_2O Emissions from Stationary Combustion - Gas - Electricity Generation	N_2O	4.4	<0.01	0.99	48%	<0.001
2.G SF_6 Emissions from Electrical Transmission and Distribution	SF_6	4.2	<0.01	0.99	18%	<0.001
2.G N_2O Emissions from Product Uses	N_2O	4.2	<0.01	0.99	24%	<0.001
3.B.4 N_2O Emissions from Manure Management: Other Livestock	N_2O	4.2	<0.01	0.99	24%	<0.001
4.D.1 CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CH_4	3.8	<0.01	0.99	30%	<0.001
2.B.9 HFC-23 Emissions from HCFC-22 Production	HFCs	3.7	<0.01	0.99	10%	<0.001
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs	2.8	<0.01	0.99	17%	<0.001
1.A.5 CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	2.5	<0.01	0.99	17%	<0.001
1.A.5 CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	2.5	<0.01	0.99	19%	<0.001

CRF Source/Sink Category	Greenhouse Gas	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
1.A.2 N_2O Emissions from Stationary Combustion - Industrial	N_2O	2.5	<0.01	0.99	201%	0.001
3.G CO_2 Emissions from Liming	CO_2	2.4	<0.01	0.99	111%	<0.001
4.E.1 N_2O Emissions from Settlement Soils	N_2O	2.4	<0.01	1.00	56%	<0.001
5.B CH_4 Emissions from Composting	CH_4	2.3	<0.01	1.00	50%	<0.001
5.B N_2O Emissions from Composting	N_2O	2.0	<0.01	1.00	50%	<0.001
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs	2.0	<0.01	1.00	24%	<0.001
2.C.3 CO_2 Emissions from Aluminum Production	CO_2	1.9	<0.01	1.00	2%	<0.001
2.B.7 CO_2 Emissions from Soda Ash Production	CO_2	1.8	<0.01	1.00	9%	<0.001
2.C.3 PFC Emissions from Aluminum Production	PFCs	1.8	<0.01	1.00	7%	<0.001
1.A.3.a N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.6	<0.01	1.00	67%	<0.001
1.A.4.a CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	1.6	<0.01	1.00	15%	<0.001
2.C.2 CO_2 Emissions from Ferroalloy Production	CO_2	1.6	<0.01	1.00	12%	<0.001
1.A.2 CH_4 Emissions from Stationary Combustion - Industrial	CH_4	1.5	<0.01	1.00	49%	<0.001
2.B.6 CO_2 Emissions from Titanium Dioxide Production	CO_2	1.5	<0.01	1.00	13%	<0.001
2.B.4 N_2O Emissions from Caprolactam, Glyoxal, and Glyoxylic Acid Production	N_2O	1.4	<0.01	1.00	32%	<0.001
2.A.3 CO_2 Emissions from Glass Production	CO_2	1.3	<0.01	1.00	5%	<0.001
1.A.4.a CH_4 Emissions from Stationary Combustion - Commercial	CH_4	1.2	<0.01	1.00	147%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Gas - Electricity Generation	CH_4	1.1	<0.01	1.00	2%	<0.001
2.C.4 SF_6 Emissions from Magnesium Production and Processing	SF_6	1.0	<0.01	1.00	8%	<0.001
2.C.6 CO_2 Emissions from Zinc Production	CO_2	1.0	<0.01	1.00	16%	<0.001
1.A.3.b CH_4 Emissions from Mobile Combustion: Road	CH_4	0.9	<0.01	1.00	26%	<0.001
1.A.3.e CH_4 Emissions from Mobile Combustion: Other	CH_4	0.9	<0.01	1.00	52%	<0.001
1.A.4.b N_2O Emissions from Stationary Combustion - Residential	N_2O	0.9	<0.01	1.00	215%	<0.001
2.B.10 CO_2 Emissions from Phosphoric Acid Production	CO_2	0.9	<0.01	1.00	20%	<0.001

CRF Source/Sink Category	Greenhouse Gas	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
1.A.3.d N_2O Emissions from Mobile Combustion: Marine	N_2O	0.6	<0.01	1.00	44%	<0.001
2.C.5 CO_2 Emissions from Lead Production	CO_2	0.5	<0.01	1.00	15%	<0.001
4.A.1 N_2O Emissions from Forest Soils	N_2O	0.5	<0.01	1.00	318%	<0.001
3.F CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.4	<0.01	1.00	18%	<0.001
5.C.1 N_2O Emissions from Incineration of Waste	N_2O	0.4	<0.01	1.00	328%	<0.001
1.A.3.d CH_4 Emissions from Mobile Combustion: Marine	CH_4	0.4	<0.01	1.00	86%	<0.001
1.A.1 CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.4	<0.01	1.00	NA	<0.001
2.B.8 CH_4 Emissions from Petrochemical Production	CH_4	0.3	<0.01	1.00	57%	<0.001
4.C.1 N_2O Emissions from Grass Fires	N_2O	0.3	<0.01	1.00	146%	<0.001
1.A.4.a N_2O Emissions from Stationary Combustion - Commercial	N_2O	0.3	<0.01	1.00	179%	<0.001
4.C.1 CH_4 Emissions from Grass Fires	CH_4	0.3	<0.01	1.00	146%	<0.001
1.A.3.c N_2O Emissions from Mobile Combustion: Railways	N_2O	0.3	<0.01	1.00	69%	<0.001
2.E N_2O Emissions from Electronics Industry	N_2O	0.2	<0.01	1.00	9%	<0.001
5.B.2 CH_4 Emissions from Anaerobic Digestion at Biogas Facilities	CH_4	0.2	<0.01	1.00	50%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Coal - Electricity Generation	CH_4	0.2	<0.01	1.00	10%	<0.001
3.F N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.2	<0.01	1.00	17%	<0.001
4.D.2 CH_4 Emissions from Land Converted to Coastal Wetlands	CH_4	0.2	<0.01	1.00	30%	<0.001
2.B.5 CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.2	<0.01	1.00	10%	<0.001
4.D.1 N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	N_2O	0.1	<0.01	1.00	116%	<0.001
4.A.4 N_2O Emissions from Drained Organic Soils	N_2O	0.1	<0.01	1.00	128%	<0.001
1.A.3.c CH_4 Emissions from Mobile Combustion: Railways	CH_4	0.1	<0.01	1.00	26%	<0.001
2.C.4 HFC-134a Emissions from Magnesium Production and Processing	HFCs	0.1	<0.01	1.00	25%	<0.001
1.A.5 N_2O Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1	<0.01	1.00	199%	<0.001
1.B.2 N_2O Emissions from Petroleum Systems	N_2O	+	<0.01	1.00	34%	<0.001

CRF Source/Sink Category	Greenhouse Gas	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Level Assessment	Cumulative Total	Uncertainty[a]	Approach 2 Level Assessment
1.A.5 CH_4 Emissions from Stationary Combustion - U.S. Territories	CH_4	+	<0.01	1.00	55%	<0.001
1.A.3.a CH_4 Emissions from Mobile Combustion: Aviation	CH_4	+	<0.01	1.00	87%	<0.001
1.A.1 N_2O Emissions from Stationary Combustion - Wood - Electricity Generation	N_2O	+	<0.01	1.00	2%	<0.001
4.D.2 Net CO_2 Emissions from Land Converted to Wetlands	CO_2	+	<0.01	1.00	37%	<0.001
4.A.4 CH_4 Emissions from Drained Organic Soils	CH_4	+	<0.01	1.00	80%	<0.001
2.C.2 CH_4 Emissions from Ferroalloy Production	CH_4	+	<0.01	1.00	12%	<0.001
1.B.2 N_2O Emissions from Natural Gas Systems	N_2O	+	<0.01	1.00	15%	<0.001
2.B.5 CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+	<0.01	1.00	9%	<0.001
2.C.1 CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+	<0.01	1.00	20%	<0.001
1.B.2 CO_2 Emissions from Abandoned Oil and Gas Wells	CO_2	+	<0.01	1.00	219%	<0.001
1.A.1 N_2O Emissions from Stationary Combustion - Oil - Electricity Generation	N_2O	+	<0.01	1.00	10%	<0.001
4.D.1 CH_4 Emissions from Peatlands Remaining Peatlands	CH_4	+	<0.01	1.00	78%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Wood - Electricity Generation	CH_4	+	<0.01	1.00	2%	<0.001
2.C.4 CO_2 Emissions from Magnesium Production and Processing	CO_2	+	<0.01	1.00	3%	<0.001
1.A.1 CH_4 Emissions from Stationary Combustion - Oil - Electricity Generation	CH_4	+	<0.01	1.00	9%	<0.001
4.D.1 N_2O Emissions from Peatlands Remaining Peatlands	N_2O	+	<0.01	1.00	53%	<0.001
1.A.5.b CH_4 Emissions from Mobile Combustion: Military	CH_4	+	<0.01	1.00	26%	<0.001
1.A.5.b N_2O Emissions from Mobile Combustion: Military	N_2O	+	<0.01	1.00	14%	<0.001
5.C.1 CH_4 Emissions from Incineration of Waste	CH_4	+	<0.01	1.00	NE	<0.001
1.A.4.b 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.
NE (Not Estimated)
NA (Not Available)
[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.

Table A-8: 1990-2019 Key Category Approach 1 and 2 Analysis—Trend Assessment, without LULUCF

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
1.A.1 CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,546.5	973.5	0.09	0.009	22.7	23
1.A.1 CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	175.4	616.0	0.07	0.003	16.5	39
1.A.3.b CO_2 Emissions from Mobile Combustion: Road	CO_2	1,157.4	1,535.3	0.06	0.003	13.4	53
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air conditioning	HFCs, PFCs	+	132.6	0.02	0.003	5.0	58
1.A.2 CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	157.8	49.2	0.02	0.003	4.2	62
1.A.2 CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	408.8	524.3	0.02	0.001	4.0	66
1.A.1 CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	97.5	16.2	0.01	0.001	3.1	69
5.A CH_4 Emissions from Landfills	CH_4	179.6	114.5	0.01	0.002	2.6	71
2.C.1 CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	104.7	41.3	0.01	0.002	2.5	74
1.B.1 Fugitive Emissions from Coal Mining	CH_4	96.5	47.4	0.01	0.001	1.9	76
1.A.4.a CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	142.0	192.8	0.01	0.001	1.8	78
2.B.9 HFC-23 Emissions from HCFC-22 Production	HFCs	46.1	3.7	0.01	0.001	1.6	79
1.A.4.b CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	97.8	63.5	0.01	<0.001	1.4	81
1.B.2 CH_4 Emissions from Natural Gas Systems	CH_4	187.7	156.4	0.01	0.001	1.3	82
1.B.2 CO_2 Emissions from Petroleum Systems	CO_2	9.7	43.3	0.01	0.002	1.3	83
1.A.4.b CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	237.8	275.3	0.01	<0.001	1.2	84

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
1.A.4.a CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	74.3	43.9	<0.01	<0.001	1.2	86
1.A.3.b N_2O Emissions from Mobile Combustion: Road	N_2O	37.7	9.6	<0.01	0.001	1.1	87
1.A.2 CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	287.2	264.0	<0.01	0.001	1.1	88
2.C.3 PFC Emissions from Aluminum Production	PFCs	21.5	1.8	<0.01	<0.001	0.8	89
2.G SF_6 Emissions from Electrical Transmission and Distribution	SF_6	23.2	4.2	<0.01	0.001	0.7	89
3.B.1 CH_4 Emissions from Manure Management: Cattle	CH_4	17.9	35.4	<0.01	0.001	0.6	90
1.A.3.e CO_2 Emissions from Mobile Combustion: Other	CO_2	36.0	53.7	<0.01	<0.001	0.6	91
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs	+	16.1	<0.01	<0.001	0.6	91
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	0.2	16.3	<0.01	0.002	0.6	92
1.A.3.a CO_2 Emissions from Mobile Combustion: Aviation	CO_2	187.4	178.4	<0.01	<0.001	0.5	92
3.D.1 Direct N_2O Emissions from Agricultural Soil Management	N_2O	272.5	290.4	<0.01	0.001	0.5	93
3.A.1 CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	158.4	172.3	<0.01	<0.001	0.4	93
1.A.4.a CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	12.0	1.6	<0.01	<0.001	0.4	94
2.B.3 N_2O Emissions from Adipic Acid Production	N_2O	15.2	5.3	<0.01	<0.001	0.4	94
3.D.2 Indirect N_2O Emissions from Applied Nitrogen	N_2O	43.4	54.2	<0.01	0.002	0.4	94
1.B.2 CH_4 Emissions from Petroleum Systems	CH_4	48.5	40.2	<0.01	<0.001	0.4	95
5.C.1 CO_2 Emissions from Incineration of Waste	CO_2	11.2	20.2	<0.01	<0.001	0.3	95
2.B.8 CO_2 Emissions from Petrochemical	CO_2	21.6	30.8	<0.01	<0.001	0.3	95

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
Production							
1.A.5.b CO_2 Emissions from Mobile Combustion: Military	CO_2	13.6	5.3	<0.01	<0.001	0.3	96
3.B.4 CH_4 Emissions from Manure Management: Other Livestock	CH_4	19.3	26.9	<0.01	<0.001	0.3	96
5.D N_2O Emissions from Wastewater Treatment	N_2O	18.7	26.4	<0.01	0.002	0.3	96
2.A.1 CO_2 Emissions from Cement Production	CO_2	33.5	40.9	<0.01	<0.001	0.3	96
1.A.3.d CO_2 Emissions from Mobile Combustion: Marine	CO_2	39.3	33.8	<0.01	<0.001	0.2	97
2.C.3 CO_2 Emissions from Aluminum Production	CO_2	6.8	1.9	<0.01	<0.001	0.2	97
1.A.5 CO_2 Emissions from Non-Energy Use of Fuels	CO_2	112.8	110.1	<0.01	<0.001	0.2	97
1.A.3.b CH_4 Emissions from Mobile Combustion: Road	CH_4	5.2	0.9	<0.01	<0.001	0.2	97
2.C.4 SF_6 Emissions from Magnesium Production and Processing	SF_6	5.2	1.0	<0.01	<0.001	0.2	97
1.B.2 CO_2 Emissions from Natural Gas Systems	CO_2	32.0	36.9	<0.01	<0.001	0.2	98
3.B.1 N_2O Emissions from Manure Management: Cattle	N_2O	11.2	15.4	<0.01	<0.001	0.2	98
1.A.1 N_2O Emissions from Stationary Combustion - Gas - Electricity Generation	N_2O	0.3	4.4	<0.01	<0.001	0.2	98
1.A.1 N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O	20.1	16.7	<0.01	<0.001	0.1	98
2.B.10 CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.5	4.9	<0.01	<0.001	0.1	98
1.A.4.b CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	3.0	0.0	<0.01	<0.001	0.1	98
3.H CO_2 Emissions from Urea Fertilization	CO_2	2.4	5.3	<0.01	<0.001	0.1	98
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs	0.0	2.8	<0.01	<0.001	0.1	98
2.B.10 CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	3.8	6.6	<0.01	<0.001	0.1	99
1.A.5 CO_2 Emissions from Stationary Combustion -	CO_2	0.0	2.5	<0.01	<0.001	0.1	99

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
Gas - U.S. Territories							
2.B.2 N_2O Emissions from Nitric Acid Production	N_2O	12.1	10.0	<0.01	<0.001	0.1	99
3.G CO_2 Emissions from Liming	CO_2	4.7	2.4	<0.01	<0.001	0.1	99
5.D CH_4 Emissions from Wastewater Treatment	CH_4	20.2	18.4	<0.01	<0.001	0.1	99
1.A.5 CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	21.2	19.5	<0.01	<0.001	0.1	99
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs	0.0	2.0	<0.01	<0.001	0.1	99
1.A.5 CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	0.5	2.5	<0.01	<0.001	0.1	99
5.B CH_4 Emissions from Composting	CH_4	0.4	2.3	<0.01	<0.001	0.1	99
5.B N_2O Emissions from Composting	N_2O	0.3	2.0	<0.01	<0.001	0.1	99
1.A.3.e N_2O Emissions from Mobile Combustion: Other	N_2O	4.8	6.5	<0.01	<0.001	0.1	99
1.B.1 Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	7.2	5.9	<0.01	<0.001	0.1	99
3.B.4 N_2O Emissions from Manure Management: Other Livestock	N_2O	2.8	4.2	<0.01	<0.001	<0.1	99
3.C CH_4 Emissions from Rice Cultivation	CH_4	16.0	15.1	<0.01	<0.001	<0.1	100
2.A.4 CO_2 Emissions from Other Process Uses of Carbonates	CO_2	6.3	7.5	<0.01	<0.001	<0.1	100
2.B.1 CO_2 Emissions from Ammonia Production	CO_2	13.0	12.3	<0.01	<0.001	<0.1	100
2.A.2 CO_2 Emissions from Lime Production	CO_2	11.7	13.0	<0.01	<0.001	<0.1	100
1.A.1 CH_4 Emissions from Stationary Combustion - Gas - Electricity Generation	CH_4	0.1	1.1	<0.01	<0.001	<0.1	100
2.E PFC, HFC, SF_6, and NF_3 Emissions from Electronics Industry	HiGWP	3.6	4.4	<0.01	<0.001	<0.1	100
1.A.4.b CH_4 Emissions from Stationary Combustion - Residential	CH_4	5.2	4.6	<0.01	<0.001	<0.1	100
2.B.10 CO_2 Emissions from Phosphoric Acid Production	CO_2	1.5	0.9	<0.01	<0.001	<0.1	100
1.A.2 N_2O Emissions from	N_2O	3.1	2.5	<0.01	<0.001	<0.1	100

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
Stationary Combustion - Industrial							
2.C.2 CO_2 Emissions from Ferroalloy Production	CO_2	2.2	1.6	<0.01	<0.001	<0.1	100
1.A.3.c CO_2 Emissions from Mobile Combustion: Railways	CO_2	35.5	36.7	<0.01	<0.001	<0.1	100
1.A.2 CH_4 Emissions from Stationary Combustion - Industrial	CH_4	1.8	1.5	<0.01	<0.001	<0.1	100
2.B.7 CO_2 Emissions from Soda Ash Production	CO_2	1.4	1.8	<0.01	<0.001	<0.1	100
2.B.4 N_2O Emissions from Caprolactam, Glyoxal, and Glyoxylic Acid Production	N_2O	1.7	1.4	<0.01	<0.001	<0.1	100
2.C.6 CO_2 Emissions from Zinc Production	CO_2	0.6	1.0	<0.01	<0.001	<0.1	100
1.B.2 CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4	6.6	7.0	<0.01	<0.001	<0.1	100
2.A.3 CO_2 Emissions from Glass Production	CO_2	1.5	1.3	<0.01	<0.001	<0.1	100
1.A.3.e CH_4 Emissions from Mobile Combustion: Other	CH_4	0.7	0.9	<0.01	<0.001	<0.1	100
2.B.6 CO_2 Emissions from Titanium Dioxide Production	CO_2	1.2	1.5	<0.01	<0.001	<0.1	100
1.A.3.d N_2O Emissions from Mobile Combustion: Marine	N_2O	0.8	0.6	<0.01	<0.001	<0.1	100
2.B.5 CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.4	0.2	<0.01	<0.001	<0.1	100
2.E N_2O Emissions from Electronics Industry	N_2O	+	0.2	<0.01	<0.001	<0.1	100
5.B.2 CH_4 Emissions from Anaerobic Digestion at Biogas Facilities	CH_4	+	0.2	<0.01	<0.001	<0.1	100
1.A.1 CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.5	0.4	<0.01	<0.001	<0.1	100
1.A.4.b N_2O Emissions from Stationary Combustion - Residential	N_2O	1.0	0.9	<0.01	<0.001	<0.1	100
1.A.3.a N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.7	1.6	<0.01	<0.001	<0.1	100
1.A.1 CH_4 Emissions from Stationary Combustion - Coal - Electricity Generation	CH_4	0.3	0.2	<0.01	<0.001	<0.1	100

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
2.B.8 CH_4 Emissions from Petrochemical Production	CH_4	0.2	0.3	<0.01	<0.001	<0.1	100
2.G N_2O Emissions from Product Uses	N_2O	4.2	4.2	<0.01	<0.001	<0.1	100
1.A.4.a CH_4 Emissions from Stationary Combustion - Commercial	CH_4	1.1	1.2	<0.01	<0.001	<0.1	100
3.A.4 CH_4 Emissions from Enteric Fermentation: Other Livestock	CH_4	6.3	6.3	<0.01	<0.001	<0.1	100
1.A.4.a N_2O Emissions from Stationary Combustion - Commercial	N_2O	0.4	0.3	<0.01	<0.001	<0.1	100
1.A.1 N_2O Emissions from Stationary Combustion - Oil - Electricity Generation	N_2O	0.1	+	<0.01	<0.001	<0.1	100
2.C.4 HFC-134a Emissions from Magnesium Production and Processing	HFCs	0.0	0.1	<0.01	<0.001	<0.1	100
5.C.1 N_2O Emissions from Incineration of Waste	N_2O	0.5	0.4	<0.01	<0.001	<0.1	100
1.A.3.d CH_4 Emissions from Mobile Combustion: Marine	CH_4	0.3	0.4	<0.01	<0.001	<0.1	100
3.F CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.4	0.4	<0.01	<0.001	<0.1	100
1.A.3.a CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.1	+	<0.01	<0.001	<0.1	100
1.B.2 N_2O Emissions from Petroleum Systems	N_2O	+	+	<0.01	<0.001	<0.1	100
3.F N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.2	0.2	<0.01	<0.001	<0.1	100
2.B.5 CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+	+	<0.01	<0.001	<0.1	100
1.A.1 N_2O Emissions from Stationary Combustion - Wood - Electricity Generation	N_2O	+	+	<0.01	<0.001	<0.1	100
1.A.3.c N_2O Emissions from Mobile Combustion: Railways	N_2O	0.3	0.3	<0.01	<0.001	<0.1	100
1.A.1 CH_4 Emissions from Stationary Combustion - Oil - Electricity Generation	CH_4	+	+	<0.01	<0.001	<0.1	100

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
2.C.1 CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+	+	<0.01	<0.001	<0.1	100
2.C.5 CO_2 Emissions from Lead Production	CO_2	0.5	0.5	<0.01	<0.001	<0.1	100
2.C.2 CH_4 Emissions from Ferroalloy Production	CH_4	+	+	<0.01	<0.001	<0.1	100
1.B.2 N_2O Emissions from Natural Gas Systems	N_2O	+	+	<0.01	<0.001	<0.1	100
1.A.5 N_2O Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1	0.1	<0.01	<0.001	<0.1	100
1.A.3.c CH_4 Emissions from Mobile Combustion: Railways	CH_4	0.1	0.1	<0.01	<0.001	<0.1	100
1.A.5 CH_4 Emissions from Stationary Combustion - U.S. Territories	CH_4	+	+	<0.01	<0.001	<0.1	100
1.A.1 CH_4 Emissions from Stationary Combustion - Wood - Electricity Generation	CH_4	+	+	<0.01	<0.001	<0.1	100
1.B.2 CO_2 Emissions from Abandoned Oil and Gas Wells	CO_2	+	+	<0.01	<0.001	<0.1	100
1.A.5.b CH_4 Emissions from Mobile Combustion: Military	CH_4	+	+	<0.01	<0.001	<0.1	100
1.A.5.b N_2O Emissions from Mobile Combustion: Military	N_2O	+	+	<0.01	<0.001	<0.1	100
2.C.4 CO_2 Emissions from Magnesium Production and Processing	CO_2	+	+	<0.01	<0.001	<0.1	100
5.C.1 CH_4 Emissions from Incineration of Waste	CH_4	+	+	<0.01	<0.001	<0.1	100

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

Table A-9: 1990-2019 Key Category Approach 1 and 2 Analysis—Trend Assessment, with LULUCF

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
1.A.1 CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,546.5	973.5	0.08	0.008	20.9	21
1.A.1 CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	175.4	616.0	0.06	0.003	15.5	36

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
1.A.3.b CO_2 Emissions from Mobile Combustion: Road	CO_2	1,157.4	1,535.3	0.05	0.003	12.8	49
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air conditioning	HFCs, PFCs	+	132.6	0.02	0.002	4.7	54
1.A.2 CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	157.8	49.2	0.01	0.002	3.9	58
1.A.2 CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	408.8	524.3	0.01	0.001	3.9	62
4.A.1 Net CO_2 Emissions from Forest Land Remaining Forest Land	CO_2	787.6	691.8	0.01	0.004	3.7	65
1.A.1 CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	97.5	16.2	0.01	0.001	2.9	68
5.A CH_4 Emissions from Landfills	CH_4	179.6	114.5	0.01	0.002	2.4	71
2.C.1 CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	104.7	41.3	0.01	0.002	2.3	73
1.B.1 Fugitive Emissions from Coal Mining	CH_4	96.5	47.4	0.01	0.001	1.8	75
1.A.4.a CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	142.0	192.8	0.01	<0.001	1.7	76
2.B.9 HFC-23 Emissions from HCFC-22 Production	HFCs	46.1	3.7	0.01	0.001	1.5	78
1.A.4.b CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	97.8	63.5	<0.01	<0.001	1.3	79
1.A.4.b CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	237.8	275.3	<0.01	<0.001	1.2	80
1.B.2 CH_4 Emissions from Natural Gas Systems	CH_4	187.7	156.4	<0.01	0.001	1.2	82
1.B.2 CO_2 Emissions from Petroleum Systems	CO_2	9.7	43.3	<0.01	0.001	1.2	83
1.A.4.a CO_2 Emissions from Stationary	CO_2	74.3	43.9	<0.01	<0.001	1.1	84

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
Combustion - Oil - Commercial							
1.A.3.b N_2O Emissions from Mobile Combustion: Road	N_2O	37.7	9.6	<0.01	0.001	1.0	85
1.A.2 CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	287.2	264.0	<0.01	0.001	0.9	86
2.C.3 PFC Emissions from Aluminum Production	PFCs	21.5	1.8	<0.01	<0.001	0.7	87
2.G SF_6 Emissions from Electrical Transmission and Distribution	SF_6	23.2	4.2	<0.01	<0.001	0.7	87
3.B.1 CH_4 Emissions from Manure Management: Cattle	CH_4	17.9	35.4	<0.01	<0.001	0.6	88
1.A.3.e CO_2 Emissions from Mobile Combustion: Other	CO_2	36.0	53.7	<0.01	<0.001	0.6	88
4.C.2 Net CO_2 Emissions from Land Converted to Grassland	CO_2	6.2	23.2	<0.01	0.003	0.6	89
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFC, PFCs	+	16.1	<0.01	<0.001	0.6	90
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	0.2	16.3	<0.01	0.002	0.6	90
4.E.2 Net CO_2 Emissions from Land Converted to Settlements	CO_2	62.9	79.2	<0.01	0.001	0.5	91
3.D.1 Direct N_2O Emissions from Agricultural Soil Management	N_2O	272.5	290.4	<0.01	0.001	0.5	91
4.E.1 Net CO_2 Emissions from Settlements Remaining Settlements	CO_2	109.6	124.1	<0.01	0.002	0.5	92
3.A.1 CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	158.4	172.3	<0.01	<0.001	0.4	92
1.A.3.a CO_2 Emissions from Mobile Combustion: Aviation	CO_2	187.4	178.4	<0.01	<0.001	0.4	92
1.A.4.a CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	12.0	1.6	<0.01	<0.001	0.4	93
3.D.2 Indirect N_2O Emissions from Applied Nitrogen	N_2O	43.4	54.2	<0.01	0.002	0.4	93

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
2.B.3 N_2O Emissions from Adipic Acid Production	N_2O	15.2	5.3	<0.01	<0.001	0.4	94
1.B.2 CH_4 Emissions from Petroleum Systems	CH_4	48.5	40.2	<0.01	<0.001	0.3	94
4.B.1 Net CO_2 Emissions from Cropland Remaining Cropland	CO_2	23.2	14.5	<0.01	0.007	0.3	94
2.B.8 CO_2 Emissions from Petrochemical Production	CO_2	21.6	30.8	<0.01	<0.001	0.3	95
5.C.1 CO_2 Emissions from Incineration of Waste	CO_2	11.2	20.2	<0.01	<0.001	0.3	95
4.A.1 CH_4 Emissions from Forest Fires	CH_4	0.9	9.5	<0.01	<0.001	0.3	95
1.A.5.b CO_2 Emissions from Mobile Combustion: Military	CO_2	13.6	5.3	<0.01	<0.001	0.3	95
3.B.4 CH_4 Emissions from Manure Management: Other Livestock	CH_4	19.3	26.9	<0.01	<0.001	0.3	96
5.D N_2O Emissions from Wastewater Treatment	N_2O	18.7	26.4	<0.01	0.002	0.3	96
2.A.1 CO_2 Emissions from Cement Production	CO_2	33.5	40.9	<0.01	<0.001	0.2	96
4.C.1 Net CO_2 Emissions from Grassland Remaining Grassland	CO_2	8.3	14.5	<0.01	0.009	0.2	96
1.A.3.d CO_2 Emissions from Mobile Combustion: Marine	CO_2	39.3	33.8	<0.01	<0.001	0.2	97
4.A.1 N_2O Emissions from Forest Fires	N_2O	0.6	6.2	<0.01	<0.001	0.2	97
2.C.3 CO_2 Emissions from Aluminum Production	CO_2	6.8	1.9	<0.01	<0.001	0.2	97
1.B.2 CO_2 Emissions from Natural Gas Systems	CO_2	32.0	36.9	<0.01	<0.001	0.2	97
1.A.3.b CH_4 Emissions from Mobile Combustion: Road	CH_4	5.2	0.9	<0.01	<0.001	0.2	97
2.C.4 SF_6 Emissions from Magnesium Production and Processing	SF_6	5.2	1.0	<0.01	<0.001	0.2	97
3.B.1 N_2O Emissions from Manure Management: Cattle	N_2O	11.2	15.4	<0.01	<0.001	0.1	98
1.A.5 CO_2 Emissions from Non-Energy Use of Fuels	CO_2	112.8	110.1	<0.01	<0.001	0.1	98
1.A.1 N_2O Emissions from Stationary	N_2O	0.3	4.4	<0.01	<0.001	0.1	98

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
Combustion - Gas - Electricity Generation							
1.A.1 N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O	20.1	16.7	<0.01	<0.001	0.1	98
2.B.10 CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.5	4.9	<0.01	<0.001	0.1	98
1.A.4.b CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	3.0	0.0	<0.01	<0.001	0.1	98
3.H CO_2 Emissions from Urea Fertilization	CO_2	2.4	5.3	<0.01	<0.001	0.1	98
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs	0.0	2.8	<0.01	<0.001	0.1	98
2.B.10 CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	3.8	6.6	<0.01	<0.001	0.1	99
1.A.5 CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	0.0	2.5	<0.01	<0.001	0.1	99
2.B.2 N_2O Emissions from Nitric Acid Production	N_2O	12.1	10.0	<0.01	<0.001	0.1	99
3.G CO_2 Emissions from Liming	CO_2	4.7	2.4	<0.01	<0.001	0.1	99
5.D CH_4 Emissions from Wastewater Treatment	CH_4	20.2	18.4	<0.01	<0.001	0.1	99
1.A.5 CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	0.5	2.5	<0.01	<0.001	0.1	99
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs	0.0	2.0	<0.01	<0.001	0.1	99
1.A.5 CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	21.2	19.5	<0.01	<0.001	0.1	99
5.B CH_4 Emissions from Composting	CH_4	0.4	2.3	<0.01	<0.001	0.1	99
4.B.2 Net CO_2 Emissions from Land Converted to Cropland	CO_2	51.8	54.2	<0.01	<0.001	0.1	99
5.B N_2O Emissions from Composting	N_2O	0.3	2.0	<0.01	<0.001	0.1	99

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
1.A.3.e N_2O Emissions from Mobile Combustion: Other	N_2O	4.8	6.5	<0.01	<0.001	0.1	99
1.B.1 Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	7.2	5.9	<0.01	<0.001	<0.1	99
3.B.4 N_2O Emissions from Manure Management: Other Livestock	N_2O	2.8	4.2	<0.01	<0.001	<0.1	99
3.C CH_4 Emissions from Rice Cultivation	CH_4	16.0	15.1	<0.01	<0.001	<0.1	99
2.A.2 CO_2 Emissions from Lime Production	CO_2	11.7	13.0	<0.01	<0.001	<0.1	100
2.A.4 CO_2 Emissions from Other Process Uses of Carbonates	CO_2	6.3	7.5	<0.01	<0.001	<0.1	100
1.A.1 CH_4 Emissions from Stationary Combustion - Gas - Electricity Generation	CH_4	0.1	1.1	<0.01	<0.001	<0.1	100
2.B.1 CO_2 Emissions from Ammonia Production	CO_2	13.0	12.3	<0.01	<0.001	<0.1	100
2.E PFC, HFC, SF_6, and NF_3 Emissions from Electronics Industry	HiGWP	3.6	4.4	<0.01	<0.001	<0.1	100
1.A.3.c CO_2 Emissions from Mobile Combustion: Railways	CO_2	35.5	36.7	<0.01	<0.001	<0.1	100
1.A.4.b CH_4 Emissions from Stationary Combustion - Residential	CH_4	5.2	4.6	<0.01	<0.001	<0.1	100
2.B.10 CO_2 Emissions from Phosphoric Acid Production	CO_2	1.5	0.9	<0.01	<0.001	<0.1	100
1.A.2 N_2O Emissions from Stationary Combustion - Industrial	N_2O	3.1	2.5	<0.01	<0.001	<0.1	100
2.C.2 CO_2 Emissions from Ferroalloy Production	CO_2	2.2	1.6	<0.01	<0.001	<0.1	100
4.D.2 Net CO_2 Emissions from Land Converted to Wetlands	CO_2	0.4	+	<0.01	<0.001	<0.1	100
4.E.1 N_2O Emissions from Settlement Soils	N_2O	2.0	2.4	<0.01	<0.001	<0.1	100
4.A.1 N_2O Emissions from Forest Soils	N_2O	0.1	0.5	<0.01	<0.001	<0.1	100
1.B.2 CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4	6.6	7.0	<0.01	<0.001	<0.1	100

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
2.B.7 CO_2 Emissions from Soda Ash Production	CO_2	1.4	1.8	<0.01	<0.001	<0.1	100
4.A.2 Net CO_2 Emissions from Land Converted to Forest Land	CO_2	98.2	99.1	<0.01	<0.001	<0.1	100
2.C.6 CO_2 Emissions from Zinc Production	CO_2	0.6	1.0	<0.01	<0.001	<0.1	100
1.A.2 CH_4 Emissions from Stationary Combustion - Industrial	CH_4	1.8	1.5	<0.01	<0.001	<0.1	100
2.B.4 N_2O Emissions from Caprolactam, Glyoxal, and Glyoxylic Acid Production	N_2O	1.7	1.4	<0.01	<0.001	<0.1	100
2.A.3 CO_2 Emissions from Glass Production	CO_2	1.5	1.3	<0.01	<0.001	<0.1	100
2.B.6 CO_2 Emissions from Titanium Dioxide Production	CO_2	1.2	1.5	<0.01	<0.001	<0.1	100
1.A.3.e CH_4 Emissions from Mobile Combustion: Other	CH_4	0.7	0.9	<0.01	<0.001	<0.1	100
4.C.1 N_2O Emissions from Grass Fires	N_2O	0.1	0.3	<0.01	<0.001	<0.1	100
4.C.1 CH_4 Emissions from Grass Fires	CH_4	0.1	0.3	<0.01	<0.001	<0.1	100
1.A.3.d N_2O Emissions from Mobile Combustion: Marine	N_2O	0.8	0.6	<0.01	<0.001	<0.1	100
4.D.1 Net CO_2 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CO_2	7.4	7.7	<0.01	<0.001	<0.1	100
2.B.5 CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.4	0.2	<0.01	<0.001	<0.1	100
2.E N_2O Emissions from Electronics Industry	N_2O	+	0.2	<0.01	<0.001	<0.1	100
5.B.2 CH_4 Emissions from Anaerobic Digestion at Biogas Facilities	CH_4	+	0.2	<0.01	<0.001	<0.1	100
1.A.1 CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.5	0.4	<0.01	<0.001	<0.1	100
1.A.4.b N_2O Emissions from Stationary Combustion - Residential	N_2O	1.0	0.9	<0.01	<0.001	<0.1	100
1.A.1 CH_4 Emissions from Stationary Combustion - Coal - Electricity Generation	CH_4	0.3	0.2	<0.01	<0.001	<0.1	100

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
1.A.3.a N_2O Emissions from Mobile Combustion: Aviation	N_2O	1.7	1.6	<0.01	<0.001	<0.1	100
2.B.8 CH_4 Emissions from Petrochemical Production	CH_4	0.2	0.3	<0.01	<0.001	<0.1	100
1.A.4.a CH_4 Emissions from Stationary Combustion - Commercial	CH_4	1.1	1.2	<0.01	<0.001	<0.1	100
1.A.4.a N_2O Emissions from Stationary Combustion - Commercial	N_2O	0.4	0.3	<0.01	<0.001	<0.1	100
4.D.2 CH_4 Emissions from Land Converted to Coastal Wetlands	CH_4	0.2	0.2	<0.01	<0.001	<0.1	100
1.A.1 N_2O Emissions from Stationary Combustion - Oil - Electricity Generation	N_2O	0.1	+	<0.01	<0.001	<0.1	100
2.G N_2O Emissions from Product Uses	N_2O	4.2	4.2	<0.01	<0.001	<0.1	100
2.C.4 HFC-134a Emissions from Magnesium Production and Processing	HFCs	0.0	0.1	<0.01	<0.001	<0.1	100
5.C.1 N_2O Emissions from Incineration of Waste	N_2O	0.5	0.4	<0.01	<0.001	<0.1	100
1.A.3.d CH_4 Emissions from Mobile Combustion: Marine	CH_4	0.3	0.4	<0.01	<0.001	<0.1	100
3.A.4 CH_4 Emissions from Enteric Fermentation: Other Livestock	CH_4	6.3	6.3	<0.01	<0.001	<0.1	100
3.F CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.4	0.4	<0.01	<0.001	<0.1	100
4.D.1 CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CH_4	3.7	3.8	<0.01	<0.001	<0.1	100
1.A.3.a CH_4 Emissions from Mobile Combustion: Aviation	CH_4	0.1	+	<0.01	<0.001	<0.1	100
1.B.2 N_2O Emissions from Petroleum Systems	N_2O	+	+	<0.01	<0.001	<0.1	100
3.F N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.2	0.2	<0.01	<0.001	<0.1	100
2.B.5 CH_4 Emissions from Silicon Carbide	CH_4	+	+	<0.01	<0.001	<0.1	100

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
Production and Consumption							
1.A.1 N_2O Emissions from Stationary Combustion - Wood - Electricity Generation	N_2O	+	+	<0.01	<0.001	<0.1	100
1.A.3.c N_2O Emissions from Mobile Combustion: Railways	N_2O	0.3	0.3	<0.01	<0.001	<0.1	100
2.C.5 CO_2 Emissions from Lead Production	CO_2	0.5	0.5	<0.01	<0.001	<0.1	100
1.A.1 CH_4 Emissions from Stationary Combustion - Oil - Electricity Generation	CH_4	+	+	<0.01	<0.001	<0.1	100
2.C.1 CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+	+	<0.01	<0.001	<0.1	100
4.D.1 N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	N_2O	0.1	0.1	<0.01	<0.001	<0.1	100
1.B.2 N_2O Emissions from Natural Gas Systems	N_2O	+	+	<0.01	<0.001	<0.1	100
2.C.2 CH_4 Emissions from Ferroalloy Production	CH_4	+	+	<0.01	<0.001	<0.1	100
1.A.5 N_2O Emissions from Stationary Combustion - U.S. Territories	N_2O	0.1	0.1	<0.01	<0.001	<0.1	100
1.A.3.c CH_4 Emissions from Mobile Combustion: Railways	CH_4	0.1	0.1	<0.01	<0.001	<0.1	100
1.A.5 CH_4 Emissions from Stationary Combustion - U.S. Territories	CH_4	+	+	<0.01	<0.001	<0.1	100
4.D.1 CH_4 Emissions from Peatlands Remaining Peatlands	CH_4	+	+	<0.01	<0.001	<0.1	100
1.A.1 CH_4 Emissions from Stationary Combustion - Wood - Electricity Generation	CH_4	+	+	<0.01	<0.001	<0.1	100
4.A.4 N_2O Emissions from Drained Organic Soils	N_2O	0.1	0.1	<0.01	<0.001	<0.1	100
1.B.2 CO_2 Emissions from Abandoned Oil and Gas Wells	CO_2	+	+	<0.01	<0.001	<0.1	100
1.A.5.b CH_4 Emissions from Mobile Combustion: Military	CH_4	+	+	<0.01	<0.001	<0.1	100

CRF Source/Sink Category	Greenhouse Gas	1990 Estimate (MMT CO_2 Eq.)	2019 Estimate (MMT CO_2 Eq.)	Approach 1 Trend Assessment	Approach 2 Trend Assessment	% Contribution to Trend	Cumulative Total
4.D.1 N_2O Emissions from Peatlands Remaining Peatlands	N_2O	+	+	<0.01	<0.001	<0.1	100
1.A.5.b N_2O Emissions from Mobile Combustion: Military	N_2O	+	+	<0.01	<0.001	<0.1	100
4.A.4 CH_4 Emissions from Drained Organic Soils	CH_4	+	+	<0.01	<0.001	<0.1	100
2.C.4 CO_2 Emissions from Magnesium Production and Processing	CO_2	+	+	<0.01	<0.001	<0.1	100
5.C.1 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) Volume 1, Chapter 4: Methodological Choice and Identification of Key Categories, *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 for years 1990, 1995, 2000, 2005, and 2009-2019 are presented in Columns 2 through 8 of Table A-12 through Table A-25 with totals by fuel type in Column 8 and totals by end-use sector in the last rows.[1] 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 Annex 6.5 Constants, Units, and Conversions). 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 use data were aggregated by sector (i.e., residential, commercial, industrial, transportation, electric power, 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 2019 total adjusted energy consumption across all sectors, including U.S. Territories, and energy types was 72,607.0 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 use 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 reported separately, and the remaining "other" electricity use was consequently combined with the commercial electricity data. Further information on these electricity end uses is described in EIA's *Monthly Energy Review* (EIA 2020b). Within the transportation sector, electricity use from electric vehicle charging in commercial and residential locations, not specifically reported by EIA, was calculated and re-allocated from the residential and commercial sectors to the transportation sector, for the years 2010 to present. The methodology for estimating electricity consumption by electric vehicles is outlined in Browning (2018).

There are also three basic differences between the consumption data presented in Table A-10 and Table A-12 through Table A-25 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)[2] rather than the lower heating values (LHV)[3] 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

[1] Adjusted consumption data for other years in the time series are available along with all other data tables for this report on U.S. EPA's homepage at <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>.

[2] Also referred to as gross calorific values (GCV).

[3] Also referred to as net calorific values (NCV).

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 energy use within U.S. Territories. Therefore, estimates for U.S. Territories[4] were added to domestic consumption of fossil fuels. Energy use data from U.S. Territories are presented in Column 7 of Table A-12 through Table A-25. 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 (IPPU) 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 use 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.

Examples of iron and steel production adjustments in allocating emissions in Energy and IPPU sectors:

The consumption of coking coal, natural gas, distillate fuel, and coal used in iron and steel production are adjusted within the Energy chapter to avoid double counting of emissions from consumption of these fuels during activities in IPPU related sectors. These fuels are adjusted based on activity data utilized in calculating emissions estimates within the Iron and Steel Production section. Iron and steel production is an industrial process in which coal coke is used as a raw material rather than as a fuel;[5] as such, the total use of industrial coking coal, as reported by EIA, is adjusted downward to account for this consumption within the iron and steel category. In this case, if the reported amount of coking coal used in these processes is greater than the amount of coking coal consumption reported by the

[4] 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.

[5] In addition to iron and steel, lead and zinc production are also industrial processes in which coal coke is used as a raw material. Iron and steel, lead and zinc production accounts for the major portion of consumption of coal coke in the United States.

EIA, the excess amount of coking coal used in these processes that is greater than the amount reported from consumption is subtracted from the industrial other coal fuel type.

In 2019, 17,924 thousand tons of coking coal were consumed,[6] resulting in an Energy sector adjustment of 382 TBtu. Natural gas, fuel oil, and coal are other fossil fuels also used in the production of iron and steel; therefore, the consumption of these fuels in industrial processes is subtracted from the industrial fossil fuel combustion sector to account for the amount of fuel used in the iron and steel calculation. In 2019, the iron and steel industry consumed 2,465 tons of coal (bituminous), 49,238 million ft^3 of natural gas, and 2,321 thousand gallons of distillate fuel as fuel. This resulted in Energy chapter adjustments of roughly 59 TBtu for coal, 51 TBtu for natural gas, and less than 1 TBtu for distillate fuel. In addition, an additional 132 TBtu is adjusted to account for coking coal consumed for industrial processes other than iron and steel, lead, and zinc production in 2019.

Step 3: Adjust for Conversion of Fossil Fuels and Exports

First, ethanol has been added to the motor gasoline stream for many years, but prior to 1993 this addition was not captured in EIA motor gasoline statistics. Starting in 1993, ethanol was included in gasoline statistics. Carbon dioxide emissions from ethanol added to motor gasoline 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 LULUCF, therefore, fuel consumption estimates are adjusted to remove ethanol. Thus, motor gasoline consumption statistics given in this report exclude ethanol and may be slightly lower than in EIA sources for finished gasoline that includes ethanol.

Second, EIA distillate fuel oil consumption statistics include “biodiesel” and “other renewable diesel fuel” consumption starting in 2009. Carbon dioxide emissions from biodiesel and other renewable diesel added to diesel fuel 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 LULUCF, therefore, fuel consumption estimates are adjusted to remove biodiesel and other renewable diesel fuel. Thus, distillate fuel oil consumption statistics for the transportation sector in this report may be slightly lower than in EIA sources.

Third, 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. Since October 2000, a portion of the CO_2 produced by the coal gasification plant has been exported to Canada by pipeline. The energy in this synthetic natural gas enters the natural gas distribution stream, however it is accounted for in EIA coal combustion statistics.[7] The exported CO_2 is not emitted to the atmosphere in the United States, and therefore the energy associated with the amount of CO_2 exported 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 were 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.

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

[6] Coking coal includes non-imported coke consumption from the iron and steel, lead, and zinc industries.

[7] To avoid double-counting, EIA’s MER statistics account for supplemental gaseous fuels (including synthetic natural gas) in their primary energy category (i.e., coal, petroleum, or biomass) (EIA 2020b).

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-26, 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-27). Emissions from international bunker fuels have been estimated separately and not included in national totals.[8]

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-12 through Table A-25) by fuel-specific C content coefficients (see Table A-28 and Table A-29) that reflect the amount of C per unit of energy in each fuel. The C content coefficients used in the Inventory were derived in part 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.

For geothermal electricity production, C content was estimated by multiplying net generation for each geotype (see Table A-32) by technology-specific C content coefficients (see Table A-28). For industrial energy and non-energy hydrocarbon gas liquids (HGL)[9] consumption, annually variable C contents were estimated by multiplying annual energy and non-energy consumption for each HGL component (e.g., ethane, ethylene, propane, propylene) by its respective C content coefficient (see Table A-29).

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, electric power, 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 electric power were distributed to each end-use sector according to its share of aggregate electricity use (see Table A-30). This pro-rated approach to allocating emissions from electric power 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 3.1.

Box A-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.

[8] 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.

[9] EIA defines HGL as "a group of hydrocarbons including ethane, propane, normal butane, isobutane, and natural gasoline, and their associated olefins, including ethylene, propylene, butylene, and isobutylene" (EIA 2020b).

For EPA's GHGRP 2010 through 2019 reporting years, facility-level fossil fuel combustion emissions reported through EPA's GHGRP were categorized and distributed to specific industry types by utilizing facility-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.[10]

As with previous Inventory reports, 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.[11] The efforts in reconciling fuels focus 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.

This year's analysis includes the full time series presented in the CRF tables. Analyses were conducted linking GHGRP facility-level reporting with the information published by EIA in its MECS data in order to disaggregate the full 1990 through 2019 time series in the CRF tables. 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. This includes incorporating the latest MECS data as it becomes available.

[10] 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, available at: <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

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

Table A-10: 2019 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]				Total Adjusted Consumption (TBtu)
									Unadjusted NEU Consumption			
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Bunker Fuel**	**Ind.**	**Trans.**	**Terr.**	
Total Coal	**NE**	**16.7**	**657.0**	**NE**	**10,181.2**	**27.1**	**10,882.0**		**142.3**			**10,739.8**
Residential Coal	NE						NE					NE
Commercial Coal		16.7					16.7					16.7
Industrial Other Coal			524.2				524.2		9.5			514.7
Transportation Coal				NE			NE					NE
Electric Power Coal					10,181.2		10,181.2					10,181.2
U.S. Territory Coal (bit)						27.1	27.1					27.1
Natural Gas	**5,204.9**	**3,645.1**	**10,245.4**	**1,035.2**	**11,645.4**	**48.2**	**31,824.2**		**332.2**			**31,492.1**
Total Petroleum	**932.2**	**624.5**	**8,556.1**	**26,527.7**	**188.6**	**278.9**	**37,108.1**	**1,618.1**	**5,024.8**	**132.1**	**10.7**	**30,322.4**
Asphalt & Road Oil			843.9				843.9		843.9			
Aviation Gasoline				23.4			23.4					23.4
Distillate Fuel Oil	426.7	271.6	1,053.6	6,570.4	53.9	79.5	8,455.6	134.8	5.8			8,315.0
Jet Fuel				3,608.0	NA	30.8	3,638.8	1,147.1				2,491.7
Kerosene	10.3	1.7	2.0			0.5	14.5					14.5
LPG (Propane)	495.2	172.0		7.5			674.8					674.8
HGL			2,887.4			6.4	2,893.8		2,758.8			135.0
Lubricants			117.6	132.1		1.0	250.7		117.6	132.1	1.0	
Motor Gasoline		176.3	129.7	15,654.0		105.0	16,065.0					16,065.0
Residual Fuel		2.7		532.2	58.8	46.2	639.9	336.2				303.7
Other Petroleum												
AvGas Blend Components			(1.2)				(1.2)					(1.2)
Crude Oil												
MoGas Blend Components												
Misc. Products			180.2			9.6	189.8		180.2		9.6	
Naphtha (<401 deg. F)			396.7				396.7		396.7			
Other Oil (>401 deg. F)			234.1				234.1		234.1			
Pentanes Plus			334.6				334.6		166.6			167.9
Petroleum Coke		0.2	602.3		75.9		678.4		56.4			622.0
Still Gas			1,533.5				1,533.5		158.7			1,374.7
Special Naphtha			95.6				95.6		95.6			
Unfinished Oils			135.9				135.9					135.9
Waxes			10.4				10.4		10.4			
Geothermal					**52.8**		**52.8**					**52.8**
Total (All Fuels)	**6,137.1**	**4,286.4**	**19,458.5**	**27,562.9**	**22,067.9**	**354.3**	**79,867.1**	**1,618.1**	**5,499.2**	**132.1**	**10.7**	**72,607.0**

Note: Parentheses indicate negative values.

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-26), and international bunker fuel consumption (see Table A-27).

[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-11: 2019 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**	**16.7**	**514.7**	**NE**	**10,181.2**	**27.1**	**10,739.8**	**NE**	**1.6**	**49.2**	**NE**	**973.5**	**2.5**	**1,026.8**
Residential Coal	NE						NE	NE						NE
Commercial Coal		16.7					16.7		1.6					1.6
Industrial Other Coal			514.7				514.7			49.2				49.2
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					10,181.2		10,181.2					973.5		973.5
U.S. Territory Coal (bit)						27.1	27.1						2.5	2.5
Natural Gas	**5,204.9**	**3,645.1**	**9,913.3**	**1,035.2**	**11,645.4**	**48.2**	**31,492.1**	**275.3**	**192.8**	**524.3**	**54.8**	**616.0**	**2.5**	**1,665.7**
Total Petroleum	**932.2**	**624.5**	**3,531.3**	**24,777.4**	**188.6**	**268.3**	**30,322.4**	**63.5**	**43.9**	**264.0**	**1,788.4**	**16.2**	**19.5**	**2,195.5**
Asphalt & Road Oil														
Aviation Gasoline				23.4			23.4				1.6			1.6
Distillate Fuel Oil	426.7	271.6	1,047.7	6,435.6	53.9	79.5	8,315.0	31.6	20.1	77.7	477.1	4.0	5.9	616.5
Jet Fuel				2,460.9	NA	30.8	2,491.7				177.7	NA	2.2	180.0
Kerosene	10.3	1.7	2.0			0.5	14.5	0.8	0.1	0.1			0.0	1.1
LPG (Propane)	495.2	172.0		7.5			674.8	31.1	10.8		0.5			42.4
HGL			128.6			6.4	135.0			8.2			0.4	8.7
Lubricants														
Motor Gasoline		176.3	129.7	15,654.0		105.0	16,065.0		12.6	9.2	1,116.7		7.5	1,146.1
Residual Fuel		2.7		196.0	58.8	46.2	303.7		0.2		14.7	4.4	3.5	22.8
Other Petroleum														
AvGas Blend Components			(1.2)				(1.2)			(0.1)				(0.1)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			167.9				167.9			11.2				11.2
Petroleum Coke		0.2	545.9		75.9		622.0		+	55.7		7.8		63.5
Still Gas			1,374.7				1,374.7			91.7				91.7
Special Naphtha														
Unfinished Oils			135.9				135.9			10.1				10.1
Waxes														
Geothermal					**52.8**		**52.8**					**0.4**		**0.4**
Total (All Fuels)	**6,137.1**	**4,286.4**	**13,959.3**	**25,812.7**	**22,067.9**	**343.6**	**72,607.0**	**338.8**	**238.3**	**837.6**	**1,843.2**	**1,606.0**	**24.6**	**4,888.5**

Note: Parentheses indicate negative values.

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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-12: 2018 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**	**18.7**	**564.3**	**NE**	**12,053.0**	**27.1**	**12,663.1**	**NE**	**1.8**	**54.0**	**NE**	**1,152.9**	**2.5**	**1,211.1**
Residential Coal	NE						NE	NE						NE
Commercial Coal		18.7					18.7		1.8					1.8
Industrial Other Coal			564.3				564.3			54.0				54.0
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					12,053.0		12,053.0					1,152.9		1,152.9
U.S. Territory Coal (bit)						27.1	27.1						2.5	2.5
Natural Gas	**5,174.4**	**3,638.3**	**9,733.5**	**962.2**	**10,912.1**	**48.1**	**30,468.6**	**273.8**	**192.5**	**515.1**	**50.9**	**577.4**	**2.5**	**1,612.3**
Total Petroleum	**963.6**	**746.0**	**3,593.7**	**24,526.1**	**260.4**	**268.3**	**30,358.0**	**65.7**	**52.6**	**269.0**	**1,770.3**	**22.2**	**19.5**	**2,199.3**
Asphalt & Road Oil														
Aviation Gasoline				22.4			22.4				1.5			1.5
Distillate Fuel Oil	448.8	285.7	1,102.2	6,396.0	80.6	79.5	8,392.7	33.3	21.2	81.7	474.2	6.0	5.9	622.2
Jet Fuel				2,386.0	NA	30.8	2,416.8				172.3	NA	2.2	174.5
Kerosene	8.2	1.3	1.6			0.5	11.7	0.6	0.1	0.1			0.0	0.9
LPG (Propane)	506.5	176.0		7.7			690.2	31.8	11.1		0.5			43.4
HGL			127.3			6.4	133.7			8.1			0.4	8.6
Lubricants														
Motor Gasoline		279.5	205.6	15,527.5		105.0	16,117.7		19.9	14.7	1,107.7		7.5	1,149.8
Residual Fuel		3.1		186.5	78.3	46.2	314.0		0.2		14.0	5.9	3.5	23.6
Other Petroleum														
AvGas Blend Components			(1.6)				(1.6)			(0.1)				(0.1)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			112.7				112.7			7.5				7.5
Petroleum Coke		0.4	569.8		101.5		671.6		+	58.2		10.4		68.6
Still Gas			1,445.3				1,445.3			96.4				96.4
Special Naphtha														
Unfinished Oils			30.9				30.9			2.3				2.3
Waxes														
Geothermal					**54.5**		**54.5**					**0.4**		**0.4**
Total (All Fuels)	**6,138.0**	**4,403.0**	**13,891.5**	**25,488.3**	**23,279.9**	**343.5**	**73,544.1**	**339.5**	**246.9**	**838.0**	**1,821.2**	**1,752.9**	**24.6**	**5,023.1**

Note: Parentheses indicate negative values.

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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-13: 2017 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**	**20.7**	**611.9**	**NE**	**12,622.2**	**27.1**	**13,281.9**	**NE**	**2.0**	**58.5**	**NE**	**1,207.1**	**2.5**	**1,270.0**
Residential Coal	NE						NE	NE						NE
Commercial Coal		20.7					20.7		2.0					2.0
Industrial Other Coal			611.9				611.9			58.5				58.5
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					12,622.2		12,622.2					1,207.1		1,207.1
U.S. Territory Coal (bit)						27.1	27.1						2.5	2.5
Natural Gas	**4,563.5**	**3,272.9**	**9,171.3**	**798.6**	**9,555.2**	**48.1**	**27,409.5**	**241.5**	**173.2**	**485.3**	**42.3**	**505.6**	**2.5**	**1,450.4**
Total Petroleum	**783.0**	**529.6**	**3,346.0**	**24,681.1**	**217.7**	**271.6**	**29,828.9**	**53.2**	**37.1**	**250.3**	**1,770.4**	**18.9**	**19.7**	**2,149.5**
Asphalt & Road Oil														
Aviation Gasoline				20.9			20.9				1.4			1.4
Distillate Fuel Oil	343.9	256.6	952.1	6,247.1	54.7	79.3	7,933.8	25.5	19.0	70.5	462.7	4.1	5.9	587.6
Jet Fuel				2,378.1	NA	30.8	2,408.9				171.8	NA	2.2	174.0
Kerosene	8.4	1.2	1.1			0.5	11.2	0.6	0.1	0.1			+	0.8
LPG (Propane)	430.7	155.7		7.1			593.5	27.1	9.8		0.4			37.3
HGL			175.6			6.4	182.0			11.2			0.4	11.6
Lubricants														
Motor Gasoline		111.8	81.9	15,808.6		108.5	16,110.7		7.9	5.8	1,117.6		7.7	1,138.9
Residual Fuel		3.8		219.3	65.8	46.2	335.0		0.3		16.5	4.9	3.5	25.2
Other Petroleum														
AvGas Blend Components			(0.2)				(0.2)			(+)				(+)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			87.0				87.0			5.8				5.8
Petroleum Coke		0.5	553.0		97.2		650.8		0.1	56.5		9.9		66.4
Still Gas			1,419.0				1,419.0			94.7				94.7
Special Naphtha														
Unfinished Oils			76.4				76.4			5.7				5.7
Waxes														
Geothermal					**54.3**		**54.3**					**0.4**		**0.4**
Total (All Fuels)	**5,346.4**	**3,823.1**	**13,129.2**	**25,479.7**	**22,449.5**	**346.8**	**70,574.7**	**294.6**	**212.3**	**794.1**	**1,812.6**	**1,732.0**	**24.7**	**4,870.4**

Note: Parentheses indicate negative values.

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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-14: 2016 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**	**23.7**	**658.2**	**NE**	**12,996.4**	**34.9**	**13,713.2**	**NE**	**2.3**	**62.8**	**NE**	**1,242.0**	**3.2**	**1,310.3**
Residential Coal	NE						NE							NE
Commercial Coal		23.7					23.7		2.3					2.3
Industrial Other Coal			658.2				658.2			62.8				62.8
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					12,996.4		12,996.4					1,242.0		1,242.0
U.S. Territory Coal (bit)						34.9	34.9						3.2	3.2
Natural Gas	**4,505.8**	**3,223.5**	**8,968.6**	**757.2**	**10,301.3**	**63.6**	**27,820.1**	**238.4**	**170.5**	**474.5**	**40.1**	**545.0**	**3.4**	**1,471.8**
Total Petroleum	**793.4**	**535.2**	**3,330.1**	**24,508.8**	**243.9**	**270.1**	**29,681.6**	**54.0**	**37.6**	**249.7**	**1,757.2**	**21.5**	**19.6**	**2,139.5**
Asphalt & Road Oil														
Aviation Gasoline				20.5			20.5				1.4			1.4
Distillate Fuel Oil	349.9	262.5	924.6	6,156.0	54.9	79.2	7,827.1	25.9	19.5	68.5	456.2	4.1	5.9	580.0
Jet Fuel				2,298.8	NA	29.6	2,328.3				166.0	NA	2.1	168.2
Kerosene	13.7	2.1	2.3			0.4	18.4	1.0	0.2	0.2			+	1.3
LPG (Propane)	429.9	150.0		7.1			587.0	27.0	9.4		0.4			36.9
HGL			227.4			6.3	233.7			14.5			0.4	14.9
Lubricants														
Motor Gasoline		115.9	81.0	15,854.0		108.4	16,159.4		8.2	5.7	1,120.2		7.7	1,141.8
Residual Fuel		4.4		172.4	70.7	46.2	293.7		0.3		12.9	5.3	3.5	22.1
Other Petroleum														
AvGas Blend Components			(0.3)				(0.3)			(+)				(+)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			56.5				56.5			3.8				3.8
Petroleum Coke		0.3	591.4		118.3		710.1		+	60.4		12.1		72.5
Still Gas			1,438.6				1,438.6			96.0				96.0
Special Naphtha														
Unfinished Oils			8.6				8.6			0.6				0.6
Waxes														
Geothermal					**54.0**		**54.0**					**0.4**		**0.4**
Total (All Fuels)	**5,299.3**	**3,782.5**	**12,957.0**	**25,266.0**	**23,595.6**	**368.6**	**71,268.9**	**292.3**	**210.4**	**787.0**	**1,797.3**	**1,808.9**	**26.2**	**4,922.0**

Note: Parentheses indicate negative values.

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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-15: 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**	**733.9**	**NE**	**14,138.3**	**44.9**	**14,948.1**	**NE**	**3.0**	**70.0**	**NE**	**1,351.4**	**4.1**	**1,428.5**
Residential Coal	NE						NE	NE						NE
Commercial Coal		31.1					31.1		3.0					3.0
Industrial Other Coal			733.9				733.9			70.0				70.0
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					14,138.3		14,138.3					1,351.4		1,351.4
U.S. Territory Coal (bit)						44.9	44.9						4.1	4.1
Natural Gas	**4,776.9**	**3,315.6**	**8,778.2**	**744.8**	**9,926.5**	**57.4**	**27,599.4**	**252.7**	**175.4**	**464.4**	**39.4**	**525.2**	**3.0**	**1,460.2**
Total Petroleum	**949.5**	**658.0**	**3,406.4**	**23,880.2**	**276.0**	**306.5**	**29,476.6**	**65.4**	**46.5**	**255.9**	**1,711.1**	**23.7**	**22.2**	**2,124.8**
Asphalt & Road Oil														
Aviation Gasoline				21.1			21.1				1.5			1.5
Distillate Fuel Oil	493.6	322.4	1,040.3	6,132.1	70.4	77.8	8,136.7	36.6	23.9	77.1	454.6	5.2	5.8	603.3
Jet Fuel				2,181.9	NA	36.0	2,217.9				157.6	NA	2.6	160.2
Kerosene	10.1	1.4	1.7			0.1	13.4	0.7	0.1	0.1			+	1.0
LPG (Propane)	445.7	148.0		6.6			600.3	28.0	9.3		0.4			37.7
HGL			243.3			6.2				15.5			0.4	15.9
Lubricants														
Motor Gasoline		181.8	124.7	15,481.9		116.6	15,905.0		12.8	8.8	1,092.8		8.2	1,122.6
Residual Fuel		4.0		56.6	93.9	69.6	224.0		0.3		4.2	7.0	5.2	16.8
Other Petroleum														
AvGas Blend Components			(0.3)				(0.3)			(+)				(+)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			80.9				80.9			5.4				5.4
Petroleum Coke		0.5	600.8		111.7		713.0		0.1	61.3		11.4		72.8
Still Gas			1,332.9				1,332.9			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)	**5,726.4**	**4,004.8**	**12,918.5**	**24,625.1**	**24,395.0**	**408.8**	**72,078.4**	**318.1**	**224.9**	**790.3**	**1,750.5**	**1,900.6**	**29.4**	**5,013.8**

Note: Parentheses indicate negative values.

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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-16: 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**	**837.2**	**NE**	**16,427.4**	**43.8**	**17,348.5**	**NE**	**3.8**	**79.6**	**NE**	**1,568.6**	**4.0**	**1,656.1**
Residential Coal	NE						NE	NE						NE
Commercial Coal		40.2					40.2		3.8					3.8
Industrial Other Coal			837.2				837.2			79.6				79.6
Transportation Coal							NE				NE			NE
Electric Power Coal					16,427.4		16,427.4					1,568.6		1,568.6
U.S. Territory Coal (bit)						43.8	43.8						4.0	4.0
Natural Gas	**5,242.5**	**3,571.9**	**8,817.9**	**759.7**	**8,361.7**	**60.6**	**26,814.3**	**277.7**	**189.2**	**467.0**	**40.2**	**442.9**	**3.2**	**1,420.2**
Total Petroleum	**1,017.0**	**567.3**	**3,603.2**	**23,209.1**	**295.5**	**294.9**	**28,987.1**	**69.9**	**40.1**	**271.0**	**1,674.6**	**25.3**	**21.4**	**2,102.3**
Asphalt & Road Oil														
Aviation Gasoline				21.7			21.7				1.5			1.5
Distillate Fuel Oil	513.7	343.6	1,308.5	5,945.6	82.2	64.8	8,258.5	38.1	25.5	97.1	441.0	6.1	4.8	612.6
Jet Fuel				2,054.3	NA	35.0	2,089.3				148.4	NA	2.5	150.9
Kerosene	13.7	2.0	2.8			0.1	18.7	1.0	0.1	0.2			+	1.4
LPG (Propane)	489.5	160.5		7.2			657.1	30.8	10.1		0.4			41.3
HGL			177.9			6.4	184.3			11.4			0.4	11.8
Lubricants														
Motor Gasoline		52.7	205.6	15,103.0		126.7	15,488.0		3.8	14.7	1,077.4		9.0	1,104.9
Residual Fuel		7.9		77.4	95.1	61.9	242.4		0.6		5.8	7.1	4.7	18.2
Other Petroleum														
AvGas Blend Components			(0.1)				(0.1)			(+)				(+)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			44.5				44.5			3.0				3.0
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)	**6,259.5**	**4,179.4**	**13,258.3**	**23,968.8**	**25,138.7**	**399.3**	**73,204.1**	**347.6**	**233.1**	**817.6**	**1,714.8**	**2,037.2**	**28.7**	**5,179.0**

Note: Parentheses indicate negative values.

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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-17: 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**	**836.8**	**NE**	**16,450.6**	**30.8**	**17,359.5**	**NE**	**3.9**	**79.5**	**NE**	**1,571.3**	**2.8**	1,657.6
Residential Coal	NE						NE	NE						NE
Commercial Coal		41.4					41.4		3.9					3.9
Industrial Other Coal			836.8				836.8			79.5				79.5
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)						30.8	30.8						2.8	2.8
Natural Gas	**5,022.9**	**3,379.8**	**8,525.6**	**887.3**	**8,376.3**	**58.2**	**26,250.1**	**266.4**	**179.2**	**452.1**	**47.0**	**444.2**	**3.1**	**1,392.0**
Total Petroleum	**904.6**	**511.4**	**3,644.8**	**23,127.0**	**255.2**	**301.6**	**28,744.5**	**61.8**	**36.1**	**272.8**	**1,659.2**	**22.4**	**21.9**	**2,074.3**
Asphalt & Road Oil														
Aviation Gasoline				22.4			22.4				1.5			1.5
Distillate Fuel Oil	432.8	302.6	1,107.1	5,857.6	55.4	71.0	7,826.6	32.1	22.4	82.1	434.5	4.1	5.3	580.5
Jet Fuel				2,036.9	NA	30.0	2,067.0				147.1	NA	2.2	149.3
Kerosene	8.3	1.0	1.5			0.1	10.9	0.6	0.1	0.1			+	0.8
LPG (Propane)	463.5	151.6		6.9			622.0	29.1	9.5		0.4			39.1
HGL			294.0			6.3	300.3			18.7			0.4	19.2
Lubricants														
Motor Gasoline		31.4	207.0	15,001.9		121.2	15,361.5		2.2	14.6	1,060.5		8.6	1,086.0
Residual Fuel		24.4		201.4	77.2	72.9	375.9		1.8		15.1	5.8	5.5	28.2
Other Petroleum														
AvGas Blend Components			(0.4)				(0.4)			(+)				(+)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			47.5				47.5			3.2				3.2
Petroleum Coke		0.4	600.9		122.5		723.7		+	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)	**5,927.5**	**3,932.6**	**13,007.2**	**24,014.3**	**25,135.8**	**390.7**	**72,408.0**	**328.2**	**219.3**	**804.4**	**1,706.3**	**2,038.3**	**27.8**	**5,124.3**

Note: Parentheses indicate negative values.

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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-18: 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**	**822.6**	**NE**	**15,821.2**	**36.9**	**16,724.2**	**NE**	**4.1**	**78.2**	**NE**	**1,511.7**	**3.4**	**1,597.4**
Residential Coal	NE						NE	NE						NE
Commercial Coal		43.6					43.6		4.1					4.1
Industrial Other Coal			822.6				822.6			78.2				78.2
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					15,821.2		15,821.2					1,511.7		1,511.7
U.S. Territory Coal (bit)						36.9	36.9						3.4	3.4
Natural Gas	**4,242.1**	**2,959.5**	**8,204.3**	**779.8**	**9,286.8**	**49.2**	**25,521.6**	**225.1**	**157.0**	**435.3**	**41.4**	**492.8**	**2.6**	**1,354.3**
Total Petroleum	**843.9**	**498.9**	**3,546.0**	**22,917.9**	**214.2**	**376.4**	**28,397.3**	**58.1**	**35.5**	**267.9**	**1,647.5**	**18.3**	**27.4**	**2,054.8**
Asphalt & Road Oil														
Aviation Gasoline				25.1			25.1				1.7			1.7
Distillate Fuel Oil	440.6	324.5	1,153.1	5,712.7	52.4	62.9	7,746.2	32.7	24.1	85.5	423.5	3.9	4.7	574.3
Jet Fuel				1,985.2	NA	39.1	2,024.3				143.4	NA	2.8	146.2
Kerosene	7.7	1.2	2.0			0.6	11.6	0.6	0.1	0.1			+	0.8
LPG (Propane)	395.6	135.5		7.1			538.2	24.9	8.5		0.4			33.8
HGL			280.1			11.1	291.2			17.9			0.7	18.6
Lubricants														
Motor Gasoline		6.0	39.0	14,976.7		135.5	15,157.1		0.4	2.8	1,062.6		9.6	1,075.4
Residual Fuel		31.4		211.1	76.7	127.3	446.5		2.4		15.8	5.8	9.6	33.5
Other Petroleum														
AvGas Blend Components			(+)				(+)			(+)				(+)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			42.5				42.5			2.8				2.8
Petroleum Coke		0.4	649.0		85.1		734.4		+	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)	**5,086.0**	**3,502.0**	**12,572.8**	**23,697.6**	**25,375.3**	**462.5**	**70,696.3**	**283.2**	**196.7**	**781.5**	**1,688.9**	**2,023.3**	**33.4**	**5,007.0**

Note: Parentheses indicate negative values.

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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-19: 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**	**905.7**	**NE**	**18,035.2**	**36.9**	**19,039.5**	**NE**	**5.8**	**86.0**	**NE**	**1,722.4**	**3.4**	**1,817.6**
Residential Coal	NE						NE	NE						NE
Commercial Coal		61.7					61.7		5.8					5.8
Industrial Other Coal			905.7				905.7			86.0				86.0
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					18,035.2		18,035.2					1,722.4		1,722.4
U.S. Territory Coal (bit)						36.9	36.9						3.4	3.4
Natural Gas	**4,804.6**	**3,216.1**	**7,875.8**	**733.5**	**7,712.2**	**27.1**	**24,369.3**	**255.1**	**170.7**	**418.1**	**38.9**	**409.4**	**1.4**	**1,293.7**
Total Petroleum	**1,024.9**	**596.6**	**3,494.4**	**23,163.6**	**295.0**	**395.7**	**28,970.2**	**70.4**	**42.6**	**264.0**	**1,667.2**	**25.8**	**28.8**	**2,098.9**
Asphalt & Road Oil														
Aviation Gasoline				27.1			27.1				1.9			1.9
Distillate Fuel Oil	513.8	384.8	1,206.2	5,813.9	63.7	58.6	8,040.9	38.1	28.5	89.4	431.0	4.7	4.3	596.2
Jet Fuel				2,029.9	NA	47.1	2,077.0				146.6	NA	3.4	150.0
Kerosene	18.5	3.2	3.6			1.1	26.4	1.4	0.2	0.3			0.1	1.9
LPG (Propane)	492.6	142.5		7.3			642.4	31.0	9.0		0.5			40.4
HGL			159.6			9.0	168.7			10.2			0.6	10.8
Lubricants														
Motor Gasoline		12.2	70.7	15,027.5		152.3	15,262.7		0.9	5.0	1,067.9		10.8	1,084.6
Residual Fuel		53.7	46.9	258.0	93.1	127.5	579.2		4.0	3.5	19.4	7.0	9.6	43.5
Other Petroleum														
AvGas Blend Components			+				+			+				+
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			27.6				27.6			1.8				1.8
Petroleum Coke		0.2	600.3		138.3		738.8		+	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)	**5,829.5**	**3,874.5**	**12,275.9**	**23,897.1**	**26,094.7**	**459.7**	**72,431.3**	**325.5**	**219.2**	**768.1**	**1,706.1**	**2,158.1**	**33.6**	**5,210.7**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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: 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**	**993.0**	**NE**	**19,133.5**	**36.9**	**20,232.9**	**NE**	**6.6**	**94.2**	**NE**	**1,827.2**	**3.4**	**1,931.4**
Residential Coal	NE						NE	NE						NE
Commercial Coal		69.7					69.7		6.6					6.6
Industrial Other Coal			993.0				993.0			94.2				94.2
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					19,133.5		19,133.5					1,827.2		1,827.2
U.S. Territory Coal (bit)						36.9	36.9						3.4	3.4
Natural Gas	**4,878.1**	**3,164.7**	**7,685.4**	**719.0**	**7,527.6**	**27.8**	**24,002.6**	**258.9**	**168.0**	**407.9**	**38.2**	**399.5**	**1.5**	**1,274.0**
Total Petroleum	**1,118.1**	**633.3**	**3,574.2**	**23,427.7**	**370.3**	**412.4**	**29,536.1**	**76.9**	**45.4**	**270.3**	**1,686.7**	**31.4**	**30.1**	**2,140.8**
Asphalt & Road Oil														
Aviation Gasoline				27.0			27.0				1.9			1.9
Distillate Fuel Oil	559.1	389.5	1,138.9	5,674.9	79.7	65.8	7,908.0	41.5	28.9	84.5	421.2	5.9	4.9	586.9
Jet Fuel				2,097.5	NA	36.6	2,134.0				151.5	NA	2.6	154.1
Kerosene	29.1	4.8	7.3			7.5	48.7	2.1	0.4	0.5			0.5	3.6
LPG (Propane)	529.8	140.0		7.5			677.3	33.3	8.8		0.5			42.6
HGL			148.0			17.6	165.5			9.5			1.1	10.6
Lubricants														
Motor Gasoline		36.9	184.7	15,348.7		116.3	15,686.6		2.6	13.1	1,091.2		8.3	1,115.3
Residual Fuel		61.7	32.2	272.2	154.1	168.7	688.8		4.6	2.4	20.4	11.6	12.7	51.7
Other Petroleum														
AvGas Blend Components			(0.2)				(0.2)			(+)				(+)
Crude Oil														
MoGas Blend Components														
Misc. Products														
Naphtha (<401 deg. F)														
Other Oil (>401 deg. F)														
Pentanes Plus			78.4				78.4			5.2				5.2
Petroleum Coke		0.3	633.0		136.6		770.0		+	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)	**5,996.2**	**3,867.6**	**12,252.6**	**24,146.7**	**27,083.3**	**477.1**	**73,823.5**	**335.8**	**219.9**	**772.4**	**1,724.8**	**2,258.6**	**35.0**	**5,346.6**

Note: Parentheses indicate negative values.

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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: 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**	**918.1**	**NE**	**18,225.3**	**36.9**	**19,253.7**	**NE**	**6.9**	**87.1**	**NE**	**1,740.2**	**3.4**	**1,837.5**
Residential Coal	NE						NE	NE						NE
Commercial Coal		73.4					73.4		6.9					6.9
Industrial Other Coal			918.1				918.1			87.1				87.1
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					18,225.3		18,225.3					1,740.2		1,740.2
U.S. Territory Coal (bit)						36.9	36.9						3.4	3.4
Natural Gas	**4,883.1**	**3,186.6**	**7,126.2**	**714.9**	**7,022.4**	**27.4**	**22,960.6**	**259.1**	**169.1**	**378.1**	**37.9**	**372.5**	**1.5**	**1,218.1**
Total Petroleum	**1,126.3**	**658.5**	**3,433.7**	**23,286.7**	**382.4**	**480.4**	**29,368.1**	**77.3**	**47.1**	**259.7**	**1,678.2**	**32.2**	**35.0**	**2,129.5**
Asphalt & Road Oil														
Aviation Gasoline				26.6			26.6				1.8			1.8
Distillate Fuel Oil	550.9	373.9	994.9	5,497.8	69.6	67.2	7,554.2	40.9	27.7	73.8	407.8	5.2	5.0	560.3
Jet Fuel				2,134.2	NA	51.2	2,185.4				154.1	NA	3.7	157.8
Kerosene	27.7	4.2	4.4			8.7	45.1	2.0	0.3	0.3			0.6	3.3
LPG (Propane)	547.8	139.0		28.1			714.9	34.4	8.7		1.8			44.9
HGL			116.0			26.2	142.2			7.4			1.7	9.0
Lubricants														
Motor Gasoline		69.9	320.4	15,414.3		152.7	15,957.3		5.0	22.8	1,098.7		10.9	1,137.4
Residual Fuel		71.3	67.3	185.7	181.0	174.4	679.6		5.4	5.1	13.9	13.6	13.1	51.0
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			64.3				64.3			4.3				4.3
Petroleum Coke		0.2	624.0		131.8		756.1		+	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)	**6,009.4**	**3,918.5**	**11,478.0**	**24,001.5**	**25,681.3**	**544.7**	**71,633.5**	**336.4**	**223.1**	**724.8**	**1,716.2**	**2,145.3**	**39.8**	**5,185.6**

Note: Parentheses indicate negative values.

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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: 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**	**1,248.1**	**NE**	**20,737.2**	**32.7**	**22,123.5**	**0.8**	**9.3**	**118.0**	**NE**	**1,982.8**	**3.0**	**2,113.9**
Residential Coal	8.4						8.4	0.8						0.8
Commercial Coal		97.0					97.0		9.3					9.3
Industrial Other Coal			1,248.1				1,248.1			118.0				118.0
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					20,737.2		20,737.2					1,982.8		1,982.8
U.S. Territory Coal (bit)						32.7	32.7						3.0	3.0
Natural Gas	**4,946.4**	**3,073.2**	**7,330.7**	**623.9**	**6,014.5**	**24.3**	**22,013.1**	**262.2**	**162.9**	**388.6**	**33.1**	**318.9**	**1.3**	**1,167.0**
Total Petroleum	**1,369.0**	**745.0**	**4,488.3**	**25,514.3**	**1,222.1**	**713.6**	**34,052.3**	**96.1**	**53.8**	**337.3**	**1,835.7**	**98.0**	**51.7**	**2,472.5**
Asphalt & Road Oil														
Aviation Gasoline				35.4			35.4				2.4			2.4
Distillate Fuel Oil	771.6	404.2	1,127.6	6,186.8	114.5	135.9	8,740.6	57.6	30.2	84.2	462.1	8.5	10.2	652.8
Jet Fuel				2,621.7	NA	65.5	2,687.2				189.3	NA	4.7	194.1
Kerosene	83.8	21.6	39.1			5.8	150.2	6.1	1.6	2.9			0.4	11.0
LPG (Propane)	513.5	131.6		28.2			673.3	32.3	8.3		1.8			42.3
HGL			281.9			73.6	355.4			18.0			4.7	22.7
Lubricants														
Motor Gasoline		71.5	556.5	16,385.8		202.0	17,215.7		5.1	39.4	1,160.8		14.3	1,219.6
Residual Fuel		115.8	237.4	256.4	876.5	230.9	1,717.0		8.7	17.8	19.3	65.8	17.3	128.9
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			98.9				98.9			6.6				6.6
Petroleum Coke		0.3	706.6		231.1		938.0		+	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**					**0.5**		**0.5**
Total (All Fuels)	**6,323.7**	**3,915.2**	**13,067.1**	**26,138.2**	**28,024.0**	**770.7**	**78,238.9**	**359.1**	**226.0**	**844.0**	**1,868.8**	**2,400.1**	**56.0**	**5,753.8**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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-23: 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**	**1,379.3**	**NE**	**20,220.2**	**4.6**	**21,707.3**	**1.1**	**8.8**	**130.2**	**NE**	**1,926.4**	**0.4**	**2,066.8**
Residential Coal	11.4						11.4	1.1						1.1
Commercial Coal		91.9					91.9		8.8					8.8
Industrial Other Coal			1,379.3				1,379.3			130.2				130.2
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					20,220.2		20,220.2					1,926.4		1,926.4
U.S. Territory Coal (bit)						4.6	4.6						0.4	0.4
Natural Gas	**5,104.6**	**3,251.5**	**8,659.3**	**672.0**	**5,293.4**	**12.7**	**22,993.5**	**270.8**	**172.5**	**459.4**	**35.7**	**280.8**	**0.7**	**1,219.8**
Total Petroleum	**1,427.4**	**754.7**	**3,706.1**	**24,349.1**	**1,144.1**	**575.5**	**31,957.1**	**100.0**	**54.4**	**278.7**	**1,760.3**	**88.5**	**41.3**	**2,323.2**
Asphalt & Road Oil														
Aviation Gasoline				36.3			36.3				2.5			2.5
Distillate Fuel Oil	777.2	421.7	1,002.7	5,437.0	174.7	87.2	7,900.6	58.1	31.5	75.0	406.5	13.1	6.5	590.7
Jet Fuel				2,700.3	NA	68.6	2,768.9				195.0	NA	5.0	200.0
Kerosene	94.6	29.7	15.6			2.4	142.2	6.9	2.2	1.1			0.2	10.4
LPG (Propane)	555.6	150.6		11.9			718.1	34.9	9.5		0.7			45.1
HGL			393.8			91.8	485.6			25.3			5.9	31.2
Lubricants														
Motor Gasoline		61.0	205.8	15,720.2		187.0	16,173.9		4.4	14.7	1,122.3		13.3	1,154.7
Residual Fuel		91.6	184.1	443.5	870.8	138.6	1,728.5		6.9	13.8	33.3	65.4	10.4	129.8
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			172.9				172.9			11.6				11.6
Petroleum Coke		0.2	697.3		98.6		796.2		+	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**					**0.5**		**0.5**
Total (All Fuels)	**6,543.4**	**4,098.2**	**13,744.8**	**25,021.1**	**26,705.8**	**592.8**	**76,706.0**	**371.9**	**235.7**	**868.3**	**1,796.0**	**2,296.2**	**42.4**	**5,610.3**

Note: Parentheses indicate negative values.

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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-24: 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**	**1,557.0**	**NE**	**17,466.3**	**4.7**	**19,162.2**	**1.7**	**11.2**	**147.2**	**NE**	**1,659.9**	**0.4**	**1,820.4**
Residential Coal	17.5						17.5	1.7						1.7
Commercial Coal		116.8					116.8		11.2					11.2
Industrial Other Coal			1,557.0				1,557.0			147.2				147.2
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					17,466.3		17,466.3					1,659.9		1,659.9
U.S. Territory Coal (bit)						4.7	4.7						0.4	0.4
Natural Gas	**4,954.2**	**3,096.0**	**8,725.9**	**724.0**	**4,302.0**		**21,802.0**	**262.8**	**164.2**	**462.8**	**38.4**	**228.2**		**1,156.4**
Total Petroleum	**1,260.7**	**713.7**	**3,633.1**	**21,660.2**	**754.5**	**324.6**	**28,346.8**	**88.8**	**51.7**	**271.3**	**1,551.6**	**58.7**	**23.3**	**2,045.4**
Asphalt & Road Oil														
Aviation Gasoline				39.6			39.6				2.7			2.7
Distillate Fuel Oil	791.1	418.7	967.1	4,379.3	108.0	62.6	6,726.7	58.5	31.0	71.5	323.9	8.0	4.6	497.5
Jet Fuel				2,428.8	NA	57.2	2,486.0				172.2	NA	4.1	176.3
Kerosene	74.3	22.1	15.4			2.0	113.9	5.4	1.6	1.1			0.1	8.3
LPG (Propane)	395.3	108.9		17.8			521.9	24.9	6.8		1.1			32.8
HGL			277.8			35.6	313.5			17.8			2.3	20.1
Lubricants														
Motor Gasoline		22.4	247.2	14,407.5		85.2	14,762.3		1.6	17.5	1,022.6		6.1	1,047.8
Residual Fuel		141.5	286.2	387.3	566.0	81.9	1,462.8		10.6	21.5	29.1	42.5	6.1	109.8
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			170.3				170.3			11.4				11.4
Petroleum Coke		0.1	600.7		80.6		681.4		+	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**					**0.4**		**0.4**
Total (All Fuels)	**6,232.4**	**3,926.5**	**13,916.0**	**22,384.2**	**22,568.4**	**329.2**	**69,356.7**	**353.2**	**227.1**	**881.3**	**1,590.0**	**1,947.2**	**23.8**	**5,022.6**

Note: Parentheses indicate negative values.

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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-25: 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**	**1,668.2**	**NE**	**16,261.0**	**5.4**	**18,090.1**	**3.0**	**12.0**	**157.8**	**NE**	**1,546.5**	**0.5**	**1,719.8**
Residential Coal	31.1						31.1	3.0						3.0
Commercial Coal		124.5					124.5		12.0					12.0
Industrial Other Coal			1,668.2				1,668.2			157.8				157.8
Transportation Coal				NE			NE				NE			NE
Electric Power Coal					16,261.0		16,261.0					1,546.5		1,546.5
U.S. Territory Coal (bit)						5.4	5.4						0.5	0.5
Natural Gas	**4,486.6**	**2,679.6**	**7,712.8**	**679.2**	**3,308.5**		**18,866.7**	**237.8**	**142.0**	**408.8**	**36.0**	**175.4**		**1,000.0**
Total Petroleum	**1,375.8**	**1,022.6**	**3,846.1**	**19,977.0**	**1,289.4**	**294.8**	**27,805.8**	**97.8**	**74.3**	**287.2**	**1,433.1**	**97.5**	**21.2**	**2,011.1**
Asphalt & Road Oil														
Aviation Gasoline				45.0			45.0				3.1			3.1
Distillate Fuel Oil	959.3	525.5	1,098.2	3,554.7	96.5	56.4	6,290.7	70.9	38.9	81.2	262.9	7.1	4.2	465.2
Jet Fuel				2,590.1		48.6	2,638.7				184.2		3.5	187.7
Kerosene	63.9	11.8	12.3			2.0	90.0	4.7	0.9	0.9			0.1	6.6
LPG (Propane)	352.6	102.4		22.9			477.9	22.2	6.4		1.4			30.0
HGL			227.1			33.4	260.5			14.6			2.1	16.7
Lubricants														
Motor Gasoline		153.0	254.8	13,464.1		75.9	13,947.7		10.9	18.1	958.9		5.4	993.3
Residual Fuel		229.8	364.1	300.3	1,162.6	78.5	2,135.3		17.3	27.3	22.6	87.3	5.9	160.3
Other Petroleum														
AvGas Blend Components			0.2				0.2			+				+
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			126.1				126.1			8.4				8.4
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**					**0.5**		**0.5**
Total (All Fuels)	**5,893.5**	**3,826.6**	**13,227.1**	**20,656.3**	**20,911.6**	**300.2**	**64,815.3**	**338.6**	**228.3**	**853.8**	**1,469.1**	**1,820.0**	**21.7**	**4,731.5**

Note: Parentheses indicate negative values.

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 Eq.

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-26), and international bunker fuel consumption (see Table A-27).

[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-26: Unadjusted Non-Energy Fuel Consumption (TBtu)

Sector/Fuel Type	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Industry	**4,644.2**	**5,153.6**	**5,575.9**	**5,482.5**	**4,508.4**	**4,735.1**	**4,658.8**	**4,590.5**	**4,815.5**	**4,724.3**	**4,922.4**	**4,906.3**	**5,079.3**	**5,390.8**	**5,499.2**
Industrial Coking Coal	0.0	37.8	53.5	80.4	6.4	64.8	60.8	132.5	119.3	48.8	121.8	89.1	112.4	125.0	132.8
Industrial Other Coal	7.6	10.5	11.5	11.0	11.0	9.6	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Natural Gas to Chemical Plants, Other Uses	305.9	371.0	401.7	270.4	232.7	310.0	309.7	310.6	311.5	330.6	332.2	332.5	332.2	332.2	332.2
Asphalt & Road Oil	1,170.2	1,178.2	1,275.7	1,323.2	873.1	877.8	859.5	826.7	783.3	792.6	831.7	853.4	849.2	792.8	843.9
HGL	1,302.2	1,651.6	1,759.3	1,659.5	1,748.0	1,899.9	1,954.4	1,983.7	2,155.2	2,142.8	2,216.8	2,257.1	2,329.7	2,677.4	2,758.8
Lubricants	186.3	177.8	189.9	160.2	134.5	135.9	127.4	118.3	125.1	130.7	142.1	135.1	124.9	121.9	117.6
Pentanes Plus	125.2	169.0	171.6	98.1	63.8	77.7	27.3	42.2	47.1	44.2	80.2	56.1	86.4	111.8	166.6
Naphtha (<401 deg. F)	347.8	373.0	613.5	698.7	471.9	490.6	487.3	453.9	517.8	442.6	428.1	420.0	436.2	447.1	396.7
Other Oil (>401 deg. F)	753.9	801.0	722.2	708.0	424.8	452.5	388.5	287.2	223.9	247.2	229.0	222.5	262.9	239.1	234.1
Still Gas	36.7	47.9	17.0	67.7	133.9	147.8	163.6	160.6	166.7	164.5	162.2	166.1	163.8	166.9	158.7
Petroleum Coke	123.1	120.6	98.7	186.9	180.7	61.0	62.4	67.8	62.4	61.4	62.5	61.2	57.0	58.9	56.4
Special Naphtha	107.1	70.8	97.4	62.5	46.2	26.1	22.6	14.7	100.0	106.1	99.3	93.6	100.3	92.0	95.6
Other (Wax/Misc.)															
Distillate Fuel Oil	7.0	6.8	11.7	11.7	17.5	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
Waxes	33.3	40.6	33.1	31.4	12.2	17.1	15.1	15.3	16.5	14.8	12.4	12.8	10.2	12.4	10.4
Miscellaneous Products	137.8	97.1	119.2	112.8	151.8	158.7	164.7	161.6	171.2	182.7	188.9	191.3	198.8	198.0	180.2
Transportation	**176.0**	**167.9**	**179.4**	**151.3**	**127.1**	**154.8**	**148.4**	**135.4**	**143.4**	**149.4**	**162.8**	**154.4**	**142.0**	**137.0**	**132.1**
Lubricants	176.0	167.9	179.4	151.3	127.1	154.8	148.4	135.4	143.4	149.4	162.8	154.4	142.0	137.0	132.1
U.S. Territories	**50.8**	**55.4**	**140.8**	**114.9**	**40.3**	**27.4**	**14.6**	**17.6**	**10.5**	**10.7**	**10.3**	**10.5**	**10.7**	**10.7**	**10.7**
Lubricants	0.7	2.0	3.1	4.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Other Petroleum (Misc. Prod.)	50.1	53.4	137.7	110.3	39.3	26.4	13.6	16.6	9.5	9.6	9.3	9.5	9.6	9.6	9.6
Total	**4,871.1**	**5,377.0**	**5,896.1**	**5,748.7**	**4,675.8**	**4,917.3**	**4,821.7**	**4,743.5**	**4,969.4**	**4,884.3**	**5,095.6**	**5,071.1**	**5,232.0**	**5,538.5**	**5,642.0**

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-27: International Bunker Fuel Consumption (TBtu)

Fuel Type	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Aviation Jet Fuel	539.4	703.4	880.1	853.1	749.1	865.4	919.9	916.3	931.6	987.8	1,022.3	1,051.1	1,103.2	1,146.8	1,147.1
Marine Residual Fuel Oil	715.7	523.2	444.1	581.0	604.8	619.8	518.4	459.5	379.8	369.2	406.8	450.7	445.3	417.6	336.2
Marine Distillate Fuel Oil	158.1	125.8	85.6	126.3	109.9	126.9	106.3	90.7	74.5	81.1	112.1	116.0	119.8	133.0	134.8
Total	**1,413.2**	**1,352.4**	**1,409.7**	**1,560.4**	**1,463.7**	**1,612.1**	**1,544.6**	**1,466.4**	**1,386.0**	**1,438.1**	**1,541.2**	**1,617.8**	**1,668.4**	**1,697.3**	**1,618.1**

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-28: Key Assumptions for Estimating CO_2 Emissions

Fuel Type	C Content Coefficient (MMT C/QBtu)
Coal	
Residential Coal	(See footnote b)
Commercial Coal	(See footnote b)
Industrial Coking Coal	31.00
Industrial Other Coal	(See footnote b)
Electric Power Coal	(See footnote b)
U.S. Territory Coal (bit)	25.14
Natural Gas	
Pipeline Natural Gas	(See footnote b)
Petroleum	
Asphalt & Road Oil	20.55
Aviation Gasoline	18.86
Distillate Fuel Oil No. 1	19.98
Distillate Fuel Oil No. 2[a]	(See footnote b)
Distillate Fuel Oil No. 4	20.47
Jet Fuel	(See footnote b)
Kerosene	19.96
LPG (Propane)	17.15
HGL (Energy Use)	(See footnote b)
HGL (Non-Energy Use)	(See footnote b)
Lubricants	20.20
Motor Gasoline	(See footnote b)
Residual Fuel Oil No. 5	19.89
Residual Fuel Oil No. 6[a]	20.48
Other Petroleum	
AvGas Blend Components	18.87
Crude Oil	(See footnote b)
MoGas Blend Components	(See footnote b)
Misc. Products	(See footnote b)
Misc. Products (Territories)	20.00
Naphtha (<401 deg. F)	18.55
Other Oil (>401 deg. F)	20.17
Pentanes Plus	18.24
Petroleum Coke	27.85
Still Gas	18.20
Special Naphtha	19.74
Unfinished Oils	(See footnote b)
Waxes	19.80
Geothermal	
Flash Steam	2.18
Dry Steam	3.22
Binary	0.00
Binary/Flash Steam	0.00

[a] 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.

[b] These coefficients vary annually due to fluctuations in fuel quality (see Table A-29).

Sources: C coefficients from EIA (2009), EPA (2010), and EPA (2020).

Table A-29: Annually Variable C Content Coefficients by Year (MMT C/QBtu)

Fuel Type	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Residential Coal[a]	26.19	26.13	26.00	26.04	25.73	25.75	25.81	25.88	25.90	25.88	25.98	26.01	26.09	26.09	26.11
Commercial Coal	26.19	26.13	26.00	26.04	25.73	25.75	25.81	25.88	25.90	25.88	25.98	26.01	26.09	26.09	26.11
Industrial Other Coal	25.81	25.79	25.74	25.79	25.86	25.86	25.88	25.94	25.93	25.95	26.00	26.03	26.06	26.08	26.07
Electric Power Coal	25.94	25.92	25.98	26.08	26.04	26.05	26.05	26.06	26.05	26.04	26.07	26.06	26.08	26.09	26.08
Pipeline Natural Gas	14.46	14.47	14.47	14.46	14.47	14.48	14.48	14.47	14.46	14.45	14.43	14.43	14.43	14.43	14.43
HGL (Energy Use)	17.51	17.51	17.52	17.45	17.31	17.43	17.40	17.41	17.39	17.41	17.43	17.43	17.45	17.45	17.47
HGL (Non-Energy Use)	17.24	17.25	17.22	17.19	17.09	16.93	16.84	16.86	16.88	16.86	16.89	16.85	16.84	16.82	16.85
Motor Gasoline	19.42	19.36	19.47	19.32	19.44	19.39	19.38	19.35	19.28	19.46	19.25	19.27	19.28	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
MoGas Blend Components	19.42	19.36	19.33	19.36	19.46	19.46	19.46	19.46	19.46	19.46	19.46	19.46	19.46	19.46	19.46
Misc. Products	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	0.00
Unfinished Oils	20.15	20.21	20.22	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31
Crude Oil	20.15	20.21	20.22	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31
Distillate Fuel Oil No. 2	20.17	20.17	20.39	20.37	20.23	20.24	20.22	20.22	20.23	20.23	20.22	20.21	20.20	20.22	20.22

[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: Coal C content coefficients calculated from USGS (1990), PSU (2010), Gunderson (2019), IGS (2019), ISGS (2019), and EIA (2001 through 2018); pipeline natural gas C content coefficients calculated from EIA (2020b) and EPA (2010); petroleum carbon contents from EPA (2010) and ICF (2020). See Annex 2.2 for information on how these C content coefficients are calculated.

Table A-30: Electricity Consumption by End-Use Sector (Billion Kilowatt-Hours)

End-Use Sector	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Residential	924	1,043	1,192	1,359	1,365	1,446	1,423	1,374	1,394	1,407	1,403	1,410	1,377	1,466	1,437
Commercial	838	953	1,159	1,275	1,307	1,330	1,328	1,327	1,337	1,352	1,361	1,367	1,353	1,381	1,360
Industrial	1,070	1,163	1,235	1,169	1,044	1,103	1,124	1,123	1,129	1,136	1,128	1,117	1,125	1,145	1,146
Transportation[a]	5	5	5	8	8	8	8	8	8	9	9	9	10	11	12
Total	**2,837**	**3,164**	**3,592**	**3,811**	**3,724**	**3,887**	**3,883**	**3,832**	**3,868**	**3,903**	**3,900**	**3,902**	**3,864**	**4,003**	**3,954**

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

[a] Includes electricity used for electric vehicle charging in the residential and commercial sectors.

Source: Retail sales of electricity to end-users obtained from EIA (2020b). Industrial electricity consumption includes direct use.

Table A-31: Electric Power Generation by Fuel Type (Percent)

Fuel Type	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Coal	54.1%	52.7%	53.3%	51.1%	45.7%	46.0%	43.5%	38.6%	40.2%	39.9%	34.2%	31.4%	30.9%	28.4%	24.2%
Natural Gas	10.7%	13.1%	14.2%	17.5%	22.1%	22.7%	23.5%	29.1%	26.4%	26.3%	31.6%	32.7%	30.9%	34.0%	37.3%
Nuclear	19.9%	21.1%	20.7%	20.0%	21.0%	20.3%	20.0%	19.8%	20.2%	20.3%	20.4%	20.6%	20.8%	20.1%	20.4%
Renewables	11.3%	10.9%	8.8%	8.3%	10.2%	10.0%	12.2%	11.9%	12.5%	12.8%	13.0%	14.7%	16.8%	16.8%	17.6%
Petroleum	4.1%	2.1%	2.9%	3.0%	0.9%	0.9%	0.7%	0.5%	0.6%	0.7%	0.7%	0.6%	0.5%	0.6%	0.4%
Other Gases[a]	+%	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%
Net Electricity Generation (Billion kWh)[b]	*2,905*	*3,197*	*3,643*	*3,902*	*3,808*	*3,971*	*3,947*	*3,888*	*3,901*	*3,936*	*3,917*	*3,917*	*3,877*	*4,017*	*3,962*

Note: Does not include electricity generation from purchased steam as the fuel used to generate the steam cannot be determined. Does not include non-renewable waste (i.e., municipal solid waste from non-biogenic sources, and tire-derived fuels).

Source: EIA (2020b).

+ Does not exceed 0.05 percent.

[a] Other gases include blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.

[b] Represents net electricity generation from the electric power sector. Excludes net electricity generation from commercial and industrial combined-heat-and-power and electricity-only plants. Net electricity generation differs from the total presented in Table A-30 (i.e., end-use consumption of electricity) due to electricity transmitted across U.S. borders, as well as transmission and distribution losses.

Table A-32: Geothermal Net Generation by Geotype (Billion Kilowatt-Hours)

Geotype	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Binary	0.08	0.28	0.24	0.68	1.92	2.41	2.16	2.43	2.75	3.12	3.36	3.62	3.56	3.84	4.34
Flash Steam	6.15	7.63	7.43	7.93	7.14	6.83	7.17	7.02	7.03	6.92	7.00	6.65	6.69	6.39	5.92
Dry Steam	9.21	5.47	6.43	6.09	5.95	5.98	5.98	6.11	6.00	5.84	5.56	5.55	5.67	5.73	5.21
Total	**15.43**	**13.38**	**14.09**	**14.69**	**15.01**	**15.22**	**15.32**	**15.56**	**15.77**	**15.88**	**15.92**	**15.83**	**15.93**	**15.97**	**15.47**

Source: EIA (2020a).

References

Browning, L. (2018). Updated Methodology for Estimating Electricity Use from Highway Plug-In Electric Vehicles. Technical Memo, October 2018.

EIA (2020a) Form EIA-923 detailed data with previous form data (EIA-906/920), Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA. March 2020.

EIA (2020b) *Monthly Energy Review*. November 2020, Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2019/11).

EIA (2001 through 2018) *Annual Coal Distribution Report,* Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA.

EIA (2009) Manufacturing Consumption of Energy 2006. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Released July 2009.

EPA (2020) *The Emissions & Generation Resource Integrated Database (eGRID) 2018 Technical Support Document*. Clean Air Markets Division, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2010) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Gunderson, J. (2019) Montana Coal Sample Database. Data received 28 February 2019 from Jay Gunderson, Montana Bureau of Mines & Geology.

ICF (2020) Potential Improvements to Energy Sector Hydrocarbon Gas Liquid Carbon Content Coefficients. Memorandum from ICF to Vincent Camobreco, U.S. Environmental Protection Agency. December 7, 2020.

Illinois State Geological Survey (ISGS) (2019) *Illinois Coal Quality Database*, Illinois State Geological Survey.

Indiana Geological Survey (IGS) (2019) *Indiana Coal Quality Database 2018*, Indiana Geological Survey.

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.

Pennsylvania State University (PSU) (2010) Coal Sample Bank and Database. Data received by SAIC 18 February 2010 from Gareth Mitchell, The Energy Institute, Pennsylvania State University.

UNFCCC (2014) Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>.

USGS (1998) *CoalQual Database Version 2.0*, U.S. Geological Survey.

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 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. 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 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-33.

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; approximately one-quarter 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-third 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 use statistics account for more than 20 different petroleum products.

Table A-33: Carbon Content Coefficients Used in this Report (MMT Carbon/QBtu)

Fuel Type	1990	1995	2000	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Coal																	
Residential Coal[a,b]	26.19	26.13	26.00	26.26	25.91	25.71	25.73	25.75	25.81	25.88	25.90	25.88	25.98	26.01	26.09	26.09	26.11
Commercial Coal[a]	26.19	26.13	26.00	26.26	25.91	25.71	25.73	25.75	25.81	25.88	25.90	25.88	25.98	26.01	26.09	26.09	26.11
Industrial Coking Coal[a]	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[a]	25.81	25.79	25.74	25.83	25.81	25.81	25.86	25.86	25.88	25.94	25.93	25.95	26.00	26.03	26.06	26.08	26.07
Utility Coal[a,c]	25.94	25.92	25.98	26.03	26.03	26.04	26.04	26.05	26.05	26.06	26.05	26.04	26.07	26.06	26.08	26.09	26.08
Pipeline Natural Gas[d]	**14.46**	**14.47**	**14.47**	**14.46**	**14.46**	**14.46**	**14.47**	**14.48**	**14.48**	**14.47**	**14.46**	**14.45**	**14.43**	**14.43**	**14.43**	**14.43**	**14.43**
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
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
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
Distillate Fuel Oil No. 2	20.17	20.17	20.39	20.33	20.25	20.25	20.23	20.24	20.22	20.22	20.23	20.23	20.22	20.21	20.20	20.22	20.22
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
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
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
LPG (Propane)	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15
HGL (Energy Use)[d]	17.51	17.51	17.52	17.43	17.43	17.42	17.31	17.43	17.40	17.41	17.39	17.41	17.43	17.43	17.45	17.45	17.47
HGL (Non-Energy Use)[d]	17.24	17.25	17.22	17.15	17.14	17.15	17.09	16.93	16.84	16.86	16.88	16.86	16.89	16.85	16.84	16.82	16.85
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
Motor Gasoline[d]	19.42	19.36	19.47	19.47	19.57	19.35	19.44	19.39	19.38	19.35	19.28	19.46	19.25	19.27	19.28	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
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
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
Mo. Gas Blend Comp[c]	19.42	19.36	19.33	19.45	19.56	19.46	19.46	19.46	19.46	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	20.28	20.28	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31
Misc. Products[e]	00.00	00.00	00.00	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	0.00
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	20.00	20.00	20.00
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
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
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	18.24	18.24	18.24
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
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
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
Unfinished Oils[d]	20.15	20.21	20.22	20.28	20.28	20.31	20.31	20.31	20.31	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

Fuel Type	1990	1995	2000	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
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
Geothermal[f]																	
Flash	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18
Steam	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22

[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, starting in 2008, the number cited here is developed from commercial/institutional consumption.

[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.

[e] The miscellaneous products category reported by EIA is assumed to be mostly petroleum refinery sulfur compounds that do not contain carbon (EIA 2019).

[f] C contents based on geotype (i.e., flash steam and dry steam) were obtained from EPA's *Emissions & Generation Resource Integrated Database (eGRID) 2018 Technical Support Document* (EPA 2020a). C contents were obtained in pounds CO_2/megawatt hour and were applied to net generation by geotype (in megawatt hours) from EIA (2020a). C contents were converted to MMT Carbon/QBtu in this table. C contents for binary and binary/flash geotypes are zero and have been excluded from this table.

Coal

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-34.[12]

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 8,672 coal samples, 6,588 of which were collected by the U.S. Geological Survey (USGS) (1998), 504 samples that come from the Pennsylvania State University database (PSU 2010), and the remainder from individual State Geological Surveys. Samples obtained directly from individual State Geological Surveys include 908 samples from the Montana Bureau of Mines & Geology (Gunderson 2019), 745 samples from the Indiana Geological Survey Coal Quality Database (IGS 2019), and 460 samples from the Illinois State Geological Survey (ISGS 2019). Because the data obtained directly from the State Geological Surveys for these three states included both samples collected by the USGS and additional samples, these data were used to determine C content coefficients for these states instead of the USGS and Pennsylvania State University data.

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 of 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 by coal type. 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[13] through 2019 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.[14] 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.

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[12] 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.

[13] U.S. Energy Information Administration (EIA). *Annual Coal Distribution Report* (2001-2019b); *Coal Industry Annual* (1990-2001).

[14] In 2008, EIA began collecting and reporting data on commercial and institutional coal consumption, rather than residential and commercial consumption. Thus, the residential/commercial coal coefficient reported in Table A-33 for 2009 to the present 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.

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.

Table A-34: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank (MMT C/QBtu) (1990-2019)

Consuming Sector	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Electric Power	25.94	25.92	25.98	26.08	26.04	26.05	26.05	26.06	26.05	26.04	26.07	26.06	26.08	26.09	26.08
Industrial Coking	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
Other Industrial	25.81	25.79	25.74	25.79	25.86	25.86	25.88	25.94	25.93	25.95	26.00	26.03	26.06	26.08	26.07
Residential/ Commercial[a]	26.19	26.13	26.00	26.04	25.73	25.75	25.81	25.88	25.90	25.88	25.98	26.01	26.09	26.09	26.11
Coal Rank[b]															
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
Bituminous	25.38	25.42	25.45	25.45	25.42	25.42	25.42	25.41	25.41	25.41	25.40	25.40	25.40	25.41	25.41
Sub-bituminous	26.46	26.47	26.46	26.48	26.47	26.47	26.49	26.49	26.49	26.49	26.49	26.49	26.20	26.49	26.49
Lignite	26.58	26.59	26.61	26.62	26.67	26.63	26.61	26.61	26.62	26.63	26.66	26.64	26.67	26.76	26.75

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

[b] Emission factors for coal rank are weighted based on production in each state.

Sources: C content coefficients calculated from USGS (1998), PSU (2010), Gunderson (2019), IGS (2019), ISGS (2019), EIA (1990 through 2001; 2001 through 2020a; 2001 through 2020b).

Step 5: Develop National-Level Carbon Contents by Rank for Comparison to IPCC Defaults

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

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

where,

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

Data Sources

The ultimate analysis of coal samples was based on 8,672 coal samples, 6,588 of which are from USGS (1998), 504 from the Pennsylvania State University Coal Database (PSU 2010), and the remainder from individual State Geological Surveys. Samples obtained directly from individual State Geological Surveys include 908 samples from the Montana Bureau of Mines & Geology (Gunderson 2019), 745 samples from the Indiana Geological Survey Coal Quality Database (IGS 2019), and 460 samples from the Illinois State Geological Survey (ISGS 2019). Because the data obtained directly from the State Geological Surveys for these three states included both samples collected by the USGS and additional samples, these data were used to determine C content coefficients for these states instead of the USGS and Pennsylvania State University data. 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. Additional samples that were not contained in the USGS's CoalQual Database, many of which were more recent samples taken after 1989, were obtained directly from the State Geological Surveys for Montana, Illinois, and Indiana. Whole-seam channel samples provided by PSU, Illinois, and Indiana, and both whole-seam channel and drill core samples provided by Montana, were included in the development of carbon factors.

Data on coal consumption by sector and state of origin, as well as coal production by state and rank, were obtained from EIA. EIA's *Annual Coal Report* (EIA 2001 through 2020a) is the source for state coal production by rank from 2001 through 2019. In prior years, 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 2019 was obtained from the EIA's *Annual Coal Distribution Report* (EIA 2001 through 2020b). For 1990 through 2000, end-use data was obtained from the *Coal Industry Annual* (EIA 1990 through 2001).

Uncertainty

Carbon contents vary considerably by state. Bituminous coal production and sub-bituminous coal production represented 47.2 percent and 45.0 percent of total U.S. supply in 2019, respectively. Of the states that have been producing bituminous coal since 1990, state average C content coefficients for bituminous coal vary from a low of 85.58 kg CO_2 per MMBtu in Texas to a high of 96.36 kg CO_2 per MMBtu in Arkansas. The next lowest average emission factor for bituminous coal is found in Missouri (91.71 kg CO_2 per MMBtu). In 2019, Missouri production accounted for less than 0.1 percent of overall bituminous production. More than 50 percent of bituminous coal was produced in three states in 2019: West Virginia, Kentucky, 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-35).

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 90 percent of

total sub-bituminous coal production in the United States throughout the time series (1990 through 2019). Thus, the C content coefficient for Wyoming (97.21 kg CO_2 per MMBtu), based on 503 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.

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 0.78 percent, which is for sub-bituminous (range: -0.32 to +0.78 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-35: 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	98.32	98.09	-	98.65
Arizona	15	93.94	97.34	-	-
Arkansas	77	96.36	-	-	94.97
Colorado	317	94.37	96.52	-	101.10
Georgia	35	95.00	-	-	-
Idaho	1	-	94.90	-	-
Illinois	460	92.53	-	-	-
Indiana	745	92.30	-	-	-
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	-	-	-	92.87
Mississippi	8	-	-	-	98.18
Missouri	111	91.71	-	-	-
Montana	908	96.01	96.61	-	98.34
Nebraska	6	103.59	-	-	-
Nevada	2	94.41	-	-	99.86
New Mexico	185	94.28	94.88	103.92	-
North Dakota	202	-	93.97	-	99.47
Ohio	674	91.84	-	-	-
Oklahoma	63	92.33	-	-	-
Pennsylvania	849	93.33	-	103.68	-
Tennessee	61	92.81	-	-	-
Texas	64	85.58	94.19	-	94.46
Utah	169	95.75	91.29	-	-
Virginia	465	93.51	-	98.54	-
Washington	18	94.53	97.35	102.53	106.55
West Virginia	612	93.84	-	-	-
Wyoming	503	94.80	97.21	-	-
U.S. Average	**8,672**	**93.46**	**96.01**	**102.15**	**98.95**

Note: "-" Indicates no sample data available. Average is weighted by number of samples.
Sources: Calculated from USGS (1998) and PSU (2010), Gunderson (2019), IGS (2019), and ISGS (2019).

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[15] 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.

[15] 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.

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 -1,036 Btu per cubic foot, and has varied by less than 1 percent (1,025 to 1,037 Btu per cubic foot) over the past 10 years. Meanwhile, the average heat content of the 6,743 samples was 1,027 Btu per cubic foot, and the median heat content was 1,031 Btu per cubic foot. Thus, the average heat content of the sample set falls well within the typical range of natural gas consumed in the United States, suggesting that these samples continue to be representative of natural gas "as consumed" in the United States. The average and median composition of these samples appear in Table A-36.

Table A-36: 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-37.

Table A-37: 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 (both on a per cubic foot basis). The regression used carbon content as the dependent variable and heat content as the independent variable. The resulting R-squared values[16] 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:

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

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

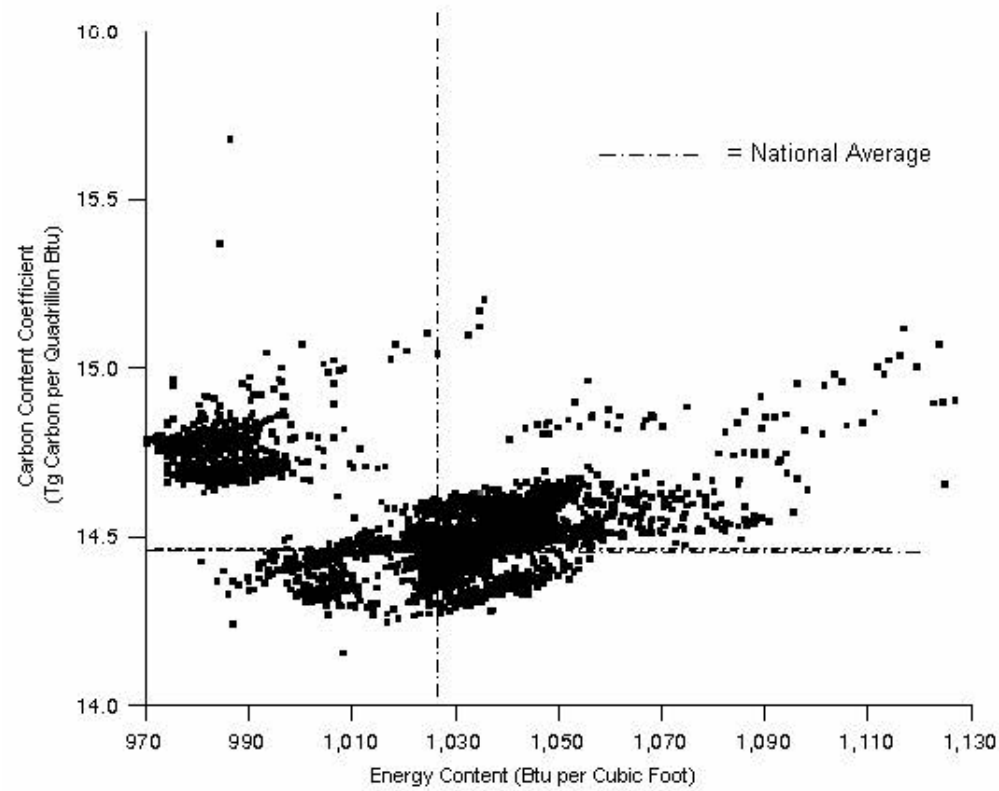
This equation was used to estimate the annual predicted carbon content of natural gas from 1990 to 2019 based on the EIA's national average pipeline-quality gas heat content for each year (EIA 2020a). The table of average C contents for each year is shown below in Table A-38.

Table A-38: Carbon Content Coefficients for Natural Gas (MMT Carbon/QBtu)

Fuel Type	1990	1995	2000	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Natural Gas	14.46	14.47	14.47	14.46	14.46	14.46	14.47	14.48	14.48	14.47	14.46	14.45	14.43	14.43	14.43	14.43	14.43

Source: Calculated from EPA (2010) and EIA (2020a).

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. 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 14.43 MMT C/QBtu (see Table A-38), 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.

Furthermore, research was done on CO_2 emission factors for fuel gas used by upstream oil and gas producers in order to determine whether a different CO_2 emission factor for fuel gas used in offshore oil and gas production than the emission factor for the processed gas that enters the transmission, storage and distribution networks used in power and industrial plants and by other users is warranted. It was determined that a different factor was not warranted as natural gas carbon content is based on the heating value of the gas and EIA reports that the heat content of dry natural gas produced (which is used in upstream oil and gas production) is the same value as natural gas consumed in downstream operations (EIA 2020a). Therefore, the same carbon factor is used for all natural gas consumption including upstream operations.

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 were updated in 2010 for the 1990 through 2008 Inventory 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 EPA's *Mandatory Reporting of Greenhouse Gases Rule* (EPA 2009b).

Petroleum products vary between 5.6 degrees API gravity[17] (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

[17] 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.

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.

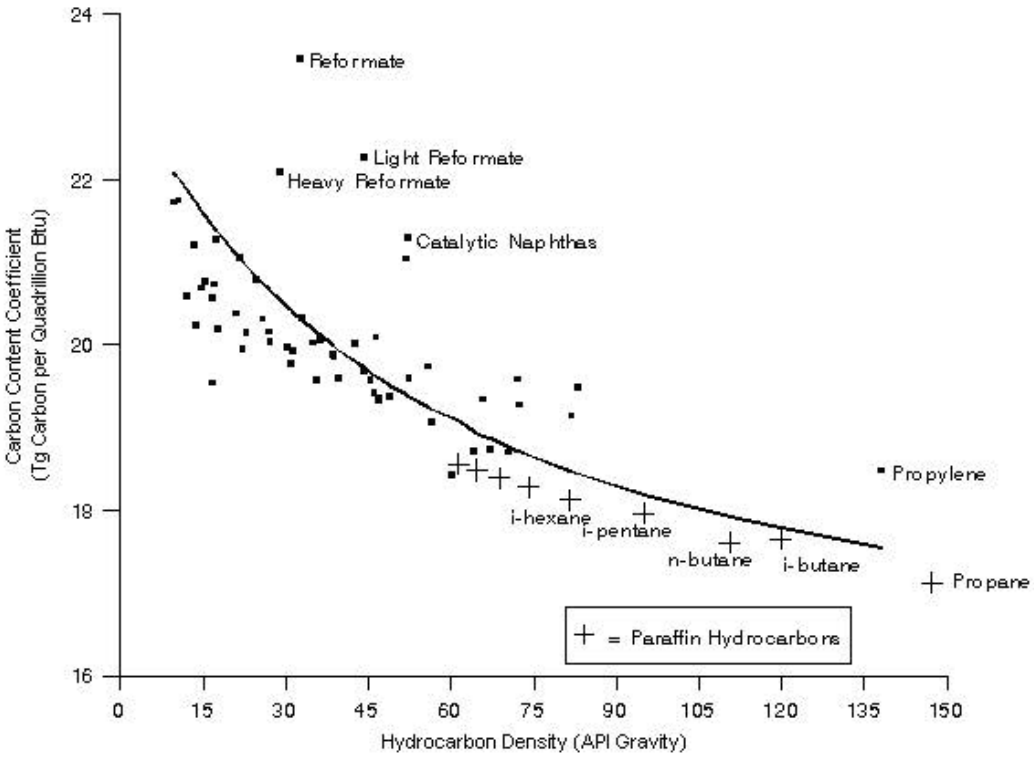
Petroleum Chemistry

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.

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.

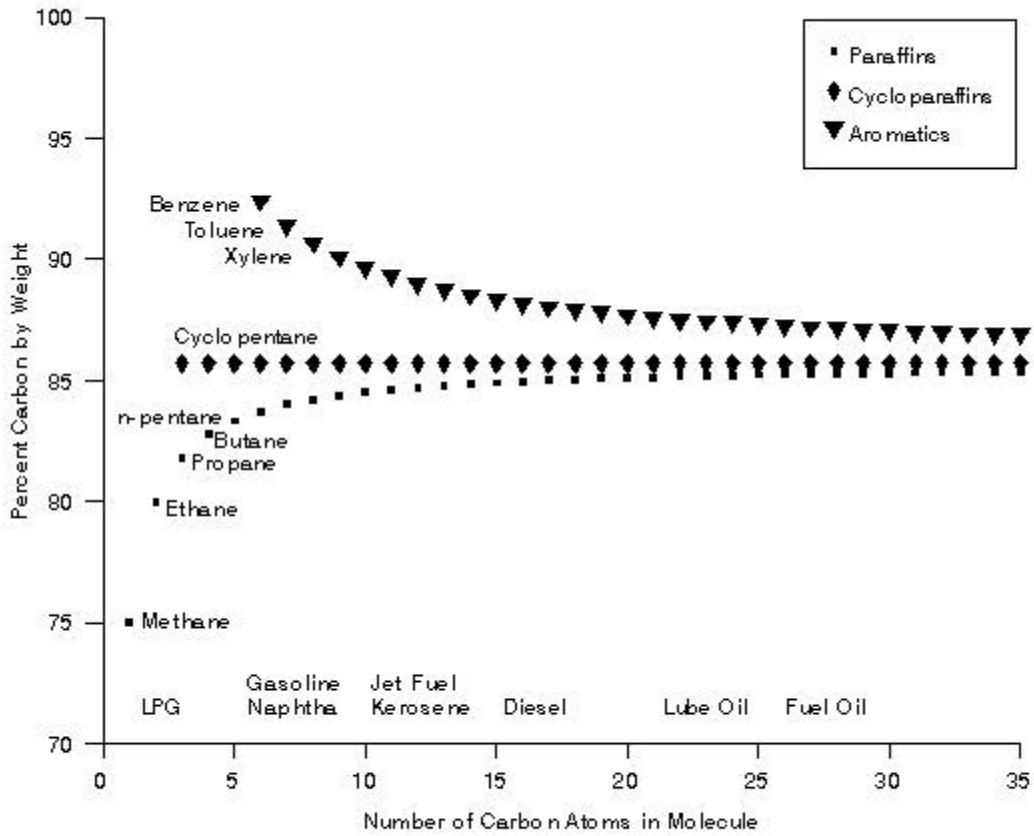
Olefins. Olefins are a very reactive and unstable form of paraffin: a straight chain with two carbon atoms double bonded together (thus are unsaturated) compared to the carbon atoms in a paraffin (which are saturated with hydrogen). They are never found in crude oil but are created in moderate quantities 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-39. A description of the methods and data sources for estimating the key parameters for each individual petroleum product appears below.

Table A-39: Carbon Content Coefficients and Underlying Data for Petroleum Products

Fuel	Carbon Content (MMT C/QBtu)	Gross Heat of Combustion (MMBtu/Barrel)	Density (API Gravity)	Percent Carbon
Motor Gasoline	19.27	(See a)	(See a)	(See a)
LPG (Propane)	17.15	3.841	155.3	81.80
HGL (Energy Use)[b]	17.47	(See b)	(See b)	(See b)
HGL (Non-Energy Use)[b]	16.85	(See b)	(See b)	(See 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	20.22	(See c)	(See c)	(See c)
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	6.287	15.5	84.67
Asphalt and Road Oil	20.55	6.636	5.6	83.47
Lubricants	20.20	6.065	25.7	85.80
Naphtha (< 400 deg. F)[c]	18.55	5.248	62.4	84.11
Other Oil (>400 deg. F)[c]	20.17	5.825	35.8	87.30
Aviation Gasoline	18.86	5.048	69.0	85.00
Kerosene	19.96	5.670	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	18.24	4.638	81.3	83.70

Note: "-" Indicates no sample data available.
[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] HGL is a blend of multiple paraffinic hydrocarbons: ethane, propane, isobutane, and normal butane, and their associated olefins: ethylene, propylene, isobutylene, and butylene, each with their own heat content, density, and C content, see Table A-41.
[c] Petrochemical feedstocks have been split into naphthas and other oils for this Inventory report. Parameters presented are for naphthas with a boiling temperature less than 400 degrees Fahrenheit. Other oils are petrochemical feedstocks with higher boiling points. They are assumed to have the same characteristics as distillate fuel oil no. 2.
Sources: EIA (1994); EIA (2009a); EPA (2020b); 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.[18] "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 22 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 2019 time period: regular, mid-grade, and premium

[18] 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.

conventional gasoline (all years) and regular, mid-grade, and premium reformulated gasoline (November 1994 to 2019). Leaded and oxygenated gasoline are not separately included in the data used for this report.[19]

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. The density of motor gasoline across grades and formulations for 1990-2008 is taken from the National Institute of Petroleum and Energy Research. Values from 2008 have been used as a proxy for 2009 through 2019.

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-40.

Table A-40: 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.[20] 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 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 federal Renewable Fuel Standard (RFS) program requires a certain volume of renewable fuel, including ethanol, be blended into the national fuel supply.[21] 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

[19] 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.

[20] 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.

[21] See https://www.epa.gov/renewable-fuel-standard-program.

produced using corn as feedstock,[22] although production pathways utilizing agricultural waste, woody biomass and other resources are in development.

Methodology for Years 1990-1999:

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,[23] the density of the constituent, share of the constituent[24] 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-40 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.

Methodology for Years 2000-Present:

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. The EIA publishes prime supplier sales volumes of motor gasoline by type (conventional, oxygenated, and reformulated) and by grade (regular, midgrade and premium) for each month from 1983 to present (EIA 2020c). Gasoline sold in May through August was assumed to be summer grade, gasoline sold in September was assumed to be half summer and half winter grade, and gasoline sold in other months was assumed to be winter grade.

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

Fuel properties are gathered through the Alliance of North American Fuel Survey (NAFS) published by the Alliance of Automobile Manufacturers (AAM), an association which is now part of the Alliance for Automotive Innovation. This fuel survey is conducted twice per year, in January and July, and includes measured properties of both regular and premium gasoline. While the exact number of samples vary by year and location, fuel samples are drawn from multiple retail locations in each of over 20 U.S. cities for each biannual survey.

The carbon content and net heating value are calculated according to ASTM D3343, Standard Test Method for the Estimation of Hydrogen Content of Aviation Fuels, and ASTM D3338, Standard Test Method for the Net Heat of Combustion of Aviation Fuels, respectively using fuel properties inputs from the NAFS for each year and season. These methods use a correlation between the measured fuel distillation range, API gravity, and aromatic content to estimate the hydrogen content and net heating values. The C content of hydrocarbon fuel calculated according to ASTM D3343 applies to hydrocarbon containing fuels only and is not applicable towards oxygenated fuel blends. However, recently

[22] See https://www.epa.gov/fuels-registration-reporting-and-compliance-help/public-data-renewable-fuel-standard.

[23] 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.

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

EPA has proposed an amendment to 40 CFR §600.113-12, containing equations allowing for the estimation of base fuel blendstock properties using the bulk oxygenated fuel properties. This technique is applied here for oxygenated gasoline calculations.

The fuels sampled in the NAFS by AAM are assumed to be representative of the seasonal fuels sold throughout the U.S. Also, the method of calculation of the fuel properties of the hydrocarbon fraction of the fuel from blended fuel properties was developed for Tier 3 certification test fuels, and not commercial fuel blends as used here.

Data Sources

Data for the density of motor gasoline were derived from NIPER (1990 through 2009). Data on the characteristics of reformulated gasoline, including C share, were also taken from NIPER (1990 through 2009) and Alliance of North American Fuel Survey (NAFS) published by the Alliance of Automobile Manufacturers (AAM), an association which is now part of the Alliance for Automotive Innovation.

Standard heat contents for motor gasoline of 5.222 MMBtu per barrel conventional gasoline and 5.150 MMBtu per barrel reformulated gasoline[25] 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 2009. The number of samples analyzed that underlie the calculation of the average make-up of each seasonal formulation and grade varies from approximately 50 to over 400, with the greatest number of samples each season being of conventional, regular or premium gasoline. Further, not all sample data submitted to NIPER contains data for each of the properties, such that the number of samples underlying each constituent average value for each season, grade and formulation may be variable within the single gasoline type (e.g., of the 1,073 samples for which some data was obtained for gasoline sold in Winter 1995 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

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

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 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 2019.

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 2019, only the kerosene-based portion of total consumption is considered significant.

<u>Methodology</u>

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 2019.

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 for distillate No. 1 and No. 4 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 and 6.135 MMBtu per barrel, respectively for distillates No. 1 and No. 4, and densities of 35.3 and 23.2 degrees API to calculate C coefficients for each distillate type.

The carbon content and net heating value (NHV) of diesel fuel No. 2 is calculated according to ASTM D3343, Standard Test Method for the Estimation of Hydrogen Content of Aviation Fuels, and ASTM D3338, Standard Test Method for the Net Heat of Combustion of Aviation Fuels, respectively using fuel properties inputs from the NAFS for each year and season. These methods use a correlation between the measured fuel distillation range, API gravity, and aromatic content to estimate the hydrogen content and net heating values.

Data Sources

Fuel properties for distillate No. 2 were derived from diesel surveys taken by the Alliance of Automobile Manufacturers, an association which is now part of the Alliance for Automotive Innovation. The density of distillate fuel oil No. 4 is taken from *Perry's Chemical Engineer's Handbook, 8th Ed*. (Green & Perry, ed. 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, ed. 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, ed. 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 $\pm$1 percent.

Hydrocarbon Gas Liquids (HGL)

EIA identifies four categories of paraffinic hydrocarbons (i.e., ethane, propane, isobutane, and n-butane) and four categories of olefinic hydrocarbons (i.e., ethylene, propylene, isobutylene, and butylene) and HGL. HGL also includes pentanes plus, or natural gasoline, but this category is calculated separately from other HGL components in this report. Because each of these compounds is a pure paraffinic or olefinic 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-41 summarizes the physical characteristic of HGL.

Table A-41: Physical Characteristics of Hydrocarbon Gas Liquids

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	80.00	3.082	17.16
Propane	C_3H_8	12.76	81.80	3.836	16.76
Isobutane	C_4H_{10}	11.42	82.80	3.974	17.77
n-butane	C_4H_{10}	10.98	82.30	4.326	17.75
Ethylene	C_2H_4	11.07	85.71	2.436	17.99
Propylene	C_3H_6	12.45	85.71	3.835	17.99
Isobutylene	C_4H_8	10.68	85.71	4.355	18.78
Butylene	C_4H_8	10.70	85.71	4.377	18.74

Source: Densities – CRC Handbook of Chemistry and Physics (2008/09) and EPA (2009c); Carbon Contents – derived from the atomic weights of the elements (EPA 2009b); 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, HGL.

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

A C content coefficient for HGL used as fuel is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics, excluding pentanes plus, which is calculated separately.

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

The mix of HGL consumed for non-fuel use differs significantly from the mix of HGL that is combusted. EIA (2020a) states that HGL consumption in the residential, commercial, and transportation sector is 100 percent propane, therefore a constant, non-weighted propane C content coefficient is applied to HGL (LPG – Propane) in these sectors. While the majority of HGL consumed for fuel use in the industrial sector is propane, ethane is the largest component of HGL used for non-fuel applications. C content coefficients for HGL used for fuel use and non-fuel applications are 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 HGL fuel use and non-fuel use consumption appear below in

Table A-42.

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 HGL is from EPA (2013). HGL consumption was based on data obtained from EIA (2020b). Non-fuel use of HGL was obtained from EIA (2020b).

Uncertainty

Because HGL consists of pure paraffinic and olefinic 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-42: Industrial Sector Consumption and Carbon Content Coefficients of Hydrocarbon Gas Liquids, 1990-2019

	1990	2000	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Energy Consumption (QBtu)															
Fuel Use	**0.96**	**1.95**	**0.77**	**0.58**	**0.24**	**9.21**	**9.09**	**9.26**	**10.28**	**9.52**	**9.65**	**9.43**	**9.10**	**9.85**	**9.78**
Ethane	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.06
Propane	0.60	1.19	0.50	0.37	0.15	6.28	6.28	6.38	7.15	6.42	6.38	6.16	5.92	6.55	6.41
Butane	0.11	0.17	0.06	0.05	0.01	0.50	0.33	0.37	0.57	0.57	0.62	0.41	0.19	0.17	0.25
Isobutane	0.02	0.14	+	+	+	0.12	0.15	0.19	0.28	0.29	0.46	0.60	0.65	0.75	0.88
Ethylene	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Propylene	0.21	0.42	0.18	0.13	0.05	2.25	2.28	2.28	2.26	2.19	2.18	2.23	2.27	2.29	2.20
Butylene	+	+	+	+	+	0.02	+	+	(0.02)	0.01	(0.03)	(0.01)	0.02	0.04	+
Isobutylene	+	+	+	+	+	+	0.01	+	(+)	(+)	(+)	+	+	(+)	+
Non-Fuel Use	**2.12**	**2.92**	**2.72**	**2.57**	**2.67**	**1.91**	**1.89**	**1.93**	**2.11**	**2.09**	**2.21**	**2.21**	**2.31**	**2.67**	**2.82**
Ethane	0.48	0.71	0.72	0.68	0.81	0.88	0.96	0.96	1.01	1.05	1.09	1.15	1.26	1.50	1.56
Propane	0.89	1.17	1.23	1.16	1.19	0.57	0.57	0.57	0.64	0.58	0.57	0.55	0.53	0.59	0.58
Butane	0.16	0.17	0.15	0.17	0.11	0.11	0.07	0.08	0.13	0.13	0.14	0.09	0.04	0.04	0.06
Isobutane	0.03	0.14	0.01	0.01	0.02	0.03	0.03	0.04	0.06	0.07	0.10	0.14	0.15	0.17	0.20
Ethylene	+	+	+	+	+	0.01	0.01	+	+	+	+	+	+	+	+
Propylene	0.31	0.41	0.43	0.41	0.42	0.20	0.21	0.20	0.20	0.20	0.20	0.20	0.20	0.21	0.20
Butylene	+	+	+	+	+	+	+	+	(+)	+	(0.01)	(+)	+	0.01	+
Isobutylene	+	+	+	+	+	+	+	+	(+)	(+)	(+)	+	+	(+)	+
Carbon Content (MMT C/QBtu)															
Fuel Use	17.51	17.52	17.43	17.42	17.31	17.43	17.40	17.41	17.39	17.41	17.43	17.43	17.45	17.45	17.47
Non-Fuel Use	17.24	17.22	17.14	17.15	17.09	16.93	16.84	16.86	16.88	16.86	16.89	16.85	16.84	16.82	16.85

Note: "+" indicated a value less than 0.01 QBtu.
Sources: Fuel use of HGL based on data from EIA (2020b). Non-fuel use of HGL from (EIA 2020b). Volumes converted using the energy contents provided in Table A-41. C contents from EPA (2013).

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-43 below shows the composition of those samples.

Table A-43: 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-43.

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 (2009b). 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 (2009b). 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. (Meyers 2004). 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 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-44, below.

Table A-44: 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* (Martin, S.W. 1960).

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 $\pm$ 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 unfinished oils have the same C content as crude oil. The miscellaneous products category reported by EIA includes miscellaneous products that are not reported elsewhere in the EIA data set. According to EIA recovered sulfur compounds from petroleum and natural gas processing, and potentially carbon black feedstock could be reported in this category. Recovered sulfur has no carbon content and would not be reported in the Inventory. Based on this information, the miscellaneous products category reported by EIA was assumed to be mostly petroleum refinery sulfur compounds that do not contain carbon (EIA 2019). Therefore, the carbon content for miscellaneous products was assumed to be zero across the time series.

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

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

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

The following section describes changes to carbon content coefficients of fossil fuels, organized by the calendar year in which the update was implemented. Additional information on which Inventory year these changes appear is provided within each section.

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-45. 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. The coefficients developed in 1994 were in use through the 1990 through 2000 Inventory) and are provided in Table A-45**.**

Table A-45: 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. EIA, *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. EIA, Office of Coal, Nuclear, Electric and Alternative Fuels (Washington, DC 1992).

Subsequent Updates

In 2002 a database compiled by the U.S. Geological Survey (USGS), CoalQual 2.0 (1998), was adopted to update the 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 updated methodology first appeared in the 1990-2004 Inventory. The methodology employed for these estimates has remained unchanged since 2002,[27] however, the underlying coal data sample set has been updated over the years to integrate new data sets as they became available.

[27] In 2009, the analysis of the USGS Coal Qual data was updated to make a technical correction that affected the value for lignite and those sectors which consume lignite. The updated coefficients resulting from this correction were first implemented for the 1990 through 2007 Inventory.

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 new coefficients developed in the 2010 update were first implemented for the 1990 through 2008 Inventory.

In 2019 sample data from the Montana Bureau of Mines & Geology (908 samples), the Illinois State Geological Survey Coal Quality Database (460 samples), and the Indiana Geological Survey Coal Quality Database (745 samples) were used to calculate updated carbon contents by rank for Montana, Illinois, and Indiana. Combining revised carbon contents for these three states with the carbon contents for all other states calculated from the USGS and Pennsylvania State University samples yielded updated national average carbon contents by coal rank and end-use sector. The new coefficients developed in the 2019 update were first implemented for the 1990 through 2017 Inventory. See Table A-46 above for the carbon content coefficients values used in this Inventory.

Natural Gas

2010 and 2019 Updates

A revised analytical methodology introduced in 2010 underlies the natural gas C coefficients used in this report. This methodology was first implemented in the 1990 through 2008 Inventory. Prior to the 1990 through 2008 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. Previously, 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 revised analysis conducted in 2010 used the same set of samples, but utilized 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 calculated 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).

In 2019, this analysis was updated again to calculate annually variable national average C content coefficients for years 2009 through 2017 in the time series using heat contents published in EIA (2019). The resulting average was 14.43 MMT C/QBtu, which is slightly less than the previous weighted national average of 14.47 MMT C/QBtu. The 2019 update was first implemented in the 1990 through 2017 Inventory. The average C contents from the 1994 calculations are presented in Table A-46 below for comparison.

Table A-46: 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

2010 Update

All of the petroleum product C coefficients except that for Aviation Gasoline Blending Components were updated in 2010 for the 1990 through 2008 Inventory and held constant through the current Inventory. EPA updated these factors to better align the fuel properties data that underlie the Inventory factors with those published in EPA's *Mandatory Reporting of Greenhouse Gases Rule* (EPA 2009b), Suppliers of Petroleum Products (MM) and Stationary Combustion (C) subparts. The coefficients that were applied in previous reports are provided in Table A- 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 Greenhouse Gas Reporting Rule (EPA 2009b). In some cases, the heat content applied to the conversion to a carbon-per-unit-energy basis was also updated. Additionally, the category Misc. Products (U.S. Territories), which is based upon the coefficients calculated for crude oil, was allowed to vary annually with the crude oil coefficient. The petrochemical feedstock category was eliminated 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) were estimated and are presented in Table A-39 above. Each of the C coefficients applied in previous Inventories are provided below for comparison (Table A-47).

Table A-47: Carbon Content Coefficients and Underlying Data for Petroleum Products

Fuel	Carbon Content (MMT C/QBtu)	Gross Heat of Combustion (MMBtu/Barrel)	Density (API Gravity)	Percent Carbon
Motor Gasoline	19.27	5.220	59.1	86.60
LPG (Propane)	17.15	3.841	155.3	81.80
HGL (Energy Use)[a]	17.47	(See b)	(See b)	(See b)
HGL (Non-Energy Use)[a]	16.85	(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[d]	0.00	0.00	30.5	85.49
Pentanes Plus	18.24	4.620	81.7	83.70
Natural Gasoline	18.24	4.620	81.7	83.70

Note: "-" Indicates no sample data available.
[a] HGL is a blend of multiple paraffinic and olefinic hydrocarbons: ethane, propane, isobutane, and normal butane, each with their own heat content, density and C content, see Table A-41.
[b] Heat, density, and percent carbon values are provided separately for ethane, and isobutene, butane, ethylene, isobutylene, and butylene.
[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.
[d] The miscellaneous products category reported by EIA is assumed to be mostly petroleum refinery sulfur compounds that do not contain carbon (EIA 2019).
Sources: EIA (1994), EIA (2008a), EPA (2009c), EPA (2020b), ICF (2020), 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. The coefficient revised in 1995 was first implemented in the 1990 through 2007 Inventory.

2010 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 EPA's *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.

Hydrocarbon Las Liquids (HGL)

Summary of Previous Updates

The C content coefficient of HGL is updated annually to reflect changes in the consumption mix of the underlying compounds: ethane; propane; isobutane; normal butane; ethylene; propylene; isobutylene; and butylene. According to EIA, LPG is a subset of HGL, which include the paraffinic 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-47).

However, in 2010 the assumptions that underlie the selection of density and heat content data for each pure LPG compound were updated, leading to a significant revision of the assumed properties of ethane. In 2010, the physical characteristics of ethane, which constitutes over 90 percent of LPG consumption for non-fuel uses, were 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-48, below, compares the values applied for each of the compounds under the two sets of coefficient calculations, those used in the 1990 through 2007 Inventory and those used in the 1990 through 2008 Inventory to the 1990 through 2018 Inventory. 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 was 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-48: Physical Characteristics of Liquefied Petroleum Gases

		1990-2007	2010 Update	1990-2007	2010 Update	1990-2007	2010 Update
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).

2020 Update

The coefficients were revised again for the 1990 through 2019 Inventory. This change was made in order to align the coefficients used for this report with the updated heat content values used in EIA's energy data statistics (EIA 2020a; EIA 2020b). EIA (2020a) states, "LPG is a subset of HGL, which include the paraffinic compounds: ethane; propane; isobutane; and normal butane," therefore the Inventory revised the fuel type classification of LPG to HGL to indicate this fuel types includes both paraffinic and olefinic compounds. Furthermore, EIA (2020a) states that HGL consumption in the residential, commercial, and transportation sectors is 100 percent propane. Therefore, a constant, non-weighted propane C content coefficient is applied to HGL consumption in these sectors and is referred to as "LPG – Propane" throughout the Inventory.

The mix of HGL consumed for non-fuel use differs significantly from the mix of HGL that is combusted. C content coefficients for HGL used for fuel use and non-fuel applications were developed based on the consumption mix of the individual compounds reported in U.S. energy statistics (EIA 2020b) for industrial fuel use and industrial non-fuel use across the Inventory timeseries. The C content of each HGL was obtained from EPA (2013) and applied to the fuel use and non-fuel use consumption of each compound. The carbon content coefficient for industrial fuel use and industrial non-fuel use HGL was then calculated through a weighted average that accounts for the consumption proportion for each paraffinic and olefinic compound and their associated C contents (ICF 2020).

Table A-49: Industrial Sector Consumption and Carbon Content Coefficients of Hydrocarbon Gas Liquids, 1990-2019

	1990	2000	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Energy Consumption (QBtu)															
Fuel Use	**0.96**	**1.95**	**0.77**	**0.58**	**0.24**	**9.21**	**9.09**	**9.26**	**10.28**	**9.52**	**9.65**	**9.43**	**9.10**	**9.85**	**9.78**
Ethane	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.06
Propane	0.60	1.19	0.50	0.37	0.15	6.28	6.28	6.38	7.15	6.42	6.38	6.16	5.92	6.55	6.41
Butane	0.11	0.17	0.06	0.05	0.01	0.50	0.33	0.37	0.57	0.57	0.62	0.41	0.19	0.17	0.25
Isobutane	0.02	0.14	+	+	+	0.12	0.15	0.19	0.28	0.29	0.46	0.60	0.65	0.75	0.88
Ethylene	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Propylene	0.21	0.42	0.18	0.13	0.05	2.25	2.28	2.28	2.26	2.19	2.18	2.23	2.27	2.29	2.20
Butylene	+	+	+	+	+	0.02	+	+	(0.02)	0.01	(0.03)	(0.01)	0.02	0.04	+
Isobutylene	+	+	+	+	+	+	0.01	+	(+)	(+)	(+)	+	+	(+)	+
Non-Fuel Use	**2.12**	**2.92**	**2.72**	**2.57**	**2.67**	**1.91**	**1.89**	**1.93**	**2.11**	**2.09**	**2.21**	**2.21**	**2.31**	**2.67**	**2.82**
Ethane	0.48	0.71	0.72	0.68	0.81	0.88	0.96	0.96	1.01	1.05	1.09	1.15	1.26	1.50	1.56
Propane	0.89	1.17	1.23	1.16	1.19	0.57	0.57	0.57	0.64	0.58	0.57	0.55	0.53	0.59	0.58
Butane	0.16	0.17	0.15	0.17	0.11	0.11	0.07	0.08	0.13	0.13	0.14	0.09	0.04	0.04	0.06
Isobutane	0.03	0.14	0.01	0.01	0.02	0.03	0.03	0.04	0.06	0.07	0.10	0.14	0.15	0.17	0.20
Ethylene	+	+	+	+	+	0.01	0.01	+	+	+	+	+	+	+	+
Propylene	0.31	0.41	0.43	0.41	0.42	0.20	0.21	0.20	0.20	0.20	0.20	0.20	0.20	0.21	0.20
Butylene	+	+	+	+	+	+	+	+	(+)	+	(0.01)	(+)	+	0.01	+
Isobutylene	+	+	+	+	+	+	+	+	(+)	(+)	(+)	+	+	(+)	+
Carbon Content (MMT C/QBtu)															
Fuel Use	17.51	17.52	17.43	17.42	17.31	17.43	17.40	17.41	17.39	17.41	17.43	17.43	17.45	17.45	17.47
Non-Fuel Use	17.24	17.2	17.14	17.15	17.09	16.93	16.84	16.86	16.88	16.86	16.89	16.85	16.84	16.82	16.85

Note: "+" indicated a value less than 0.01 QBtu.
Sources: Fuel use of HGL based on data from EIA (2020b). Non-fuel use of HGL from (EIA 2020b). Volumes converted using the energy contents provided in Table A-41. C contents from EPA (2013).

Motor Gasoline

Summary of Previous Updates

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 the 1990 through 1995 Inventory. 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-39), in the list and proportion of constituents that form the blend and in the blended C share based on those constituents.

Table A-50: 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														
AvGas Blend Components	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
MoGas Blend Components[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.

2020 Updates

The annual C content of gasoline over the time series of the Inventory was determined using a combination of two data sources. The first is the measured properties of both regular and premium gasoline from the Alliance of North American Fuel Survey (NAFS). The second is the prime supplier sales volumes of motor gasoline by type and grade from the EIA.

References

AAM (2009) *Diesel Survey*. Alliance of Automobile Manufacturers, Winter 2008.

API (1990 through 2008) *Sales of Natural Gas Liquids and Liquefied Refinery Gases*, American Petroleum Institute.

ASTM (1985) *ASTM and Other Specifications for Petroleum Products and Lubricants,* American Society for Testing and Materials. Philadelphia, PA.

Boldt, K. and B.R. Hall (1977) *Significance of Tests for Petroleum Products*, Philadelphia, PA, American Society for Testing and Materials, p. 30.

Chemical Rubber Company (CRC) (2008/2009), *Handbook of Chemistry and Physics*, 89th Ed., editor D. Lide, Cleveland, OH: CRC Press.

DOC (1929) *Thermal Properties of Petroleum Products*, U.S. Department of Commerce, National Bureau of Standards. Washington, D.C. pp. 16-21.

EIA (2020) *Monthly Energy Review, November 2020*, Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2020/11).

EIA (2020b) *Petroleum Supply Annual*, Energy Information Administration, U.S. Department of Energy, Washington, D.C.

EIA (2020c) Prime Supplier Sales Volume, U.S. Department of Energy, Washington, D.C. Available online at https://www.eia.gov/dnav/pet/pet_cons_prim_dcu_nus_m.htm.

EIA (2019) Personal communication between EIA and ICF on November 11, 2019.

EIA (2001 through 2020a) *Annual Coal Report,* U.S. Department of Energy, Energy Information Administration. Washington, D.C. DOE/EIA 0584.

EIA (2001 through 2020b) *Annual Coal Distribution Report,* U.S. Department of Energy, Energy Information Administration. Washington, D.C. DOE/EIA.

EIA (2008a) *Monthly Energy Review, September 2006* and Published Supplemental Tables on Petroleum Product detail. Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2007/9).

EIA (2008b) *Documentation for Emissions of Greenhouse Gases in the United States 2006*. DOE/EIA-0638(2006). October 2008.

EIA (2009a) *Annual Energy Review,* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0384(2008).

EIA (2009b) *Petroleum Supply Annual*, Energy Information Administration, U.S. Department of Energy, Washington, D.C.

EIA (2001) *Cost and Quality of Fuels for Electric Utility Plants 2000*, Energy Information Administration. Washington, D.C. August 2001. Available online at <http://www.eia.doe.gov/cneaf/electricity/cq/cq_sum.html>.

EIA (1990 through 2001) *Coal Industry Annual,* U.S. Department of Energy, Energy Information Administration. Washington, D.C. DOE/EIA 0584.

EIA (1994) *Emissions of Greenhouse Gases in the United States 1987-1992*, Energy Information Administration, U.S. Department of Energy. Washington, D.C. November, 1994. DOE/EIA 0573.

EIA (1993) *Btu Tax on Finished Petroleum Products,* Energy Information Administration, Petroleum Supply Division (unpublished manuscript, April 1993).

EPA (2020a) *The Emissions & Generation Resource Integrated Database (eGRID) 2018 Technical Support Document*. Clean Air Markets Division, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2020b) EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Updated Gasoline and Diesel Fuel CO2 Emission Factors – Memo.

EPA (2013) Memo: Table of Final 2013 Revisions to the Greenhouse Gas Reporting Rule, Amendments to Table C-1 to 40 CFR part 98, subpart C:Table C–1 to Subpart C—Default CO2 Emission Factors and High Heat Values for Various

Types of Fuel. Available online at: https://www.epa.gov/sites/production/files/2015-01/documents/memo-2013-technical-revisions.pdf

EPA (2010) *Carbon Content Coefficients Developed for EPA's Inventory of Greenhouse Gases and Sinks*. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2009a) "Industry Overview and Current Reporting Requirements for Petroleum Refining and Petroleum Imports," Petroleum Product Suppliers Technical Support Document for the Proposed Mandatory Reporting Rule. Office of Air and Radiation. January 30, 2009.

EPA (2009b) *Mandatory Reporting of Greenhouse Gases Rule*. Federal Register Docket ID EPA-HQ-OAR-2008-0508-2278, September 30, 2009.

EPA (2009c) Technical Support Document, Petroleum Products and Natural Gas Liquids: Definitions, Emission Factors, Methods and Assumptions. *Final Rule for Mandatory Reporting of Greenhouse Gases*. September 15, 2009. Available online at: < https://www.epa.gov/sites/production/files/2015-07/documents/subpartmmproductdefinitions.pdf>.

Gas Technology Institute (1992) Database as documented in W.E. Liss, W.H. Thrasher, G.F. Steinmetz, P. Chowdiah, and A. Atari, *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States.* GRI-92/0123. March 1992.

Green & Perry, ed. (2008) *Perry's Chemical Engineers' Handbook, 8th Ed*. New York, NY, McGraw-Hill.

Gunderson, J. (2019) Montana Coal Sample Database. Data received 28 February 2019 from Jay Gunderson, Montana Bureau of Mines & Geology.

Guthrie, V.B., ed. (1960) *Characteristics of Compounds*, Petroleum Products Handbook, p.3-3. New York, NY, McGraw-Hill.

Hadaller, O.J. and A.M. Momenthy (1990) *The Characteristics of Future Fuels,* Part 1, "Conventional Heat Fuels". Seattle, WA, Boeing Corp. September 1990. pp. 46-50 (2006).

ICF (2020) Potential Improvements to Energy Sector Hydrocarbon Gas Liquid Carbon Content Coefficients. Memorandum from ICF to Vincent Camobreco, U.S. Environmental Protection Agency. December 7, 2020.

Illinois State Geological Survey (ISGS) (2019) *Illinois Coal Quality Database*, Illinois State Geological Survey.

Indiana Geological Survey (IGS) (2019) *Indiana Coal Quality Database 2018*, Indiana Geological Survey.

Intergovernmental Panel on Climate Change (IPCC) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme (Japan, 2006).Matar, S. and L. Hatch (2000) *Chemistry of Petrochemical Processes*, 2nd Ed. Gulf Publishing Company: Houston.

Martel, C.R., and L.C. Angello (1977) "Hydrogen Content as a Measure of the Combustion Performance of Hydrocarbon Fuels," in *Current Research in Petroleum Fuels,* Volume I. New York, NY, MSS Information Company, p. 116.

Martin, S.W. (1960) "Petroleum Coke," in Virgil Guthrie (ed.), *Petroleum Processing Handbook,* New York, NY, McGraw-Hill, pp. 14-15.

Meyers (2004) *Handbook of Petroleum Refining Processes*, 3rd ed., NY, NY: McGraw Hill.

National Institute for Petroleum and Energy Research (NIPER) (1990 through 2009) *Motor Gasolines, Summer* and *Motor Gasolines, Winter*.

NIPER (1993) C. Dickson, *Aviation Turbine Fuels, 1992*, NIPER-179 PPS93/2 (Bartlesville, OK: National Institute for Petroleum and Energy Research, March 1993).

Pennsylvania State University (PSU) (2010) Coal Sample Bank and Database. Data received by SAIC 18 February 2010 from Gareth Mitchell, The Energy Institute, Pennsylvania State University.

Quick, Jeffrey (2010) "Carbon Dioxide Emission Factors for U.S. Coal by Origin and Destination," *Environmental Science & Technology*, Forthcoming.

SAIC (2007) Analysis prepared by Science Applications International Corporation for EPA, Office of Air and Radiation, Market Policies Branch.

U.S. National Research Council (1927) *International Critical Tables of Numerical Data, Physics, Chemistry, and Technology,* New York, NY, McGraw-Hill.

Unzelman, G.H. (1992) "A Sticky Point for Refiners: FCC Gasoline and the Complex Model," *Fuel Reformulation*, July/August 1992, p. 29.

USGS (1998) *CoalQual Database Version 2.0*, U.S. Geological Survey.

Wauquier, J., ed. (1995) Petroleum Refining, Crude Oil, Petroleum Products and Process Flowsheets (Editions Technip Paris, 1995) pg.225, Table 5.16.

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-51. 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 (1) petrochemical feedstocks (industrial other coal, natural gas for non-fertilizer uses, hydrocarbon gas liquids (HGL), pentanes plus, naphthas, other oils, still gas, special naphtha), (2) asphalt and road oil, (3) lubricants, and (4) waxes. The storage factors[28] for the remaining other (industrial coking coal, petroleum coke, distillate fuel oil, and other petroleum) 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-51: 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]	67%
Natural Gas to Chemical Plants[b]	67%
Asphalt & Road Oil	100%
HGL[b]	67%
Lubricants	9%
Pentanes Plus[b]	67%
Naphtha (<401 deg. F)[b]	67%
Other Oil (>401 deg. F)[b]	67%
Still Gas[b]	67%
Petroleum Coke[c]	30%
Special Naphtha[b]	67%
Distillate Fuel Oil	50%
Waxes	58%
Miscellaneous Products[d]	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 2019. 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.
[d] The miscellaneous products category reported by EIA is assumed to be mostly petroleum refinery sulfur compounds that do not contain carbon (EIA 2019).

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 other products follow.

[28] 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,[29] HGL, 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.[30]

After adjustments for (1) use in industrial processes and (2) net exports, these eight fuel categories constituted approximately 240.0 MMT CO_2 Eq., or 71 percent, of the 339.1 MMT CO_2 Eq. of non-energy fuel consumption in 2019. For 2019, the storage factor for the eight fuel categories was 67 percent. In other words, of the net consumption, 67 percent was destined for long-term storage in products—including products subsequently combusted for waste disposal—while the remaining 33 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 HGL,[31] 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 2019.

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-

[29] Natural gas used as a petrochemical feedstock includes use in production of methanol. The storage factor developed for petrochemical feedstocks includes emissions from the use of products. Therefore, it is assumed that emissions from the combustion of methanol used in biodiesel are captured here and not reported as part of biodiesel combustion emissions.

[30] 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.

[31] HGL (formerly referred to as liquefied petroleum gas, or LPG) are hydrocarbons that occur as gases at atmospheric pressure and as liquids under higher pressures. HGLs include paraffins, such as ethane, propane, butanes, and pentanes plus, and HGLs include olefins, such as ethylene, propylene, and butylene. Adjustments were made in the current Inventory report to HGL activity data, carbon content coefficients, and heat contents HGL.

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 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[32] and cover a complete time series from 1990 to 2019. 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-52. As shown in the table, the United States has been a net exporter of chemical intermediates and products throughout the 1990 to 2019 period.

Table A-52: Net Exports of Petrochemical Feedstocks, 1990 – 2019 (MMT CO_2 Eq.)

	1990	2005	2010	2015	2016	2017	2018	2019
Net Exports	12.0	6.5	7.3	5.5	12.7	13.9	17.1	21.0

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), carbon black (petroleum coke and other oils), silicon carbide (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-52) and non-energy use reported in the Industrial Processes and Product Use (IPPU) sector 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, HGL, pentanes plus, naphthas, other oils, still

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

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.[33]

The C in each product or waste produced was categorized as either stored or emitted. The aggregate storage factor is the C-weighted average of storage across fuel types. As discussed later in the section on uncertainty, the sum of stored C and emitted C (i.e., the outputs of the system) exceeded total C consumption (i.e., the inputs to the system) for some years in the time series. 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-53. Summing the C stored and dividing it by total C outputs yields the overall storage factor, as shown in the following equation for 2019:

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

$$161.8 \text{ MMT } CO_2 \text{ Eq.} / (161.8 + 64.2 + 14.0) \text{ MMT } CO_2 \text{ Eq.} = 67\%$$

Table A-53: C Stored and Emitted by Products from Feedstocks in 2019 (MMT CO_2 Eq.)

Product/Waste Type	C Stored (MMT CO_2 Eq.)	C Emitted (MMT CO_2 Eq.)
Industrial Releases	**0.1**	**5.8**
TRI Releases	0.1	1.0
Industrial VOCs	NA	3.4
Non-combustion CO	NA	0.5
Hazardous Waste Incineration	NA	0.9
Energy Recovery	**NA**	**45.6**
Products	**161.7**	**12.8**
Plastics	140.3	NA
Synthetic Rubber	12.9	NA
Antifreeze and Deicers	NA	1.0
Abraded Tire Rubber	NA	0.2
Food Additives	NA	1.1
Silicones	0.5	NA
Synthetic Fiber	7.8	NA
Pesticides	0.2	0.3
Soaps, Shampoos, Detergents	NA	4.7
Solvent VOCs	NA	5.6
Total	**161.8**	**64.2**

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

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

[33] For the most part, the releases covered by the U.S. Toxic Release Inventory (TRI) represent air emissions or water discharges associated with production facilities. Similarly, VOC emissions are generally associated with production facilities. These emissions could have been accounted for as part of the Waste chapter, but because they are not necessarily associated with waste management, they were included here. Toxic releases are not a "product" category, but they are referred to as such for ease of discussion.

The 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."[34] The C released in each disposal location is provided in Table A-54.

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 2019 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-54: 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
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
Total	**97.2**	**982.6**

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

Volatile Organic Compound Emissions from Industrial Processes and Solvent Evaporation Emissions

Data on annual non-methane volatile organic compound (NMVOC) emissions were obtained (EPA 2020) 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 2019 Trends data include information on NMVOC emissions by end-use

[34] 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).

category; some of these fall into the heading of "industrial releases" in Table A-53 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 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-55 for 1990 through 2019. Industrial NMVOC emissions in 2019 were 3.4 MMT CO_2 Eq. and solvent evaporation emissions in 2019 were 5.6 MMT CO_2 Eq.

Table A-55: Industrial and Solvent NMVOC Emissions

	1990	1995	2000	2005	2015	2016	2017	2018	2019
Industrial NMVOCs[a]									
NMVOCs ('000 Short Tons)	1,279	1,358	802	825	1,349	1,277	1,205	1,205	1,205
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	3.8	3.6	3.4	3.4	3.4
Solvent Evaporation[b]									
Solvents ('000 Short Tons)	5,750	6,183	4,832	4,245	3,025	2,999	2,972	2,972	2,972
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	5.7	5.6	5.6	5.6	5.6

[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 2020) 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-56 lists the CO emissions that remain after taking into account the exclusions listed above.

Table A-56: Non-Combustion Carbon Monoxide Emissions

	1990	1995	2000	2005	2015	2016	2017	2018	2019
CO Emissions ('000 Short Tons)	489	481	623	461	389	358	327	327	327
Carbon Emitted (MMT CO_2 Eq.)	0.7	0.7	0.9	0.7	0.6	0.5	0.5	0.5	0.5

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).[35] 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 EPA.

Hazardous wastes must be treated prior to disposal according to the federal regulations established under the authority of RCRA. Combustion is one of the most common techniques for hazardous waste treatment, particularly for those wastes that are primarily organic in composition or contain primarily organic contaminants. Generally speaking, combustion devices fall into two categories: incinerators that burn waste solely for the purpose of waste management, and boilers and industrial furnaces (BIFs) that burn waste in part to recover energy from the waste. More than half of the hazardous waste combusted in the United States is burned in BIFs; because these processes are included in the energy recovery calculations described below, they are not included as part of hazardous waste incineration.

EPA's Office of Solid Waste requires biennial reporting of hazardous waste management activities, and these reports provide estimates of the amount of hazardous waste burned for incineration or energy recovery. EPA stores this information in its Resource Conservation and Recovery Act (RCRA) Information system (EPA 2013a), formerly reported in its Biennial Reporting System (BRS) database (EPA 2000a; 2009; 2015a; 2016a; 2018). 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, 2015, and 2017 (EPA 2000a; 2009; 2013a; 2015a; 2016a; 2018). 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-57). 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 2019 were 0.9 MMT CO_2 Eq. Table A-58 lists the CO_2 emissions from hazardous waste incineration.

[35] [42 U.S.C. §6924, SDWA §3004]

Table A-57: 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-58: CO_2 Emitted from Hazardous Waste Incineration (MMT CO_2 Eq.)

	1990	1995	2000	2005	2015	2016	2017	2018	2019
CO_2 Emissions	1.1	1.7	1.4	1.5	0.9	0.9	0.9	0.9	0.9

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, 2010, and 2014 (EIA 1994; 1997; 2001; 2005; 2010; 2013b; 2017). 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-59). The conversion factors listed in Annex 2.1 were used to convert the Btu values for each fuel feedstock to MMT CO_2. Petrochemical feedstocks combusted for energy recovery corresponded to 42.5 MMT CO_2 Eq. in 1991, 35.1 MMT CO_2 Eq. in 1994, 58.0 MMT CO_2 Eq. in 1998, 70.6 MMT CO_2 Eq. in 2002, 74.7 MMT CO_2 Eq. in 2006, 41.3 MMT CO_2 Eq. in 2010, and 45.6 MMT CO_2 Eq. in 2014. 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, between 2007 and 2010, and between 2011 and 2013 have been estimated by linear interpolation. The value for 1990 is assumed to be the same as the value for 1991, and the values for 2015, 2016, 2017, 2018, and 2019 are assumed to be the same as the value for 2014 (Table A-60).

Table A-59: Summary of 2014 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	4	1,329	191	106
Chemicals	325	364	6	0	310	128
Plastics and Rubber Products	326	0	0	0	0	0
Nonmetallic Mineral Products	327	0	7	0	0	16
Primary Metals	331	4	0	0	10	15
Fabricated Metal Products	332	0	0	0	0	1
Machinery	333	0	0	0	0	2
Computer and Electronic Products	334	0	0	0	0	0
Electrical Equip., Appliances, Components	335	0	0	0	0	2
Transportation Equipment	336	4	0	0	1	4
Furniture and Related Products	337	0	0	0	0	2
Miscellaneous	339	0	0	0	0	0
Total (Trillion Btu)		**372**	**17**	**1,329**	**511**	**276**
Average C Content (MMT/QBtu)		18.14	20.62	17.51	0	19.37
Fraction Oxidized		1	1	1	0	1
Total C (MMT)		**6.75**	**0.35**	**23.27**	**0.00**	**5.35**
Total C (MMT) (ex. still gas from refining)		**6.75**	**0.35**	**0.00**	**0.00**	**5.35**

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-60: Carbon Emitted from Fuels Burned for Energy Recovery (MMT CO_2 Eq.)

	1990	1995	2000	2005	2015	2016	2017	2018	2019
C Emissions	42.5	40.8	64.3	73.7	45.6	45.6	45.6	45.6	45.6

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 2019 were taken directly or derived from the American Chemistry Council (ACC 2007 through 2020b supplemented by Vallianos 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020). 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, 2014, 2015, 2016, 2017, 2018, and 2019 (Vallianos 2011; 2012; 2013; 2014; 2015; 2016; 2017; 2018; 2019; 2020). 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-61) 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 (Chemistry Industry Association of Canada 2020, Bank of Canada 2020). A C content was then assigned for each resin. These C contents were based on molecular formulae and are listed in Table A-62 and Table A-63. 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 75 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-61: 2019 Plastic Resin Production (MMT dry weight) and C Stored (MMT CO_2 Eq.)

Resin Type	2019 Production[a] (MMT dry weight)	Carbon Stored (MMT CO_2 Eq.)
Epoxy	0.2	0.7
Polyester	0.6	1.5
Urea	1.2	1.5
Melamine	0.1	0.1
Phenolic	1.6	4.5
Low-Density Polyethylene (LDPE)	3.2	10.1
Linear Low-Density Polyethylene (LLDPE)	8.6	27.1
High Density Polyethylene (HDPE)	9.4	29.4
Polypropylene (PP)	6.7	21.0
Acrylonitrile-butadiene-styrene (ABS)	0.5	1.6
Other Styrenics[b]	0.5	1.7
Polystyrene (PS)	1.7	5.6
Nylon	0.4	1.0
Polyvinyl chloride (PVC)[c]	6.7	9.5
Thermoplastic Polyester	3.1	7.2
All Other (including Polyester (unsaturated))	6.5	17.9
Total	**51.1**	**140.3**

Note: Totals may not sum due to independent rounding.
[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.

Table A-62: 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[a]
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-)
Polyvinyl Chloride (PVC)	38%	Polyvinyl chloride
Thermoplastic Polyester	63%	Polyethylene terephthalate
All Other	75%	Weighted average of other resin production

[a] Does not include alcoholic hydrogens.

Table A-63: 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 *2017 U.S. Scrap Tire Management Summary* (RMA 2018), 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, 2016b, 2019) 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 2018). Import and export data were obtained from the published by the U.S. International Trade Commission (U.S. International Trade Commission 1990 through 2019).

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-64). 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-64: 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**

Note: Totals may not sum due to independent rounding.
NA (Not Applicable)
[a] Includes consumption in Canada.

Synthetic Fibers

Annual synthetic fiber production data were obtained from the ACC, as published in the *Guide to the Business of Chemistry* (ACC 2020a), and the Fiber Economics Bureau, as published in *Chemical & Engineering News* (FEB 2001, 2003, 2005, 2007, 2009, 2010, 2011, 2012, 2013). For acrylic fiber, the most recent data available were for 2012, so it was assumed that the 2013, 2014, 2015, 2016, 2017, 2018, and 2019 consumption was equal to that of 2012. For polyester, nylon, and olefin, the most recent data were for 2019. These data are organized by year and fiber type. For each fiber, a C content was assigned based on molecular formula (see Table A-65). 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-65: 2019 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	1.3	63%	2.9
Nylon	0.5	64%	1.2
Olefin	1.1	86%	3.6
Acrylic	+	68%	0.1
Total	**3.0**	**NA**	**7.8**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT.
NA (Not Applicable)

Pesticides

Pesticide consumption data were obtained from the *1994/1995, 1996/1997, 1998/1999, 2000/2001, 2006/2007, and 2008-2012 Pesticides Industry Sales and Usage Market Estimates* (EPA 1998, 1999, 2002, 2004, 2011b, 2017) reports. The most recent data available were for 2012, so it was assumed that the 2013 through 2019

consumption was equal to that of 2012. 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 2012 total pesticide active ingredient consumption was not specified by chemical type in the *Sales and Usage* report (EPA 2017). 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-66: Active Ingredient Consumption in Pesticides (Million lbs.) and C Emitted and Stored (MMT CO_2 Eq.) in 2012

Pesticide Use[a]	Active Ingredient (Million lbs.)	C Emitted (MMT CO_2 Eq.)	C Stored (MMT CO_2 Eq.)
Agricultural Uses	606.0	0.2	0.1
Non-Agricultural Uses	58.0	+	+
Home & Garden	39.5	+	+
Industry/Gov't/Commercial	28.0	+	+
Other	342.0	0.1	0.1
Total	**1,006.0**	**0.3**	**0.2**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT CO_2 Eq.
[a] 2012 estimates (EPA 2017).

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, given in terms of the value of shipments, 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 2019 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[36] 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

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

years, it was assumed that the ratio of value of shipments to total carbon content remained constant. For 1998 through 2019, value of shipments was adjusted to 1997 dollars using the producer price index for soap and other detergent manufacturing (Bureau of Labor Statistics 2020). 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-67.

Table A-67: C Emitted from Utilization of Soaps, Shampoos, and Detergents (MMT CO_2 Eq.)

	1990	1995	2000	2005	2015	2016	2017	2018	2019
C Emissions	3.6	4.2	4.5	6.7	4.8	4.7	4.7	4.7	4.7

Antifreeze and Deicers

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

Annual production data for each glycol compound used as antifreeze and deicers were obtained from the *Guide to the Business of Chemistry* (ACC 2020a) 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[37] and from similar data published in the Chemical Market Reporter, which became ICIS Chemical Business in 2005.[38] 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 2014, 2015, 2016, 2017, 2018, and 2019 for these compounds were assumed to be the same as the 2012 values.

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-68.

Table A-68: C Emitted from Utilization of Antifreeze and Deicers (MMT CO_2 Eq.)

	1990	1995	2000	2005	2015	2016	2017	2018	2019
C Emissions	1.2	1.4	1.5	1.2	1.0	1.0	1.0	1.1	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 2020a). Historical values for adipic acid, acetic acid, and maleic anhydride were adjusted according to the most recent data in the 2019 *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

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

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

was estimated from Chemical Profiles data published on The Innovation Group website[39] and from similar data published in the Chemical Market Reporter, which became ICIS Chemical Business in 2005.[40] 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 dipropylene glycol was last reported by ICIS 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 2014, 2015, 2016, 2017, 2018, and 2019 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-69.

Table A-69: C Emitted from Utilization of Food Additives (MMT CO_2 Eq.)

	1990	1995	2000	2005	2015	2016	2017	2018	2019
C Emissions	0.6	0.7	0.7	0.8	1.1	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.

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.[41] 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 2014, 2015, 2016, 2017, 2018 and 2019 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-70.

Table A-70: C Stored in Silicone Products (MMT CO_2 Eq.)

	1990	1995	2000	2005	2015	2016	2017	2018	2019
C Storage	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5

Uncertainty

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of the feedstocks C storage factor and the quantity of C emitted from feedstocks in 2019. 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

[39] See <http://www.the-innovation-group.com/ChemProfiles>.
[40] See <http://www.icis.com/home/default.aspx>.
[41] See <http://www.icis.com/home/default.aspx>.

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 standard deviation of 6 percent and the 95 percent confidence interval of 53 percent and 73 percent. This compares to the calculated Inventory estimate of 67 percent. The analysis produced a C emission distribution with a standard deviation of 23.9 MMT CO_2 Eq. and 95 percent confidence limits of 51.9 and 136.4 MMT CO_2 Eq. This compares with a calculated Inventory estimate of 78.2 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.

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, HGL, 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 2017). 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, 2010, and 2014 (EIA 1994, 1997, 2001, 2005, 2010, 2013b, 2017). 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 77 percent, and the remaining pesticides may have a chemical make-up that is very different from the 49 pesticides that have been examined. Additionally, pesticide consumption data were only available for 1987, 1993, 1995, 1997, 1999, 2001, 2007, 2009, and 2012; the majority of the time series data were interpolated or held constant at the latest (2012) 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.[42] 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,

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

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 99.6 percent of the C in asphalt cement was retained (i.e., stored), and less than 0.4 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

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 2019. The Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the Inventory estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. Uncertainty estimates for asphalt production were assumed to be ±20 percent, while the asphalt property variables were assumed to have narrower distributions. A narrow uniform distribution, with maximum 5 percent uncertainty (± 5 percent) around the mean, was applied to the C content coefficient.

The Monte Carlo analysis produced a tight distribution of storage factor values, with the 95 percent confidence interval of 99 percent and 100 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 standard deviation of 0.1 and 95 percent confidence limits of 0.1 MMT CO_2 Eq. and 0.6 MMT CO_2 Eq. This compares to an Inventory calculated estimate of 0.3 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 (2020), the C content from U.S. production of lubricants in 2019 was approximately 5.1 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 2019 were about 4.6 MMT C, or 16.9 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.[43] 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- provides an estimated allocation of the fates of lubricant oils (Rinehart 2000), along with an estimate of the proportion of C stored in each fate. The ultimate fate of the majority of oils (about 84 percent) is combustion, either during initial use or after collection as used oil. Combustion results in 99 percent oxidation to CO_2 (EIIP 1999), with correspondingly little long-term storage of C in the form of ash. Dumping onto the ground or into storm sewers, primarily by "do-it-yourselfers" who change their own oil, is another fate that results in conversion to CO_2 given that the releases are generally small and most of the oil is biodegraded (based on the observation that land farming—application to soil—is one of the most frequently used methods for degrading refinery wastes). In the landfill environment, which tends to be anaerobic within municipal landfills, it is assumed that 90 percent of the oil persists in an undegraded form, based on analogy with the persistence of petroleum in native petroleum-bearing strata, which is also anaerobic. Re-refining adds a recycling loop to the fate of oil. Re-refined oil was assumed to have a storage factor equal to the weighted average for the other fates (i.e., after re-refining, the oil would have the same probability of combustion, landfilling, or dumping as virgin oil), that is, it was assumed that about 97 percent of the C in re-refined oil is ultimately oxidized. Because of the dominance of fates that result in eventual release as CO_2, only about 3 percent of the C in oil lubricants goes into long-term storage.

[43] For example, the U.S. EPA "RCRA (Resource Conservation and Recovery Act) On-line" web site (<http://www.epa.gov/rcraonline/>) has over 50 entries on used oil regulation and policy for 1994 through 2000.

Table A-71: 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-72 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-72: 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%**

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

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 2019. 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. This compares to the calculated Inventory estimate of 9.2 percent. The analysis produced a C emission distribution approximating a normal curve with a standard deviation of 1.5 and 95 percent confidence limits of 13.9 MMT CO_2 Eq. and 19.6 MMT CO_2 Eq. This compares to an inventory-calculated estimate of 16.9 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-73 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-73: 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	+	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-74 categorizes wax end uses identified by the NPRA and lists the estimated C storage factor of each end use.

Table A-74: 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%**

Notes: Totals may not sum due to independent rounding. Estimates of percent stored are based on ICF professional judgment.
+ Does not exceed 0.5 percent.
NA (Not Applicable)
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

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 2019. 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 47 percent and 67 percent. This compares to the calculated Inventory estimate of 57.8 percent. The analysis produced an emission distribution, with the 95 percent confidence interval values of 0.2 MMT CO_2 Eq. and 0.6 MMT CO_2 Eq. This compares with a calculated Inventory estimate of 0.3 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

The “miscellaneous products” category reported by EIA includes miscellaneous products that are not reported elsewhere in the EIA data set. The EIA does not have firm data concerning the amounts of various products that are being reported in the “miscellaneous products” category; however, EIA has indicated that recovered sulfur compounds from petroleum and natural gas processing, and potentially also carbon black feedstock could be reported in this category. Recovered sulfur has no carbon content and would not be reported in the NEU calculation or elsewhere in the Inventory. Based on this information, the miscellaneous products category reported by EIA was assumed to be mostly petroleum refinery sulfur compounds that do not contain carbon (EIA 2019). Therefore, the carbon content for miscellaneous products was updated to be zero across the time series. This resulted in recalculating historical emissions from 1990 through 2018.

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 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 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. Carbon dioxide emissions from carbide production are implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke. The “other petroleum” category is reported by U.S. Territories and accounts mostly for the same products as miscellaneous products, but probably also includes some asphalt, known to be non-emissive. The exact amount of asphalt or any of the other miscellaneous products is confidential business information, but based on judgment, the storage factor for this category was estimated at 0.1.

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

Uncertainty

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the weighted average of the remaining fuels’ C storage factors and the total quantity of C emitted from these other fuels in 2019. 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. 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 7 percent and 83 percent. This compares to the Inventory calculation of weighted average (across the various fuels) storage factor of about 11.1 percent. The analysis produced an emission distribution, with the 95 percent confidence limit of 2.8 MMT CO_2 Eq. and 16.7 MMT CO_2 Eq. This compares with the Inventory estimate of 14.4 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.

References

ACC (2020a) *"Guide to the Business of Chemistry, 2020,"* American Chemistry Council.

ACC (2020b) "U.S. Resin Production & Sales 2019 vs. 2018." Available online at: <https://plastics.americanchemistry.com/Year-End-Resin-Stats.pdf>.

ACC (2017) "U.S. Resin Production & Sales 2016 vs. 2015."

ACC (2016) "U.S. Resin Production & Sales 2015 vs. 2014."

ACC (2015) "U.S. Resin Production & Sales: 2014 vs. 2013," American Chemistry Council. Available online at: <http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf>.

ACC (2014) "U.S. Resin Production & Sales: 2013 vs. 2012," American Chemistry Council. Available online at: <http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf>.

ACC (2007 through 2011) "PIPS Year-End Resin Statistics: Production, Sales and Captive Use." Available online at: <http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf>.

APC (2003 through 2006) "APC Year-End Statistics."

APC (2001) *as cited in ACS (2001) "Production: slow gains in output of chemicals and products lagged behind U.S. economy as a whole"* Chemical & Engineering News.

APC (2000) Facts and Figures, Chemical & Engineering News, June 26, 2000.

Bank of Canada (2020) Financial Markets Department Year Average of Exchange Rates. Available online at: <https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download>.

Bank of Canada (2019) Financial Markets Department Year Average of Exchange Rates. Available online at: <https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download>.

Bank of Canada (2017) Financial Markets Department Year Average of Exchange Rates.

Bank of Canada (2016) Financial Markets Department Year Average of Exchange Rates.

Bank of Canada (2013) Financial Markets Department Year Average of Exchange Rates.

Bank of Canada (2012) Financial Markets Department Year Average of Exchange Rates.

Bank of Canada (2009) Financial Markets Department Year Average of Exchange Rates.

Bureau of Labor Statistics (2020) Producer Price Index Industry Data: Soap and Other Detergent Manufacturing. Available online at: <http://data.bls.gov/cgi-bin/dsrv?pc>.

Chemistry Industry Association of Canada (2020) Economic Review of Chemistry. Available online at: <https://canadianchemistry.ca/wp-content/uploads/2020/07/2020-Economic-Review-of-Chemistry-Final.pdf>.

Davie, I.N., J.P. Winter, and R.P. Varoney (1995) "Decomposition of Coated Papers from a Quick Service Restaurant." *Technical Association for Pulp and Paper Industry Journal.* Vol 78 (5): 127-130.

Davie, I.N. (1993) "Compostability of Petroleum Wax-based Coatings." *Technical Association for Pulp and Paper Industry Journal.* Vol 76 (2): 167-170.

EIA (2020) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, November 2020.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035 (2020/11).

EIA (2019) Personal communication between EIA and ICF on November 11, 2019.

EIA (2017) *EIA Manufacturing Consumption of Energy (MECS) 2014.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2013b) *EIA Manufacturing Consumption of Energy (MECS) 2010.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2009) *Petroleum Supply Annual*, Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at <http://www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_annual/psa_volume1/psa_volume1.html>.

EIA (2010) *EIA Manufacturing Consumption of Energy (MECS) 2006,* U.S. Department of Energy, Energy Information Administration, Washington, D.C.EIA (2005) *EIA Manufacturing Consumption of Energy (MECS) 2002,* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2001) *EIA Manufacturing Consumption of Energy (MECS) 1998,* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (1997) *EIA Manufacturing Consumption of Energy (MECS) 1994,* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (1994) *EIA Manufacturing Consumption of Energy (MECS) 1991,* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

Eldredge-Roebuck (2000) Personal communication between Joe Casola, ICF Consulting and Brandt Eldredge-Roebuck, American Plastics Council, 11 July 2000.

EIIP (2001) "Area Sources" *Asphalt Paving,* Emissions Inventory Improvement Program: State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officials and U.S. EPA, EIIP Document Series Vol. III, Ch. 17. (STAPPA/ALAPCO/EPA), Washington D.C., January 2001. Available online at <https://www.epa.gov/sites/production/files/2015-08/documents/iii17_apr2001.pdf>.

EIIP (1999) *Methods for Estimating Greenhouse Gas Emissions from Combustion of Fossil Fuels*. Emissions Inventory Improvement Program: State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officials and U.S. Environmental Protection Agency, EIIP Document Series Volume VIII, Chapter 1, STAPPA/ALAPCO/EPA, Washington, D.C. August 2000.

Environment Canada (2006) *Emissions Inventory Guidebook v1.3*. Criteria Air Contaminants Division: Quebec, Canada. Available online at: <http://www.eea.europa.eu/publications/EMEPCORINAIR5/B4611vs1.3.pdf>.

EPA (2020) "1970 - 2019 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards, April 2020. Available online at: <https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data>.

EPA (2019) *Advancing Sustainable Materials Management: 2016 and 2017 Data Tables*. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: <https://www.epa.gov/sites/production/files/2019-11/documents/2016_and_2017_facts_and_figures_data_tables_0.pdf>.

EPA (2013a, 2015a, 2016a, 2018) RCRAInfo, Biennial Report, Generation and Management (GM) Form (Section 2 - Onsite Management) and Waste Received from Offsite (WR) Form.

EPA (2017) EPA's Pesticides Industry Sales and Usage, 2008-2012 Market Estimates. Available online at: <https://www.epa.gov/sites/production/files/2017-01/documents/pesticides-industry-sales-usage-2016_0.pdf>.

EPA (2016b) Advancing Sustainable Materials Management: 2014 Facts and Figures Fact Sheet. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: <https://www.epa.gov/sites/production/files/2016-11/documents/2014_smmfactsheet_508.pdf>.

EPA (2014) Chemical Data Access Tool (CDAT). U.S. Environmental Protection Agency, June 2014. Available online at < https://chemview.epa.gov/chemview>. Accessed January 2015.

EPA (1996 through 2003a, 2005, 2007b, 2008, 2009a, 2011a, 2013b, 2014) *Municipal Solid Waste in the United States: Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: <https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management-0>.

EPA (2011b) EPA's Pesticides Industry Sales and Usage, 2006 and 2007 Market Estimates. Available online at <https://www.epa.gov/pesticides/pesticides-industry-sales-and-usage-2006-and-2007-market-estimates>.

EPA (2009) Biennial Reporting System (BRS) Database. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, D.C. Available online at <https://rcrapublic.epa.gov/rcrainfoweb/action/modules/br/summary/view>.

EPA (2006) *Air Emissions Trends - Continued Progress Through 2005*. U.S. Environmental Protection Agency, Washington D.C. December 19, 2006.

EPA (2004) EPA's Pesticides Industry Sales and Usage, 2000 and 2001 Market Estimates. Available online at < https://nepis.epa.gov/Exe/ZyPDF.cgi/3000659P.PDF?Dockey=3000659P.PDF>. Accessed September 2006.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data. Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. December 22, 2003.

EPA (2002) EPA's Pesticides Industry Sales and Usage, 1998 and 1999 Market Estimates, table 3.6. Available online at <https://nepis.epa.gov/Exe/ZyPDF.cgi/200001G5.PDF?Dockey=200001G5.PDF>. Accessed July 2003.

EPA (2001) AP 42, Volume I, Fifth Edition. Chapter 11: Mineral Products Industry. Available online at <http://www.epa.gov/ttn/chief/ap42/ch11/index.html>.

EPA (2000a) *Biennial Reporting System (BRS)*. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, D.C. Available online at <https://rcrapublic.epa.gov/rcrainfoweb/action/modules/br/summary/view>.

EPA (2000b) *Toxics Release Inventory, 1998*. U.S. Environmental Protection Agency, Office of Environmental Information, Office of Information Analysis and Access, Washington, D.C. Available online at <http://www.epa.gov/triexplorer/chemical.htm>.

EPA (1999) EPA's Pesticides Industry Sales and Usage, 1996-1997 Market Estimates and Available online at: <https://nepis.epa.gov/Exe/ZyPDF.cgi/200001IL.PDF?Dockey=200001IL.PDF>.

EPA (1998) EPA''s Pesticides Industry Sales and Usage, 1994-1995 Market Estimates. Available online at <https://nepis.epa.gov/Exe/ZyPDF.cgi/200001HF.PDF?Dockey=200001HF.PDF>.

FEB (2013) *Fiber Economics Bureau, as cited in C&EN (2013) Lackluster Year for Chemical Output: Production stayed flat or dipped in most world regions in 2012.* Chemical &Engineering News, American Chemical Society, 1 July. Available online at: <http://www.cen-online.org>.

FEB (2012) *Fiber Economics Bureau, as cited in C&EN (2012) Too Quiet After the Storm: After a rebound in 2010, chemical production hardly grew in 2011.* Chemical &Engineering News, American Chemical Society, 2 July. Available online at: <http://www.cen-online.org>.

FEB (2011) *Fiber Economics Bureau, as cited in C&EN (2011) Output Ramps up in all Regions*. Chemical & Engineering News, American Chemical Society, 4 July. Available online at: <http://www.cen-online.org>.

FEB (2010) *Fiber Economics Bureau, as cited in C&EN (2010) Output Declines in U.S., Europe*. Chemical & Engineering News, American Chemical Society, 6 July. Available online at: <http://www.cen-online.org>.

FEB (2009) *Fiber Economics Bureau, as cited in C&EN (2009) Chemical Output Slipped In Most Regions.* Chemical & Engineering News, American Chemical Society, 6 July. Available online at: <http://www.cen-online.org>.

FEB (2007) *Fiber Economics Bureau, as cited in C&EN (2007) Gains in Chemical Output Continue*. Chemical & Engineering News, American Chemical Society. July 2, 2007. Available online at: <http://www.cen-online.org>.

FEB (2005) *Fiber Economics Bureau, as cited in C&EN (2005) Production: Growth in Most Regions.* Chemical & Engineering News, American Chemical Society, 11 July. Available online at: <http://www.cen-online.org>.

FEB (2003) *Fiber Economics Bureau, as cited in C&EN (2003) Production Inches Up in Most Countries.* Chemical & Engineering News, American Chemical Society, 7 July. Available online at: <http://www.cen-online.org>.

FEB (2001) *Fiber Economics Bureau, as cited in ACS (2001) Production: slow gains in output of chemicals and products lagged behind U.S. economy as a whole* Chemical & Engineering News, American Chemical Society, 25 June. Available online at: <http://pubs.acs.org/cen>.

Financial Planning Association (2006) Canada/US Cross-Border Tools: US/Canada Exchange Rates. Available online at: <http://www.fpanet.org/global/planners/US_Canada_ex_rates.cfm>. Accessed August 16, 2006.

Gosselin, Smith, and Hodge (1984) *Clinical Toxicology of Commercial Products*. Fifth Edition, Williams & Wilkins, Baltimore.

Huurman, J.W.F. (2006) R*ecalculation of Dutch Stationary Greenhouse Gas Emissions Based on sectoral Energy Statistics 1990-2002*. Statistics Netherlands, Voorburg, The Netherlands.

IGI (2002) *100 Industry Applications.* The International Group Inc.

IISRP (2003) "*IISRP Forecasts Moderate Growth in North America to 2007*" International Institute of Synthetic Rubber Producers, Inc. New Release; available online at: <http://www.iisrp.com/press-releases/2003-Press-Releases/IISRP-NA-Forecast-03-07.html>.

IISRP (2000) *Synthetic Rubber Use Growth to Continue Through 2004, Says IISRP and RMA*. International Institute of Synthetic Rubber Producers press release.

INEGI (2006) Producción bruta total de las unidades económicas manufactureras por Subsector, Rama, Subrama y Clase de actividad. Available online at: <http://www.inegi.gob.mx/est/contenidos/espanol/proyectos/censos/ce2004/tb_manufacturas.asp>. Accessed August 15.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, eds.; Institute for Global Environmental Strategies (IGES). Hayama, Kanagawa, Japan.

James, A. (2000) Personal communication between Suzanne Bratis of ICF International and Alan James of Akzo Nobel Coatings, Inc. July 2000. (Tel: 614-294-3361).

Kelly (2000) Personal communication between Tom Smith, ICF Consulting and Peter Kelly, Asphalt Roofing Manufacturers Association, August 2000.

Maguire (2004) Personal communication with J. Maguire, National Petrochemicals and Refiners Association. August – September 2004.

Marland, G., and R.M. Rotty (1984) *Carbon dioxide emissions from fossil fuels: A procedure for estimation and results for 1950-1982*, Tellus 36b:232-261.

NPRA (2002) North American Wax - A Report Card.

Rinehart, T. (2000) Personal communication between Thomas Rinehart of U.S. Environmental Protection Agency, Office of Solid Waste, and Randall Freed of ICF International. July 2000. (Tel: 703-308-4309).

RMA (2018) 2017 *U.S. Scrap Tire Management Summary*. Rubber Manufacturers Association, Washington, D.C. July 2018.

RMA (2016) 2015 *U.S. Scrap Tire Management Summary*. Rubber Manufacturers Association, Washington, D.C. August 2016.

RMA (2014) 2013 *U.S. Scrap Tire Management Summary*. Rubber Manufacturers Association, Washington, D.C. November 2014.

RMA (2011) *U.S. Scrap Tire Management Summary: 2005-2009*. Rubber Manufacturers Association, Washington, D.C. October 2011, updated September 2013.

RMA (2009) "Scrap Tire Markets: Facts and Figures – Scrap Tire Characteristics." Available online at: <http://www.rma.org/scrap_tires/scrap_tire_markets/scrap_tire_characteristics/>. Accessed 17 September 2009.

Schneider, S. (2007) E-mail between Shelly Schneider of Franklin Associates (a division of ERG) and Sarah Shapiro of ICF International, January 10, 2007.

SPI (2000) The Society of the Plastics Industry Website, http://www.plasticsindustry.org/industry/stat3.htm, Accessed 28 June 2000.

U.S. Bureau of the Census (1994, 1999, 2004, 2009, 2014) *1992, 1997, 2002, 2007, 2012 Economic Census*. Available online at <http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=ECN&_submenuId=&_lang=en&_ts=>.

U.S. International Trade Commission (1990 through 2019) "Interactive Tariff and Trade DataWeb: Quick Query." Available online at <http://dataweb.usitc.gov/>. Accessed September 2020.

Vallianos, Jean (2020) Personal communication between Katie O'Malley of ICF and Jean Vallianos of the American Chemistry Council, November 19, 2020.

Vallianos, Jean (2019) Personal communication between Katie O'Malley of ICF and Jean Vallianos of the American Chemistry Council, October 3, 2019.

Vallianos, Jean (2018) Personal communication between Drew Stilson of ICF and Jean Vallianos of the American Chemistry Council, October 5, 2018.

Vallianos, Jean (2017) Personal communication between Drew Stilson of ICF and Jean Vallianos of the American Chemistry Council, November 1, 2017.

Vallianos, Jean (2016) Personal communication between Drew Stilson of ICF and Jean Vallianos of the American Chemistry Council, November 17, 2016.

Vallianos, Jean (2015) Personal communication between Tyler Fitch of ICF International and Jean Vallianos of the American Chemistry Council, December 20, 2015.

Vallianos, Jean (2014) Personal communication between Sarah Biggar of ICF International and Jean Vallianos of the American Chemistry Council, November 13, 2014.

Vallianos, Jean (2013) Personal communication between Sarah Biggar of ICF International and Jean Vallianos of the American Chemistry Council, November 8, 2013.

Vallianos, Jean (2012) Personal communication between Ben Eskin of ICF International and Jean Vallianos of the American Chemistry Council, September 14, 2012.

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

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 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-75 through Table A-80.

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 emissions 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, November 2020* (EIA 2020). 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 2017) and Jacobs (2010).[44] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[45] Construction and agricultural fuel use was obtained from EPA (2019) and the Federal Highway Administration (FHWA) (1996 through 2019). 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-75 provides annual energy consumption data for the years 1990 through 2019.

In this Inventory, the energy consumption estimation methodology for the electric power sector used a Tier 2 methodology as fuel consumption by technology-type for the electric power sector was estimated based on the Acid Rain Program Dataset (EPA 2020a). Total fuel consumption in the electric power sector from EIA (2020) was apportioned to each combustion technology type and fuel combination using a ratio of fuel consumption by technology type derived from EPA (2020a) data. The combustion technology and fuel use data by facility obtained from EPA (2020a) were only available from 1996 to 2019, so the consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type from EPA (2020a) to the total EIA (2020) 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 (equivalent 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-76 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 Tier 2 IPCC emission factors shown in Table A-77. Emission factors were taken from U.S. EPA publications on

[44] 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.

[45] 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.

emissions rates for combustion sources, and EPA's Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997) for combined cycle natural gas units. The EPA factors were in large part used in the *2006 IPCC Guidelines* as the factors presented.

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 2020b) 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) 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 (2020b) 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

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 IPCC.

Table A-75: Fuel Consumption by Stationary Combustion for Calculating CH_4 and N_2O Emissions (TBtu)

Fuel/End-Use Sector	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Coal	**19,637**	**20,912**	**23,105**	**22,968**	**19,705**	**20,733**	**19,535**	**16,941**	**17,828**	**17,810**	**15,455**	**14,264**	**13,770**	**13,151**	**11,112**
Residential	31	17	11	8	0	0	0	0	0	0	0	0	0	0	0
Commercial	124	117	92	97	73	70	62	44	41	40	31	24	21	19	17
Industrial	1,668	1,557	1,379	1,248	918	993	906	823	837	837	734	658	612	564	515
Electric Power	17,807	19,216	21,618	21,582	18,677	19,633	18,531	16,038	16,919	16,889	14,645	13,547	13,110	12,540	10,553
U.S. Territories[a]	5	5	5	33	37	37	37	37	31	44	45	35	27	27	27
Petroleum	**6,089**	**5,495**	**6,438**	**6,621**	**4,577**	**4,653**	**4,300**	**4,065**	**4,048**	**4,210**	**4,187**	**3,755**	**3,605**	**4,228**	**3,936**
Residential	1,376	1,261	1,427	1,369	1,126	1,118	1,025	844	905	1,017	949	793	783	964	932
Commercial	1,023	714	755	745	659	633	597	499	511	567	658	535	530	746	625
Industrial	2,599	2,336	2,412	2,790	1,929	2,076	2,009	2,058	2,146	2,174	2,100	1,997	1,949	2,157	2,069
Electric Power	797	860	1,269	1,003	383	412	273	288	185	157	173	159	71	93	42
U.S. Territories[a]	295	325	576	714	480	412	396	376	302	295	307	270	272	268	268
Natural Gas	**17,255**	**19,340**	**20,923**	**20,937**	**21,951**	**22,913**	**23,320**	**24,614**	**25,143**	**25,924**	**26,635**	**26,764**	**26,436**	**29,342**	**30,363**
Residential	4,487	4,954	5,105	4,946	4,883	4,878	4,805	4,242	5,023	5,242	4,777	4,506	4,563	5,174	5,205
Commercial	2,680	3,096	3,252	3,073	3,187	3,165	3,216	2,960	3,380	3,572	3,316	3,224	3,273	3,638	3,645
Industrial	7,713	8,726	8,659	7,331	7,126	7,685	7,876	8,204	8,526	8,818	8,778	8,969	9,171	9,733	9,913
Electric Power	2,376	2,564	3,894	5,562	6,728	7,157	7,396	9,158	8,156	8,231	9,707	10,003	9,381	10,747	11,552
U.S. Territories[a]	0	0	13	24	27	28	27	49	58	61	57	64	48	48	48
Wood	**2,095**	**2,252**	**2,138**	**1,963**	**1,778**	**2,046**	**2,055**	**1,989**	**2,160**	**2,209**	**2,127**	**2,057**	**2,014**	**2,105**	**2,094**
Residential	580	520	420	430	504	541	524	438	572	579	513	442	425	517	529
Commercial	66	72	71	70	73	72	69	61	70	76	79	84	84	84	84
Industrial	1,442	1,652	1,636	1,452	1,178	1,409	1,438	1,462	1,489	1,495	1,476	1,474	1,442	1,438	1,413
Electric Power	7	8	11	11	23	25	24	28	30	60	59	57	62	66	68
U.S. Territories	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE

Note: Totals may not sum due to independent rounding.

NE (Not Estimated)

[a] U.S. Territories coal is assumed to be primarily consumed in the electric power sector, natural gas in the industrial sector, and petroleum in the transportation sector.

Table A-76: 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
U.S. Territories	1	1.5
Petroleum		
Residential	10	0.6
Commercial	10	0.6
Industrial	3	0.6
U.S. Territories	5	0.6
Natural Gas		
Residential	5	0.1
Commercial	5	0.1
Industrial	1	0.1
U.S. Territories	1	0.1
Wood		
Residential	300	4.0
Commercial	300	4.0
Industrial	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-77: 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)		4.0	NA
Solid Fuels			
Pulverized Bituminous Combination Boilers	Dry Bottom, wall fired	0.7	5.8
	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	0.7
Bituminous Fluidized Bed Combustor	Circulating Bed	1.0	61
	Bubbling Bed	1.0	61
Bituminous Cyclone Furnace		0.2	0.6
Lignite Atmospheric Fluidized Bed		NA	71
Natural Gas			
Boilers		1.0	0.3
Gas-Fired Gas Turbines >3MW		3.7	1.3
Large Dual-Fuel Engines		258	NA
Combined Cycle		3.7	1.3
Peat			
Peat Fluidized Bed Combustion	Circulating Bed	3.0	7.0
	Bubbling Bed	3.0	3.0
Biomass			
Wood/Wood Waste Boilers		11.0	7.0
Wood Recovery Boilers		1.0	1.0

NA (Not Applicable)

[a] Ibid.

Table A-78: NOx Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Electric Power	**6,045**	**5,792**	**4,829**	**3,434**	**2,552**	**2,226**	**1,893**	**1,779**	**1,666**	**1,603**	**1,419**	**1,234**	**1,049**	**1,032**	**902**
Coal	5,119	5,061	4,130	2,926	2,175	1,896	1,613	1,516	1,419	1,366	1,209	1,051	894	879	769
Fuel Oil	200	87	147	114	85	74	63	59	55	53	47	41	35	34	30
Natural gas	513	510	376	250	186	162	138	129	121	117	103	90	76	75	66
Wood	NA	NA	36	29	21	19	16	15	14	13	12	10	9	9	8
Other Fuels[a]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Internal Combustion	213	134	140	115	86	75	63	60	56	54	48	41	35	35	30
Industrial	**2,559**	**2,650**	**2,278**	**1,515**	**1,126**	**1,087**	**1,048**	**1,016**	**984**	**952**	**921**	**890**	**859**	**859**	**859**
Coal	530	541	484	342	254	245	237	229	222	215	208	201	194	194	194
Fuel Oil	240	224	166	101	75	73	70	68	66	64	62	60	57	57	57
Natural gas	877	999	710	469	348	336	324	314	305	295	285	275	266	266	266
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	119	111	109	76	57	55	53	51	50	48	46	45	43	43	43
Internal Combustion	792	774	809	527	391	378	364	353	342	331	320	309	299	299	299
Commercial	**671**	**607**	**507**	**490**	**445**	**456**	**548**	**535**	**521**	**448**	**444**	**440**	**537**	**537**	**537**
Coal	36	35	21	19	15	15	15	14	14	14	14	13	13	13	13
Fuel Oil	88	94	52	49	39	38	37	37	37	36	35	34	33	33	33
Natural gas	181	210	161	155	122	120	118	117	116	115	112	108	105	105	105
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	366	269	273	267	269	284	378	366	354	283	283	284	386	386	386
Residential	**749**	**813**	**439**	**418**	**329**	**324**	**318**	**315**	**312**	**310**	**301**	**292**	**283**	**283**	**283**
Coal[b]	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
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	42	44	21	20	16	16	16	15	15	15	15	14	14	14	14
Other Fuels[a]	707	769	417	398	313	308	302	300	297	295	286	278	269	269	269
Total	**10,023**	**9,862**	**8,053**	**5,858**	**4,452**	**4,092**	**3,807**	**3,645**	**3,483**	**3,313**	**3,084**	**2,856**	**2,728**	**2,711**	**2,581**

Note: Totals may not sum due to independent rounding.

NA (Not Applicable)

[a] Other Fuels include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2019).

[b] Residential coal, fuel oil, and natural gas emissions are included in the Other Fuels category (EPA 2019).

Table A-79: CO Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Electric Power	**329**	**337**	**439**	**582**	**676**	**693**	**710**	**694**	**678**	**661**	**618**	**575**	**532**	**532**	**532**
Coal	213	227	221	292	339	347	356	348	340	331	310	288	267	267	267
Fuel Oil	18	9	27	37	43	44	45	44	43	42	39	36	34	34	34
Natural gas	46	49	96	122	142	145	149	146	142	139	130	121	112	112	112
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	31	43	50	51	52	51	50	48	45	42	39	39	39
Internal Combustion	52	52	63	89	103	106	108	106	104	101	94	88	81	81	81
Industrial	**797**	**958**	**1,106**	**1,045**	**834**	**853**	**872**	**861**	**851**	**840**	**806**	**771**	**737**	**737**	**737**
Coal	95	88	118	115	92	94	96	95	94	93	89	85	81	81	81
Fuel Oil	67	64	48	42	33	34	35	34	34	33	32	31	29	29	29
Natural gas	205	313	355	336	268	274	281	277	274	270	259	248	237	237	237
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	253	270	300	295	236	241	247	244	241	238	228	218	208	208	208
Internal Combustion	177	222	285	257	205	209	214	212	209	206	198	189	181	181	181
Commercial	**205**	**211**	**151**	**166**	**138**	**140**	**142**	**134**	**127**	**120**	**124**	**128**	**133**	**133**	**133**
Coal	13	14	14	14	12	12	12	12	11	10	11	11	12	12	12
Fuel Oil	16	17	17	19	16	16	16	15	14	13	14	14	15	15	15
Natural gas	40	49	83	91	76	77	78	74	70	66	68	71	73	73	73
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	136	132	36	41	35	35	35	34	32	30	31	32	33	33	33
Residential	**3,668**	**3,877**	**2,644**	**2,856**	**2,387**	**2,416**	**2,446**	**2,319**	**2,192**	**2,065**	**2,140**	**2,215**	**2,291**	**2,291**	**2,291**
Coal[b]	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
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	3,430	3,629	2,416	2,615	2,185	2,212	2,239	2,123	2,007	1,890	1,959	2,028	2,097	2,097	2,097
Other Fuels[a]	238	248	228	241	202	204	207	196	185	174	181	187	193	193	193
Total	**5,000**	**5,383**	**4,340**	**4,648**	**4,036**	**4,103**	**4,170**	**4,009**	**3,847**	**3,686**	**3,688**	**3,690**	**3,692**	**3,692**	**3,692**

Note: Totals may not sum due to independent rounding.

NA (Not Applicable)

[a] Other Fuels include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2019).

[b] Residential coal, fuel oil, and natural gas emissions are included in the Other Fuels category (EPA 2019).

Table A-80: NMVOC Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Electric Power	**43**	**40**	**56**	**44**	**39**	**38**	**37**	**36**	**35**	**34**	**33**	**31**	**29**	**29**	**29**
Coal	24	26	27	21	18	18	18	17	17	16	16	15	14	14	14
Fuel Oil	5	2	4	3	3	3	3	3	3	3	3	2	2	2	2
Natural Gas	2	2	12	10	9	8	8	8	8	8	7	7	6	6	6
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	2	1	1	1	1	1	1	1	1	1	1	1	1
Internal Combustion	11	9	11	8	7	7	7	7	7	7	6	6	6	6	6
Industrial	**165**	**187**	**157**	**120**	**99**	**100**	**101**	**101**	**100**	**99**	**100**	**101**	**101**	**101**	**101**
Coal	7	5	9	8	6	7	7	7	7	7	7	7	7	7	7
Fuel Oil	11	11	9	6	5	5	5	5	5	5	5	5	5	5	5
Natural Gas	52	66	53	41	33	34	34	34	34	34	34	34	34	34	34
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	46	45	27	22	18	18	19	19	18	18	18	19	19	19	19
Internal Combustion	49	60	58	43	35	36	36	36	36	35	36	36	36	36	36
Commercial	**18**	**21**	**28**	**33**	**38**	**40**	**42**	**40**	**39**	**35**	**36**	**36**	**47**	**47**	**47**
Coal	1	1	1	1	+	+	+	+	+	+	+	+	+	+	+
Fuel Oil	3	3	4	2	2	2	2	2	2	1	1	1	1	1	1
Natural Gas	7	10	14	9	7	7	7	7	6	6	6	6	6	6	6
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	8	8	9	22	29	31	32	31	31	28	28	28	40	40	40
Residential	**686**	**725**	**837**	**518**	**378**	**399**	**419**	**389**	**358**	**327**	**324**	**322**	**319**	**319**	**319**
Coal[b]	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
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	651	688	809	502	366	386	406	376	346	317	314	311	308	308	308
Other Fuels[a]	35	37	27	17	12	13	14	13	12	11	11	10	10	10	10
Total	**912**	**973**	**1,077**	**716**	**553**	**576**	**599**	**566**	**532**	**497**	**493**	**489**	**496**	**496**	**496**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.5 kt.
NA (Not Applicable)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2019).
[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2019).

References

EIA (2020) *Monthly Energy Review*, November 2020, Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2020/11).

EIA (2017) *International Energy Statistics 1980-2016*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: <https://www.eia.gov/beta/international/>.

EPA (2020a) Acid Rain Program Dataset 1996-2019. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2020b) "Criteria pollutants National Tier 1 for 1970 – 2019." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, April 2020 Available online at <https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data>.

EPA (2019) *MOtor Vehicle Emissions Simulator (MOVES) 2014b*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: <http://www.epa.gov/otaq/models/moves/index.htm>.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data. Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. December 22, 2003.

EPA (1997) Compilation of Air Pollutant Emission Factors, AP-42. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

FHWA (1996 through 2019) Highway Statistics. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report FHWA-PL-96-023-annual. Obtained from Tiffany Presmy at FHWA.

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.

Jacobs, G. (2010) Personal communication. Gwendolyn Jacobs, Energy Information Administration and Rubaab Bhangu, ICF International. U.S. Territories Fossil Fuel Consumption. Unpublished. U.S. Energy Information Administration. Washington, D.C.

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

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 2020a and EIA 2019d) 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 2020), 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 2019),[46] and are based on federal and state fuel tax records. These fuel consumption estimates were then combined with estimates of fuel shares by vehicle type from DOE's Transportation Energy Data Book Annex Tables A.1 through A.6 (DOE 1993 through 2017) 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 2019). 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.

In the case of motor gasoline, estimates of fuel use by recreational boats come from the Nonroad component of EPA's MOVES2014b model (EPA 2019a), 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 exceeded the EIA estimate for total gasoline consumption of all sectors. Similarly, to ensure consistency with EIA's total

[46] 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 1990 through 2008 Inventory and apply to the 2007 to 2018 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.

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 2019) for Class I railroads, the American Public Transportation Association (APTA 2007 through 2018 and APTA 2006) and Gaffney (2007) for commuter rail, the Upper Great Plains Transportation Institute (Benson 2002 through 2004), Whorton (2006 through 2014), and Railinc (2014 through 2019) for Class II and III railroads, and the U.S. Department of Energy's *Transportation Energy Data Book* (DOE 1993 through 2017) for passenger rail. Class II and III railroad diesel consumption is estimated by applying the historical average fuel usage per carload factor to yearly carloads.

Estimates of diesel fuel consumption from ships and boats were taken from EIA's *Fuel Oil and Kerosene Sales* (1991 through 2019).

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 (2020) for domestic and international commercial aircraft, and DLA Energy (2020) 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 2020), 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 Section 3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels under the methodology for Estimating CO_2 from Fossil Combustion, and in Section 3.11 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 2019a).

Table A-81 displays estimated fuel consumption by fuel and vehicle type. Table A-82 displays estimated energy consumption by fuel and vehicle type. The values in both 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 fuel 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 2016. Biodiesel fuel volumes were removed from diesel fuel consumption volumes for years 2001 through 2016, 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 2009 to 2019 biodiesel and renewable diesel fuel consumption estimates from EIA (2020a) 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 ethanol blended into motor gasoline, ethanol energy consumption data sourced from MER *Table 10.2b - Renewable Energy Consumption: Industrial and Transportation Sectors* (EIA 2019a) 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-83.[47]

[47] 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-83. 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-81Table A-81 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-81: Fuel Consumption by Fuel and Vehicle Type (million gallons unless otherwise specified)

Fuel/Vehicle Type	1990	1995	2000	2009 [a]	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Motor Gasoline[b,c]	**107,651**	**115,194**	**125,690**	**123,975**	**123,448**	**120,865**	**120,456**	**120,659**	**121,472**	**124,520**	**127,512**	**127,147**	**124,886**	**125,903**
Passenger Cars	67,846	66,171	70,637	83,793	83,458	82,939	82,833	82,910	82,325	85,192	86,720	86,671	85,236	85,935
Light-Duty Trucks	33,745	43,209	49,225	33,423	33,354	31,734	31,410	31,475	32,938	32,989	34,299	33,877	33,115	33,387
Motorcycles	189	195	203	467	412	402	461	440	425	426	444	435	427	431
Buses	38	41	42	84	82	80	92	96	101	102	102	111	116	117
Medium- and Heavy-Duty Trucks	4,230	3,965	3,971	4,791	4,786	4,400	4,377	4,479	4,486	4,575	4,704	4,802	4,775	4,814
Recreational Boats[d]	1,604	1,613	1,612	1,417	1,355	1,310	1,282	1,259	1,196	1,236	1,244	1,251	1,218	1,221
Distillate Fuel Oil (Diesel Fuel)[b,c]	**25,631**	**31,603**	**39,243**	**39,943**	**41,251**	**42,275**	**41,554**	**42,608**	**43,256**	**44,613**	**44,787**	**45,457**	**46,540**	**46,837**
Passenger Cars	771	765	356	355	365	399	396	398	400	416	420	418	423	428
Light-Duty Trucks	1,119	1,452	1,961	1,182	1,220	1,277	1,256	1,263	1,339	1,348	1,388	1,366	1,373	1,391
Buses	781	851	997	1,337	1,319	1,419	1,497	1,522	1,628	1,661	1,642	1,738	1,868	1,891
Medium- and Heavy-Duty Trucks	18,574	23,240	30,181	32,421	33,499	33,855	33,482	34,375	34,878	35,765	36,416	37,042	37,875	38,351
Recreational Boats	267	269	270	271	263	258	252	251	245	258	267	270	276	282
Ships and Non-Recreational Boats	658	1,164	1,372	841	807	1,092	832	857	720	1,285	1,078	977	910	897
Rail[e]	3,461	3,863	4,106	3,535	3,778	3,975	3,839	3,942	4,046	3,879	3,576	3,645	3,815	3,598
Jet Fuel[f]	**19,186**	**17,991**	**20,002**	**15,809**	**15,537**	**15,036**	**14,705**	**15,088**	**15,217**	**16,162**	**17,028**	**17,616**	**17,674**	**18,229**
Commercial Aircraft	11,569	12,136	14,672	12,588	11,931	12,067	11,932	12,031	12,131	12,534	12,674	13,475	13,650	13,650
General Aviation Aircraft	4,034	3,360	3,163	1,787	2,322	1,895	1,659	2,033	1,786	2,361	3,184	2,984	2,910	3,462
Military Aircraft	3,583	2,495	2,167	1,434	1,283	1,074	1,114	1,024	1,300	1,267	1,170	1,156	1,114	1,118
Aviation Gasoline[f]	**374**	**329**	**302**	221	225	225	209	186	181	176	170	174	186	195
General Aviation Aircraft	374	329	302	221	225	225	209	186	181	176	170	174	186	195
Residual Fuel Oil[f, g]	**2,006**	**2,587**	**2,963**	**1,241**	**1,818**	**1,723**	**1,410**	**1,345**	**517**	**378**	**1,152**	**1,465**	**1,246**	**1,309**
Ships and Boats	2,006	2,587	2,963	1,241	1,818	1,723	1,410	1,345	517	378	1,152	1,465	1,246	1,309
Natural Gas[f] (trillion cubic feet)	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**0.8**	**0.9**	**0.7**	**0.7**	**0.7**	**0.8**	**0.9**	**1.0**
Passenger Cars	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Buses	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Pipelines	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.7	0.7	0.7	0.8	0.9	1.0
LPG[f]	**251**	**194**	**130**	**307**	**81**	**79**	**78**	**76**	**78**	**72**	**78**	**78**	**84**	**82**
Passenger Cars	1	0.9	0.6	4	0	0	0	0	1	4	3	0	0	0
Light-Duty Trucks	34	26	18	76	19	15	8	8	17	11	10	11	13	13
Medium- and Heavy-Duty Trucks	199	154	103	174	48	55	60	57	51	49	53	53	55	52
Buses	16	13	8	52	14	9	10	10	9	8	12	14	15	17
Electricity[h,i]	**4,751**	**4,975**	**5,382**	**7,768**	**7,750**	**7,786**	**7,564**	**8,150**	**8,633**	**8,880**	**9,243**	**9,900**	**11,058**	**12,141**
Passenger Cars	+	+	+	+	4	14	31	68	113	151	190	238	338	415
Light-Duty Trucks	+	+	+	+	+	0	1	1	2	3	17	32	51	64

Buses	+	+	+	+	2	2	1	1	1	1	2	5	8	9
Rail	4,751	4,975	5,382	7,768	7,745	7,770	7,531	8,080	8,517	8,725	9,034	9,624	10,661	11,654

+ Does not exceed 0.05 trillion cubic feet

[a] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007 to 2018 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. Table VM-1 for 2019 has not been published yet. Therefore, 2018 data has been proxied for 2019.

[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.1 in the EIA Monthly 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 2019). Data from Table VM-1 is used to estimate the share of consumption between each on-road vehicle class. 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 2017). TEDB data for 2018 has not been published yet, therefore 2017 data are 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 III diesel consumption data for 2014-2019 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[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 (2019a). In previous 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 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the 2016 Inventory and apply to the 1990 through 2019 time period.

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

[h] Million kilowatt-hours

[i] Electricity consumption by passenger cars, light-duty trucks (SUVs), and buses is based on plug-in electric vehicle sales data and engine efficiencies, as outlined in Browning (2018a). In prior Inventory years, CO_2 emissions from electric vehicle charging were allocated to the residential and commercial sectors. They are now allocated to the transportation sector. These changes were first incorporated in the 2017 Inventory and applied to the 2010 through 2018 time period.

Table A-82: Energy Consumption by Fuel and Vehicle Type (TBtu)

Fuel/Vehicle Type	1990	1995	2000	2009[a]	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Motor Gasoline[b,c]	**13,464**	**14,407**	**15,720**	**15,414**	**15,349**	**15,028**	**14,977**	**15,002**	**15,361**	**15,482**	**15,854**	**15,809**	**15,528**	**15,654**
Passenger Cars	8,486	8,276	8,835	10,418	10,377	10,312	10,299	10,309	10,574	10,592	10,782	10,776	10,598	10,685
Light-Duty Trucks	4,221	5,404	6,157	4,156	4,147	3,946	3,905	3,913	4,231	4,102	4,264	4,212	4,117	4,151
Motorcycles	24	24	25	58	51	50	57	55	55	53	55	54	53	54
Buses	5	5	5	10	10	10	11	12	13	13	13	14	14	14
Medium- and Heavy-Duty Trucks	529	496	497	596	595	547	544	557	576	569	585	597	594	599
Recreational Boats[d]	201	202	202	176	168	163	159	157	(+)	154	155	156	151	152
Distillate Fuel Oil (Diesel Fuel)[b,c]	**3,555**	**4,379**	**5,437**	**5,498**	**5,675**	**5,814**	**5,713**	**5,858**	**5,946**	**6,132**	**6,156**	**6,247**	**6,396**	**6,436**
Passenger Cars	107	106	49	49	50	55	54	55	55	57	58	57	58	59
Light-Duty Trucks	155	201	272	163	168	176	173	174	184	185	191	188	189	191
Buses	108	118	138	184	181	195	206	209	224	228	226	239	257	260
Medium- and Heavy-Duty Trucks	2,576	3,220	4,182	4,463	4,608	4,656	4,603	4,726	4,794	4,916	5,005	5,091	5,205	5,270

Recreational Boats	37	37	37	37	36	36	35	34	34	35	37	37	38	39
Ships and Non-Recreational Boats	91	161	190	116	111	150	114	118	99	177	148	134	125	123
Rail[e]	480	535	569	487	520	547	528	542	556	533	492	501	524	494
Jet Fuel[f]	**2,590**	**2,429**	**2,700**	**2,134**	**2,097**	**2,030**	**1,985**	**2,037**	**2,054**	**2,182**	**2,299**	**2,378**	**2,386**	**2,461**
Commercial Aircraft	1,562	1,638	1,981	1,699	1,611	1,629	1,611	1,624	1,638	1,692	1,711	1,819	1,843	1,843
General Aviation Aircraft	545	454	427	241	314	256	224	274	241	319	430	403	393	467
Military Aircraft	484	337	293	194	173	145	150	138	175	171	158	156	150	151
Aviation Gasoline[f]	**45**	**40**	**36**	**27**	**27**	**27**	**25**	**22**	**22**	**21**	**20**	**21**	22	23
General Aviation Aircraft	45	40	36	27	27	27	25	22	22	21	20	21	22	23
Residual Fuel Oil[f,g]	**300**	**387**	**443**	**186**	**272**	**258**	**211**	**201**	**77**	**57**	**172**	**219**	**186**	**196**
Ships and Boats	300	387	443	186	272	258	211	201	77	57	172	219	186	196
Natural Gas[f]	**679**	**724**	**672**	**715**	**719**	**734**	**780**	**887**	**760**	**745**	**757**	**799**	**962**	**1,035**
Passenger Cars	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Light-Duty Trucks	+	+	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Medium- and Heavy-Duty Trucks	+	+	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.6	0.7	0.7	0.8	0.5
Buses	+	+	3	15	15	15	15	15	15	17	16	18	18	18
Pipelines	679	724	668	699	703	718	765	872	744	727	740	780	943	1,016
LPG[f]	**23**	**18**	**12**	**28**	**7**	**7**	**7**	**7**	**7**	**7**	**7**	**7**	**8**	**8**
Passenger Cars	0.1	0.1	0.1	0.4	+	+	+	+	0.1	0	0	+	+	+
Light-Duty Trucks	3	2	2	7	2	1	1	1	2	1	1	1	1	1
Medium- and Heavy-Duty Trucks	18	14	9	16	4	5	6	5	5	4	5	5	5	5
Buses	1	1	0.8	5	1	1	1	1	1	1	1	1	1	2
Electricity[h]	**3**	**3**	**3**	**4**	**5**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**5**	**5**
Passenger Cars	+	+	+	+	+	+	0.1	0.2	0.4	0.5	0.6	0.8	1.2	1.4
Light-Duty Trucks	+	+	+	+	+	+	+	+	+	+	0.1	0.1	0.2	0.2
Buses	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Rail	3	3	3	4	4	4	4	4	4	4	3	3	3	3
Total	**20,659**	**22,387**	**25,025**	**24,006**	**24,151**	**23,901**	**23,702**	**24,019**	**23,973**	**24,629**	**25,270**	**25,484**	**25,493**	**25,817**

+ Does not exceed 0.05 TBtu

[a] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007 to 2018 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. Table VM-1 for 2019 has not been published yet. Therefore, 2018 data has been proxied for 2019.

[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 2019). Data from Table VM-1 is used to estimate the share of consumption between each on-road vehicle class. 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 2017). TEDB data for 2018 has not been published yet, therefore 2017 data are 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 III diesel consumption data for 2014-2019 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[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 (2019a). In previous 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 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the 2016 Inventory and apply to the 1990–2018 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 (2019b).

[h] Electricity consumption by passenger cars, light-duty trucks (SUVs), and buses is based on plug-in electric vehicle sales data and engine efficiencies, as outlined in Browning (2018a). In Inventory years prior to 2017, CO_2 emissions from electric vehicle charging were allocated to the residential and commercial sectors. They are now allocated to the transportation sector. These changes were first incorporated in the 2017 Inventory and apply to the 2010 through 2019 time period.

Table A-83: Transportation Sector Biofuel Consumption by Fuel Type (million gallons)

Fuel Type	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Ethanol	699	1,302	1,562	10,332	12,194	12,347	12,371	12,541	12,748	13,205	13,694	13,844	14,007	14,120
Biodiesel	NA	NA	NA	322	260	886	899	1,429	1,417	1,494	2,085	1,985	1,904	1,904

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,[48] buses, and motorcycles) were obtained from the FHWA's *Highway Statistics* (FHWA 1996 through 2019).[49] 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. *Highway Statistics* Table VM-1 has not been published yet and therefore, is proxied using 2018 data. VMT from *Highway Statistics* Table VM-1 (FHWA 1996 through 2019) 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 2018). 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.[50] The resulting national VMT estimates for gasoline and diesel on-road vehicles are presented in Table A-84 and Table A-85, 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 2019 in

[48] 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.

[49] 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 1990 through 2008 Inventory and apply to the 2007 to 2019 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.

[50] 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.

Table A-86. 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 MOVES2014b model for years 2009 forward (EPA 2018a).[51] Age-specific vehicle mileage accumulations were also obtained from EPA's MOVES2014b model (EPA 2018a).[52]

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-92 through Table A-95. 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 EPA Tier 3 refer to U.S. emission regulations and California Air Resources Board (CARB) LEV, CARB LEVII, and CARB LEVII refer to California emissions regulations, rather than control technologies; however, each does correspond to particular combinations of control technologies and engine design. EPA Tier 2 and Tier 3 and its predecessors EPA Tier 1 and Tier 0 as well as CARB LEV, LEVII, and LEVIII apply to vehicles equipped with three-way catalysts. The introduction of "early three-way catalysts," and "advanced three-way catalysts," as described in the *Revised 1996 IPCC Guidelines*, roughly correspond to the introduction of EPA Tier 0 and EPA Tier 1 regulations (EPA 1998).[53] 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). EPA Tier 3 regulations affect vehicles produced starting in 2017 and are fully phased in by 2025. ARB LEVII regulations affect California vehicles produced starting in 2004 while ARB LEVIII affect California vehicles produced starting in 2015.

Emission 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 2019 were determined using confidential engine family sales data submitted to EPA (EPA 2019c). Vehicle classes and emission standard tiers to which each engine family was certified were taken from annual certification test results and data (EPA 2018d). This information was used to determine the fraction of sales of each class of vehicle that met EPA Tier 0, EPA Tier 1, EPA Tier 2, EPA Tier 3 and CARB LEV, CARB LEVII and CARB LEVII 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. EPA Tier 3 began initial phase-in by 2017 and CARB LEV III standards began initial phase-in by 2015.

Step 3: Determine CH_4 and N_2O Emission Factors by Vehicle, Fuel, and Control Technology Type

Methane and N_2O emission factors (in grams of CH_4 and N_2O per mile) for gasoline and diesel on-road vehicles utilizing EPA Tier 2, EPA Tier 3, and CARB LEV, LEVII, and LEVIII technologies were developed by Browning (2019). These emission factors were calculated based upon annual certification data submitted to EPA by vehicle manufacturers. Emission factors for earlier standards and technologies were developed by ICF (2004) based on EPA, CARB and Environment and Climate Change Canada laboratory test results of different vehicle and control technology types. The EPA, CARB and Environment and Climate Change Canada tests were designed following the Federal Test Procedure (FTP).The procedure 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 driving Segment 2 was used to define running emissions. Running emissions weresubtracted 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.

[51] Age distributions were held constant for the period 1990 to 1998, and reflect a 25-year vehicle age span. EPA (2019b) provides a variable age distribution and 31-year vehicle age span beginning in year 1999.

[52] The updated vehicle distribution and mileage accumulation rates by vintage obtained from the MOVES2014b model resulted in a decrease in emissions due to more miles driven by newer light-duty gasoline vehicles.

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

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 "Updated Methodology for Estimating CH_4 and N_2O Emissions from Highway Vehicle Alternative Fuel Vehicles" (Browning 2017). 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.[54] 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 2015. 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, 2018 and 2019, 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 five 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 Hybridcars.com from 2010 to 2018 (Hybridcars.com, 2019). For 2019, EV and PHEV sales were taken from Wards Intelligence U.S. Light Vehicle Sales Report (Ward Intelligence, 2020). EVs were divided into cars and trucks using confidential engine family sales data submitted to EPA (EPA 2019c). Fuel use per vehicle 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 GREET2019 model (ANL 2019). 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 (2017). VMT estimates for AFVs by vehicle category (passenger car, light-duty truck, medium-duty and heavy-duty vehicles) are shown in

[54] 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.

Table A-86, while more detailed estimates of VMT by control technology are shown in Table A-87.

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) were calculated using Argonne National Laboratory's GREET model (ANL 2019) and are reported in Browning (2018). These emission factors are shown in Table A-97 and Table A-98.

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-91. Consumption data for ships and boats (i.e., vessel bunkering) were obtained from DHS (2008) and EIA (1991 through 2019) for distillate fuel, and DHS (2008) and EIA (2019a) for residual fuel; marine transport fuel consumption data for U.S. Territories (EIA 2017) were added to domestic consumption, and this total was reduced by the amount of fuel used for international bunkers.[55] Gasoline consumption by recreational boats was obtained from the NONROAD component of EPA's MOVES2014b model (EPA 2019a). Annual diesel consumption for Class I rail was obtained from the Association of American Railroads (AAR 2008 through 2019), diesel consumption from commuter rail was obtained from APTA (2007 through 2019) and Gaffney (2007), and consumption by Class II and III rail was provided by Benson (2002 through 2004) and Whorton (2006 through 2014).[56] It is estimated that an average of 41 gallons of diesel consumption per Class II and III carload originated from 2000-2009 based on carload data reported from AAR (2008 through 2019) and fuel consumption data provided by Whorton, D. (2006 through 2014). Class II and Class III diesel consumption for 2014-2019 is estimated by multiplying this average historical fuel usage per carload factor by the number of shortline carloads originated each year (RailInc 2014 through 2019). Diesel consumption by commuter and intercity rail was obtained from DOE (1993 through 2018). Data on the consumption of jet fuel and aviation gasoline in aircraft were obtained from EIA (2019a) and FAA (2019), 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 (DLA 2019 and FAA 2019). Pipeline fuel consumption was obtained from EIA (2007 through 2019) (note: pipelines are a transportation source but are stationary, not mobile sources). Data on fuel consumption by non-transportation mobile sources were obtained from the NONROAD component of EPA's MOVES2014b model (EPA 2019a) for gasoline and diesel powered equipment, and from FHWA (1996 through 2019) for gasoline consumption by off-road trucks used in the agriculture, industrial, commercial, and construction sectors.[57] Specifically, this Inventory uses FHWA's Agriculture, Construction, and Commercial/Industrial MF-24 fuel volumes along with the MOVES NONROAD model gasoline volumes to estimate non-road mobile source CH_4 and N_2O emissions for these categories. For agriculture, the MF-24 gasoline volume is used directly because it includes both off-road trucks and equipment. For construction and commercial/industrial gasoline estimates, the 2014 and older MF-24 volumes represented off-road trucks only; therefore, the MOVES NONROAD gasoline volumes for construction and commercial/industrial are added to the respective categories in the Inventory. Beginning in 2015, this addition is no longer necessary since the FHWA updated its method for estimating on-road and non-road gasoline consumption. Among the method updates, FHWA now incorporates MOVES NONROAD equipment gasoline volumes in the construction and commercial/industrial categories.

Emissions of CH_4 and N_2O from non-road mobile sources were calculated using the updated 2006 IPCC Tier 3 guidance and estimates of activity from EPA's MOVES2014b model. CH_4 and N_2O emission factors were calculated from

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

[56] Diesel consumption from Class II and Class III railroad were unavailable for 2014-2017. Diesel consumption data for 2014-2018 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[57] "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.

engine certification data by engine and fuel type and weighted by activity estimates calculated by MOVES2014b to determine overall emission factors in grams per kg of fuel consumed by fuel type.

Estimates of NO_x, CO, and NMVOC Emissions

The emission estimates of NO_x, CO, and NMVOCs from mobile combustion (transportation) were obtained from EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2019b). 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-101 through Table A-103 provides complete emission estimates for 1990 through 2019.

Table A-84: Vehicle Miles Traveled for Gasoline On-Road Vehicles (billion miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles[a]	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	24.5	9.9
1997	1,489.0	821.7	24.1	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	906.0	24.0	9.6
2002	1,650.0	926.8	23.9	9.6
2003	1,663.6	944.1	24.3	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[b]	2,093.7	562.8	34.2	21.4
2008	2,014.5	580.9	35.0	20.8
2009	2,005.4	592.5	32.5	20.8
2010	2,015.4	597.4	32.3	18.5
2011	2,035.7	579.6	30.2	18.5
2012	2,051.8	576.8	30.5	21.4
2013	2,062.5	578.7	31.2	20.4
2014	2,059.3	612.4	31.7	20.0
2015	2,133.7	606.1	31.8	19.6
2016	2,176.3	630.8	32.7	20.4
2017	2,203.9	629.1	33.8	20.1
2018	2,212.7	636.4	34.7	20.1
2019	2,241.4	643.4	35.1	20.3

[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 2018 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. Table VM-1 for 2019 has not been published yet. Therefore, 2018 data has been proxied for 2019.
Notes: 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 1990 through 2014 Inventory and apply to the 1990 through 2019 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes. Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2019). 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 2018). TEDB data for 2018 has not been published yet, therefore 2017 data are used as a proxy.
Source: Derived from FHWA (1996 through 2019), DOE (1990 through 2018), Browning (2018a), and Browning (2017).

Table A-85: 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	129.5
1992	16.5	23.4	133.7
1993	17.9	24.7	140.7
1994	18.3	25.3	150.9
1995	17.3	26.9	159.1
1996	14.7	27.8	164.7
1997	13.5	29.0	173.8
1998	12.4	30.5	178.9
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	196.8
2003	8.4	39.7	199.7
2004	8.5	41.4	202.1
2005	8.5	41.9	203.4
2006	8.4	43.5	202.2
2007[b]	10.5	23.4	281.7
2008	10.1	24.2	288.0
2009	10.0	24.7	267.5
2010	10.1	24.9	265.7
2011	10.1	23.7	245.2
2012	10.2	23.5	247.5
2013	10.1	23.2	249.9
2014	10.1	24.6	254.3
2015	10.4	24.3	254.6
2016	10.4	24.9	258.3
2017	10.6	24.9	268.2
2018	10.6	25.3	276.1
2019	11.3	27.0	291.0

[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 2018 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. Table VM-1 for 2019 has not been published yet. Therefore, 2018 data has been proxied for 2019.
Note: Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2018). 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 2018). TEDB data for 2018 has not been published yet, therefore 2017 data are used as a proxy.
Source: Derived from FHWA (1996 through 2019), DOE (1993 through 2018), and Browning (2017), Browning (2018a).

Table A-86: 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	0.4
1991	0.0	0.1	0.4
1992	0.0	0.1	0.3
1993	0.0	0.1	0.4
1994	0.1	0.1	0.4
1995	0.1	0.1	0.4
1996	0.1	0.1	0.4
1997	0.1	0.1	0.4
1998	0.1	0.1	0.4
1999	0.1	0.1	0.4
2000	0.1	0.2	0.5
2001	0.1	0.2	0.6
2002	0.2	0.3	0.7
2003	0.1	0.3	0.8
2004	0.2	0.2	0.9
2005	0.2	0.3	1.3
2006	0.2	0.4	2.3
2007	0.2	0.4	2.8
2008	0.2	0.4	2.5
2009	0.2	0.4	2.6
2010	0.2	0.4	2.2
2011	0.5	0.9	5.9
2012	0.9	1.0	6.0
2013	1.8	1.4	9.1
2014	2.7	1.4	9.1
2015	3.7	1.5	9.7
2016	4.9	2.3	13.3
2017	6.2	2.6	12.8
2018	9.1	3.0	12.4
2019	11.7	3.3	13.6

[a] Heavy Duty-Vehicles includes medium-duty trucks, heavy-duty trucks, and buses.
Note: In 2017, 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 incorporated into this year's Inventory and apply to the 2005 to 2019 time period.
Source: Derived from Browning (2017), Browning (2018a), and EIA (2019h).

Table A-87: Detailed Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (10^6 Miles)

Vehicle Type/Year	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Light-Duty Cars	**3.7**	**60.2**	**105.8**	**227.6**	**232.6**	**524.5**	**911.3**	**1,801.3**	**2,727.2**	**3,727.4**	**4,929.8**	**6,208.7**	**9,056.1**	**11,729.6**
Methanol-Flex Fuel ICE	+	45.9	14.3	+	+	+	+	+	+	+	+	+	+	+
Ethanol-Flex Fuel ICE	+	0.3	19.6	90.3	114.8	111.2	139.8	163.0	127.2	110.4	124.5	87.0	85.6	70.5
CNG ICE	+	0.1	5.2	10.8	10.1	10.8	11.1	12.1	11.6	11.7	13.7	12.9	14.0	14.0
CNG Bi-fuel	+	0.2	16.9	9.3	7.4	6.6	4.1	3.2	2.3	1.7	1.4	1.5	1.8	2.2
LPG ICE	1.1	1.1	1.1	1.5	+	0.1	0.1	0.3	3.1	7.6	6.1	0.9	0.5	0.2
LPG Bi-fuel	2.7	2.8	2.8	1.7	1.2	0.3	0.2	0.2	0.1	0.1	0.1	+	+	+
Biodiesel (BD100)	+	+	1.1	41.5	34.3	127.1	156.6	274.1	298.0	337.5	501.3	512.1	521.2	511.8
NEVs	+	9.4	43.6	71.2	61.5	102.9	98.9	103.8	113.2	124.3	83.8	89.9	86.4	80.2
Electric Vehicle	+	0.3	1.3	1.2	1.3	113.8	263.5	768.6	1,438.8	2,200.3	2,921.4	3,810.8	6,097.1	8,488.8
SI PHEV - Electricity	+	+	+	+	2.0	51.7	237.0	476.0	732.7	933.7	1,276.5	1,692.0	2,247.5	2,559.8
Fuel Cell Hydrogen	+	+	+	+	+	0.1	0.1	0.1	0.1	0.1	1.1	1.4	2.0	2.0
Light-Duty Trucks	**72.7**	**87.7**	**168.2**	**390.5**	**362.3**	**873.1**	**957.3**	**1,421.4**	**1,430.5**	**1,477.1**	**2,258.4**	**2,646.0**	**3,007.5**	**3,335.3**
Ethanol-Flex Fuel ICE	+	0.3	21.9	96.4	121.7	135.4	180.1	213.6	208.8	218.2	279.1	418.4	411.9	495.8
CNG ICE	+	0.1	5.3	9.1	8.0	8.6	8.9	8.7	7.6	6.6	5.8	8.9	6.5	7.7
CNG Bi-fuel	+	0.4	44.3	20.4	19.0	18.2	14.8	16.1	19.3	20.3	26.3	24.3	28.9	29.4
LPG ICE	21.0	24.9	25.9	12.1	9.7	9.6	5.9	6.3	7.3	7.5	7.3	7.9	8.4	7.9
LPG Bi-fuel	51.7	61.2	63.6	26.8	23.8	12.4	4.9	5.9	21.8	8.7	6.5	7.9	9.0	8.1
LNG	+	+	0.1	0.2	+	+	+	+	+	+	+	0.1	0.1	0.1
Biodiesel (BD100)	+	+	3.3	220.9	175.7	685.5	736.3	1,152.2	1,132.5	1,172.2	1,615.9	1,540.6	1,481.5	1,381.3
Electric Vehicle	+	0.8	3.8	4.6	4.3	3.1	6.2	18.4	32.5	35.0	271.8	533.4	847.9	1,102.3
SI PHEV - Electricity	+	+	+	+	+	+	+	+	0.4	8.2	45.7	104.4	213.4	302.6
Fuel Cell Hydrogen	+	+	+	+	+	0.3	0.2	0.2	0.3	0.3	+	+	+	+
Medium-Duty Trucks	**255.4**	**249.9**	**244.6**	**636.7**	**476.2**	**1,510.3**	**1,574.3**	**2,503.3**	**2,519.8**	**2,670.0**	**3,741.2**	**3,590.8**	**3,448.3**	**3,539.1**
CNG ICE	+	+	0.8	5.7	5.6	7.5	8.9	9.3	10.4	11.7	12.5	13.9	14.9	16.6
CNG Bi-fuel	+	0.1	7.8	6.6	6.3	6.1	6.8	7.1	9.5	10.2	11.3	12.3	13.9	15.1
LPG ICE	215.6	210.8	192.5	33.0	29.0	27.1	25.6	23.6	22.7	17.9	16.0	14.8	12.1	9.8
LPG Bi-fuel	39.9	39.0	35.6	6.4	7.8	7.0	9.4	10.0	12.7	9.5	11.5	12.5	12.9	13.5
LNG	+	+	+	+	+	+	+	0.1	+	0.1	0.1	0.2	0.3	0.3

Biodiesel (BD100)	+	+	7.8	585.1	427.5	1,462.6	1,523.5	2,453.2	2,464.4	2,620.7	3,689.7	3,536.9	3,394.2	3,483.8
Heavy-Duty Trucks	**104.4**	**102.0**	**115.4**	**1,323.6**	**1,103.5**	**3,663.7**	**3,666.0**	**5,795.9**	**5,771.2**	**6,133.6**	**8,613.1**	**8,268.9**	**7,977.3**	**9,150.3**
Neat Ethanol ICE	+	+	+		+	+	+	+	+	+	+	+	+	+
CNG ICE	+	+	+	2.9	3.6	5.7	9.1	12.6	15.0	20.2	23.9	11.1	7.3	7.7
LPG ICE	98.1	95.9	0.9	3.2	3.4	3.4	3.9	4.7	5.2	7.3	9.4	8.5	10.5	10.8
LPG Bi-fuel	6.3	6.2	87.5	39.9	33.0	34.7	22.5	22.2	18.0	16.8	15.4	13.6	11.5	9.1
LNG	+	+	5.6	4.1	4.3	6.3	4.9	5.2	2.2	2.1	2.1	2.1	2.0	1.7
Biodiesel (BD100)	+	+	+	1.2	1.5	1.6	1.6	1.4	1.9	2.0	1.6	1.6	1.4	1.3
Buses	**20.0**	**38.7**	**140.3**	**664.5**	**673.1**	**761.9**	**754.5**	**823.8**	**824.0**	**906.5**	**922.8**	**987.9**	**995.1**	**982.8**
Neat Methanol ICE	6.4	10.4	+	+	+	+	+	+	+	+	+	+	+	+
Neat Ethanol ICE	+	4.8	0.1	+	+	+	0.1	0.1	2.7	3.6	1.4	1.0	0.5	0.2
CNG ICE	+	1.1	100.2	560.7	584.2	614.6	606.6	627.9	627.6	705.2	654.5	723.5	734.8	741.6
LPG ICE	13.2	12.7	11.5	7.2	6.5	3.9	3.8	4.0	4.4	3.2	4.4	5.2	4.9	5.1
LNG	0.4	8.5	22.3	34.7	35.5	38.1	39.7	28.4	26.2	21.0	17.5	10.7	6.8	3.3
Biodiesel (BD100)	+	+	0.9	57.5	42.5	100.4	101.0	160.0	159.3	168.8	236.7	227.1	218.9	197.1
Electric	+	1.1	5.2	4.4	4.5	4.5	3.0	3.1	3.6	3.9	7.2	19.2	27.8	33.9
Fuel Cell Hydrogen	+	+	+	+	+	0.3	0.3	0.3	0.3	0.8	1.1	1.3	1.4	1.6
Total VMT	**456.3**	**538.6**	**774.2**	**3,242.8**	**2,847.7**	**7,333.5**	**7,863.3**	**12,345.7**	**13,272.8**	**14,914.6**	**20,465.3**	**21,702.2**	**24,484.4**	**28,737.1**

+ Does not exceed 0.05 million vehicle miles traveled

Note: Throughout the rest of this Inventory, medium-duty trucks are grouped with heavy-duty trucks; they are reported separately here because these two categories may run on a slightly different range of fuel types.

In 2017, 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 incorporated into this year's Inventory and apply to the 2005 to 2019 time period. Source: Derived from Browning (2017), Browning (2018a), and EIA (2019h).

Table A-88: Age Distribution by Vehicle/Fuel Type for On-Road Vehicles,[a] 2019

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC
0	7.0%	7.7%	6.5%	9.8%	8.0%	6.1%	7.1%
1	7.0%	7.8%	6.5%	9.8%	8.1%	6.0%	7.0%
2	7.1%	7.8%	6.4%	9.9%	8.1%	5.9%	7.0%
3	7.1%	7.8%	6.3%	9.8%	8.0%	5.8%	6.5%
4	6.8%	7.4%	6.1%	9.6%	7.6%	5.6%	5.9%
5	6.7%	6.9%	5.5%	9.3%	7.1%	5.1%	5.4%
6	6.3%	6.3%	4.9%	8.8%	6.6%	4.5%	4.8%
7	6.0%	5.8%	4.4%	8.4%	6.1%	4.1%	4.3%
8	3.7%	3.8%	2.4%	5.1%	4.0%	2.5%	3.5%
9	4.0%	3.2%	1.6%	4.8%	2.2%	1.7%	3.1%
10	3.6%	2.3%	1.4%	3.1%	1.9%	2.0%	3.2%
11	4.4%	3.7%	2.7%	0.3%	4.5%	2.9%	5.7%
12	4.7%	3.7%	2.4%	0.2%	3.8%	5.7%	5.1%
13	4.1%	3.6%	3.4%	3.3%	4.6%	4.8%	4.8%
14	3.6%	3.5%	2.6%	2.0%	3.7%	4.4%	4.2%
15	3.0%	3.2%	3.2%	1.1%	3.1%	3.0%	3.6%
16	2.7%	2.7%	2.8%	1.2%	2.6%	2.6%	3.1%
17	2.3%	2.4%	2.7%	1.1%	2.1%	2.1%	2.7%
18	1.9%	2.0%	2.2%	0.6%	2.2%	2.7%	2.3%
19	1.7%	1.8%	4.3%	0.5%	1.1%	4.1%	1.8%
20	1.2%	1.4%	4.0%	0.3%	1.5%	3.2%	1.4%
21	1.0%	1.1%	1.7%	0.2%	0.5%	2.2%	1.2%
22	0.8%	0.9%	3.0%	0.1%	0.7%	2.0%	1.1%
23	0.7%	0.6%	1.8%	0.1%	0.5%	1.8%	1.0%
24	0.6%	0.6%	2.4%	0.1%	0.4%	2.2%	0.7%
25	0.5%	0.5%	1.9%	0.0%	0.2%	1.6%	0.9%
26	0.4%	0.4%	1.5%	0.0%	0.2%	1.2%	0.7%
27	0.3%	0.3%	1.1%	0.0%	0.2%	0.8%	0.6%
28	0.3%	0.2%	0.9%	0.1%	0.1%	0.8%	0.5%
29	0.2%	0.2%	1.2%	0.0%	0.1%	1.0%	0.4%
30	0.3%	0.2%	2.1%	0.0%	0.1%	1.6%	0.3%
Total	100.0%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

[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: This year's Inventory includes updated vehicle population data based on the MOVES2014b Model.

Source: EPA (2019a).

Table A-89: Annual Average Vehicle Mileage Accumulation per Vehicle [a] (miles)

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC[b]
0	13,414	15,161	17,663	13,414	15,161	41,952	7,720
1	13,159	14,876	17,666	13,159	14,876	41,527	4,122
2	12,884	14,555	17,670	12,884	14,555	41,008	3,119
3	12,590	14,203	17,669	12,590	14,203	40,964	2,578
4	12,280	13,824	16,724	12,280	13,824	38,890	2,231
5	11,954	13,421	15,782	11,954	13,421	36,611	1,984
6	11,617	12,998	14,839	11,617	12,998	34,435	1,799
7	11,269	12,558	13,897	11,269	12,558	33,049	1,652
8	10,913	12,106	12,074	10,913	12,106	37,287	1,528
9	10,550	11,647	10,309	10,550	11,647	36,330	1,428
10	10,183	11,181	9,749	10,183	11,181	37,001	1,343
11	9,815	10,716	9,890	9,815	10,716	24,963	1,266

12	9,446	10,253	8,122	9,446	10,254	33,019	1,204
13	9,080	9,799	7,911	9,080	9,799	27,000	1,142
14	8,718	9,354	6,515	8,718	9,354	24,819	1,088
15	8,361	8,924	6,018	8,361	8,924	19,678	1,042
16	8,014	8,513	5,045	8,014	8,513	18,278	1,004
17	7,676	8,123	4,844	7,676	8,123	16,178	965
18	7,351	7,761	4,448	7,351	7,761	14,926	926
19	7,040	7,429	4,855	7,040	7,429	14,515	895
20	6,746	7,130	4,537	6,746	7,130	13,128	865
21	6,472	6,869	4,141	6,472	6,870	12,555	841
22	6,217	6,650	3,691	6,217	6,650	9,151	818
23	5,985	6,477	3,467	5,985	6,477	9,480	772
24	5,779	6,352	3,428	5,779	6,353	7,739	726
25	5,599	6,280	3,028	5,599	6,280	6,476	679
26	5,448	6,266	3,024	5,448	6,266	5,996	625
27	5,329	6,266	2,333	5,329	6,266	5,336	579
28	5,243	6,266	2,337	5,243	6,266	4,758	548
29	5,192	6,266	2,122	5,192	6,266	3,806	509
30	5,192	6,266	2,149	5,192	6,266	3,142	471

[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.

Source: EPA (2019a).

Table A-90: VMT Distribution by Vehicle Age and Vehicle/Fuel Type,[a] 2019

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC
0	8.78%	9.73%	10.65%	11.25%	9.97%	9.08%	24.91%
1	8.57%	9.63%	10.69%	10.97%	9.86%	8.95%	13.26%
2	8.50%	9.43%	10.45%	10.89%	9.64%	8.56%	9.96%
3	8.26%	9.15%	10.35%	10.57%	9.35%	8.47%	7.64%
4	7.82%	8.46%	9.41%	10.01%	8.64%	7.72%	6.01%
5	7.44%	7.67%	8.11%	9.52%	7.82%	6.62%	4.91%
6	6.84%	6.84%	6.73%	8.76%	6.98%	5.49%	3.96%
7	6.30%	6.08%	5.70%	8.10%	6.23%	4.85%	3.25%
8	3.71%	3.77%	2.75%	4.76%	3.95%	3.37%	2.41%
9	3.96%	3.08%	1.54%	4.36%	2.13%	2.14%	2.04%
10	3.40%	2.12%	1.29%	2.71%	1.75%	2.65%	1.98%
11	4.04%	3.33%	2.47%	0.23%	3.92%	2.61%	3.31%
12	4.13%	3.16%	1.85%	0.15%	3.19%	6.74%	2.80%
13	3.46%	2.90%	2.49%	2.58%	3.67%	4.66%	2.52%
14	2.94%	2.71%	1.60%	1.52%	2.86%	3.87%	2.10%
15	2.30%	2.40%	1.81%	0.77%	2.26%	2.12%	1.71%
16	1.98%	1.93%	1.30%	0.84%	1.83%	1.72%	1.41%
17	1.61%	1.65%	1.23%	0.75%	1.40%	1.21%	1.19%
18	1.27%	1.30%	0.91%	0.41%	1.42%	1.45%	0.97%
19	1.11%	1.09%	1.92%	0.31%	0.68%	2.14%	0.75%
20	0.78%	0.85%	1.68%	0.16%	0.89%	1.51%	0.55%
21	0.58%	0.62%	0.64%	0.14%	0.31%	0.97%	0.45%
22	0.48%	0.51%	1.04%	0.05%	0.36%	0.66%	0.42%
23	0.37%	0.35%	0.57%	0.05%	0.26%	0.61%	0.35%
24	0.35%	0.32%	0.78%	0.04%	0.18%	0.60%	0.25%
25	0.26%	0.27%	0.53%	0.00%	0.10%	0.38%	0.27%
26	0.21%	0.19%	0.42%	0.02%	0.11%	0.25%	0.20%

27	0.17%	0.14%	0.25%	0.02%	0.10%	0.16%	0.15%
28	0.14%	0.12%	0.20%	0.04%	0.06%	0.13%	0.12%
29	0.11%	0.10%	0.24%	0.01%	0.04%	0.13%	0.09%
30	0.15%	0.10%	0.41%	0.01%	0.04%	0.18%	0.07%
Total	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

[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 by data in Table A-89. This year's Inventory includes updated vehicle population data based on the MOVES2014b model that affects this distribution.

Table A-91: Fuel Consumption for Non-Road Sources by Fuel Type (million gallons unless otherwise noted)

Vehicle Type/Year	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Aircraft[a]	**19,560**	**18,320**	**20,304**	**16,030**	**15,762**	**15,262**	**14,914**	**15,274**	**15,397**	**16,338**	**17,198**	**17,790**	**17,860**	**18,423**
Aviation Gasoline	374	329	302	221	225	225	209	186	181	176	170	174	186	195
Jet Fuel	19,186	17,991	20,002	15,809	15,537	15,036	14,705	15,088	15,217	16,162	17,028	17,616	17,674	18,229
Commercial Aviation[b]	*11,569*	*12,136*	*14,672*	*12,588*	*11,931*	*12,067*	*11,932*	*12,031*	*12,131*	*12,534*	*12,674*	*13,475*	*13,650*	*13,650*
Ships and Boats	**4,826**	**5,932**	**6,544**	**4,201**	**4,693**	**4,833**	**4,239**	**4,175**	**3,191**	**3,652**	**4,235**	**4,469**	**4,190**	**4,245**
Diesel	1,156	1,661	1,882	1,395	1,361	1,641	1,389	1,414	1,284	1,881	1,680	1,593	1,525	1,512
Gasoline	1,611	1,626	1,636	1,498	1,446	1,401	1,372	1,349	1,323	1,325	1,335	1,344	1,352	1,355
Residual	2,060	2,646	3,027	1,308	1,886	1,791	1,477	1,413	584	445	1,219	1,532	1,313	1,377
Construction/Mining Equipment[c]														
Diesel	4,317	4,718	5,181	5,885	5,727	5,650	5,533	5,447	5,313	5,200	5,483	5,978	6,262	6,464
Gasoline	472	437	357	583	678	634	651	1,100	710	367	375	375	385	387
CNG (million cubic feet)	5,082	5,463	6,032	6,378	6,219	6,121	5,957	5,802	5,598	5,430	5,629	6,018	6,204	6,321
LPG	22	24	27	27	26	25	24	24	23	22	23	25	26	27
Agricultural Equipment[d]														
Diesel	3,514	3,400	3,278	3,938	3,942	3,876	3,932	3,900	3,925	3,862	3,760	3,728	3,732	3,742
Gasoline	813	927	652	676	692	799	875	655	644	159	168	168	160	129
CNG (million cubic feet)	1,758	1,712	1,678	1,677	1,647	1,600	1,611	1,588	1,590	1,561	1,517	1,503	1,502	1,507
LPG	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rail	**3,461**	**3,864**	**4,106**	**3,535**	**3,807**	**3,999**	**3,921**	**4,025**	**4,201**	**4,020**	**3,715**	**3,832**	**3,996**	**3,755**
Diesel	3,461	3,864	4,106	3,535	3,807	3,999	3,921	4,025	4,201	4,020	3,715	3,832	3,996	3,755
Other[e]														
Diesel	2,095	2,071	2,047	2,375	2,450	2,523	2,639	2,725	2,811	2,832	2,851	2,919	3,027	3,110
Gasoline	4,371	4,482	4,673	5,291	5,525	5,344	5,189	5,201	5,281	5,083	5,137	5,178	5,238	5,287
CNG (million cubic feet)	20,894	22,584	25,035	28,163	29,891	32,035	35,085	37,436	39,705	38,069	37,709	38,674	40,390	41,474
LPG	1,412	1,809	2,191	2,130	2,165	2,168	2,181	2,213	2,248	2,279	2,316	2,408	2,526	2,616
Total (gallons)	**44,863**	**45,984**	**49,361**	**44,671**	**45,467**	**45,113**	**44,099**	**44,740**	**43,745**	**43,815**	**45,261**	**46,871**	**47,402**	**48,186**
Total (million cubic feet)	**27,735**	**29,759**	**32,745**	**36,218**	**37,757**	**39,755**	**42,653**	**44,826**	**46,893**	**45,060**	**44,854**	**46,194**	**48,097**	**49,301**

[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 2015, EPA incorporated the NONROAD2008 model into MOVES2014a. This year's Inventory uses the NONROAD component of MOVES2014b for years 1999 through 2019.
Sources: AAR (2008 through 2019), APTA (2007 through 2019), BEA (1991 through 2018), Benson (2002 through 2004), DHS (2008), DOC (1991 through 2019), DESC (2018), DOE (1993 through 2018), DOT (1991 through 2019), EIA (2002), EIA (2007b), EIA (2019a, EIA (2007 through 2019), EIA (1991 through 2019), EPA (2019b), FAA (2019), Gaffney (2007), and Whorton (2006 through 2014).

Table A-92: Emissions Control Technology Assignments for Gasoline Passenger Cars (Percent of VMT)

Model Years	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	CARB LEV	CARB LEV 2	EPA Tier 2	CARB LEV 3	EPA Tier 3
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	-	-	80%	20%	-	-	-	-	-
1995	-	-	60%	40%	-	-	-	-	-
1996	-	-	40%	54%	6%	-	-	-	-
1997	-	-	20%	68%	12%	-	-	-	-
1998	-	-	<1%	82%	18%	-	-	-	-
1999	-	-	<1%	67%	33%	-	-	-	-
2000	-	-	-	44%	56%	-	-	-	-
2001	-	-	-	3%	97%	-	-	-	-
2002	-	-	-	1%	99%	-	-	-	-
2003	-	-	-	<1%	85%	2%	12%	-	-
2004	-	-	-	<1%	24%	16%	60%	-	-
2005	-	-	-	-	13%	27%	60%	-	-
2006	-	-	-	-	18%	35%	47%	-	-
2007	-	-	-	-	4%	43%	53%	-	-
2008	-	-	-	-	2%	42%	56%	-	-
2009	-	-	-	-	<1%	43%	57%	-	-
2010	-	-	-	-	-	44%	56%	-	-
2011	-	-	-	-	-	42%	58%	-	-
2012	-	-	-	-	-	41%	59%	-	-
2013	-	-	-	-	-	40%	60%	-	-
2014	-	-	-	-	-	37%	62%	1%	-
2015	-	-	-	-	-	33%	56%	11%	<1%
2016	-	-	-	-	-	25%	50%	18%	6%
2017	-	-	-	-	-	14%	1%	29%	56%
2018	-	-	-	-	-	7%	-	42%	52%
2019	-	-	-	-	-	3%	-	44%	53%

- 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.

Sources: EPA (1998), EPA (2019d), and EPA (2019c).

Table A-93: Emissions Control Technology Assignments for Gasoline Light-Duty Trucks (Percent of VMT)[a]

Model Years	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	CARB LEV[b]	CARB LEV 2	EPA Tier 2	CARB LEV 3	EPA Tier 3
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%	8%	65%	-	-
2005	-	-	-	-	17%	17%	66%	-	-
2006	-	-	-	-	24%	22%	54%	-	-
2007	-	-	-	-	14%	25%	61%	-	-
2008	-	-	-	-	<1%	34%	66%	-	-
2009	-	-	-	-	-	34%	66%	-	-
2010	-	-	-	-	-	30%	70%	-	-
2011	-	-	-	-	-	27%	73%	-	-
2012	-	-	-	-	-	24%	76%	-	-
2013	-	-	-	-	-	31%	69%	-	-
2014	-	-	-	-	-	26%	73%	1%	-
2015	-	-	-	-	-	22%	72%	6%	-
2016	-	-	-	-	-	20%	62%	16%	2%
2017	-	-	-	-	-	9%	14%	28%	48%
2018	-	-	-	-	-	7%	-	38%	55%
2019	-	-	-	-	-	3%	-	44%	53%

- 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.
Sources: EPA (1998), EPA (2019d), and EPA (2019c).

Table A-94: Emissions Control Technology Assignments for Gasoline Heavy-Duty Vehicles (Percent of VMT)[a]

Model Years	Uncontrolled	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	CARB LEV [b]	CARB LEV 2	EPA Tier 2	CARB LEV 3	EPA Tier 3
≤1980	100%	-	-	-	-	-	-	-	-	-
1981-1984	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%	-	-	-	-	-
1999	-	-	-	-	98%	2%	-	-	-	-
2000	-	-	-	-	93%	7%	-	-	-	-
2001	-	-	-	-	78%	22%	-	-	-	-
2002	-	-	-	-	94%	6%	-	-	-	-
2003	-	-	-	-	85%	14%	-	1%	-	-
2004	-	-	-	-	-	33%	-	67%	-	-
2005	-	-	-	-	-	15%	-	85%	-	-
2006	-	-	-	-	-	50%	-	50%	-	-
2007	-	-	-	-	-	-	27%	73%	-	-
2008	-	-	-	-	-	-	46%	54%	-	-
2009	-	-	-	-	-	-	45%	55%	-	-
2010	-	-	-	-	-	-	24%	76%	-	-
2011	-	-	-	-	-	-	7%	93%	-	-
2012	-	-	-	-	-	-	17%	83%	-	-
2013	-	-	-	-	-	-	17%	83%	-	-
2014	-	-	-	-	-	-	19%	81%	-	-
2015	-	-	-	-	-	-	31%	64%	5%	-
2016	-	-	-	-	-	-	24%	10%	21%	44%
2017	-	-	-	-	-	-	8%	8%	39%	45%
2018	-	-	-	-	-	-	13%	-	35%	52%
2019	-	-	-	-	-	-	10%	-	40%	50%

- 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.

Sources: EPA (1998), EPA (2019d), and EPA (2019c).

Table A-95: Emissions 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	1996–2006
Aftertreatment	2007-2019
Diesel Medium- and Heavy-Duty Trucks and Buses	
Uncontrolled	1960–1989
Moderate control	1990–2003
Advanced control	2004–2006
Aftertreatment	2007–2019
Motorcycles	
Uncontrolled	1960–1995
Non-catalyst controls	1996–2019

Note: Detailed descriptions of emissions control technologies are provided in the following section of this Annex.

Source: EPA (1998) and Browning (2005).

Table A-96: 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 3	0.0015	0.0055
ARB LEV III	0.0012	0.0045
EPA Tier 2	0.0048	0.0072
ARB LEV II	0.0043	0.0070
ARB LEV	0.0205	0.0100
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 3	0.0012	0.0092
ARB LEV III	0.0012	0.0065
EPA Tier 2	0.0025	0.0100
ARB LEV II	0.0057	0.0084
ARB LEV	0.0223	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 3	0.0063	0.0252
ARB LEV III	0.0136	0.0411
EPA Tier 2	0.0015	0.0297
ARB LEV II	0.0049	0.0391
ARB LEV	0.0466	0.0300
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		
Aftertreatment	0.0192	0.0302
Advanced	0.0010	0.0005
Moderate	0.0010	0.0005
Uncontrolled	0.0012	0.0006
Diesel Light-Duty Trucks		
Aftertreatment	0.0214	0.0290
Advanced	0.0014	0.0009
Moderate	0.0014	0.0009
Uncontrolled	0.0017	0.0011
Diesel Medium- and Heavy-Duty Trucks and Buses		
Aftertreatment	0.0431	0.0095
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

[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.

Source: ICF (2006b and 2017a).

Table A-97: Emission Factors for N_2O for Alternative Fuel Vehicles (g/mi)

	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Light-Duty Cars														
Methanol-Flex Fuel ICE	0.035	0.035	0.034	0.010	0.008	0.008	0.008	0.008	0.008	0.008	0.007	0.007	0.006	0.005
Ethanol-Flex Fuel ICE	0.035	0.035	0.034	0.010	0.008	0.008	0.008	0.008	0.008	0.008	0.007	0.007	0.006	0.005
CNG ICE	0.021	0.021	0.027	0.010	0.008	0.008	0.008	0.008	0.008	0.008	0.007	0.007	0.006	0.005
CNG Bi-fuel	0.021	0.021	0.027	0.010	0.008	0.008	0.008	0.008	0.008	0.008	0.007	0.007	0.006	0.005
LPG ICE	0.021	0.021	0.027	0.010	0.008	0.008	0.008	0.008	0.008	0.008	0.007	0.007	0.006	0.005
LPG Bi-fuel	0.021	0.021	0.027	0.010	0.008	0.008	0.008	0.008	0.008	0.008	0.007	0.007	0.006	0.005
Biodiesel (BD100)	0.001	0.001	0.001	0.001	0.001	0.004	0.008	0.012	0.015	0.019	0.019	0.019	0.019	0.019
Light-Duty Trucks														
Ethanol-Flex Fuel ICE	0.068	0.069	0.072	0.024	0.016	0.016	0.016	0.016	0.016	0.016	0.014	0.012	0.011	0.009
CNG ICE	0.041	0.041	0.058	0.024	0.016	0.016	0.016	0.016	0.016	0.016	0.014	0.012	0.011	0.009
CNG Bi-fuel	0.041	0.041	0.058	0.024	0.016	0.016	0.016	0.016	0.016	0.016	0.014	0.012	0.011	0.009
LPG ICE	0.041	0.041	0.058	0.024	0.016	0.016	0.016	0.016	0.016	0.016	0.015	0.014	0.013	0.012
LPG Bi-fuel	0.041	0.041	0.058	0.024	0.016	0.016	0.016	0.016	0.016	0.016	0.015	0.014	0.013	0.012
LNG	0.041	0.041	0.058	0.024	0.016	0.016	0.016	0.016	0.016	0.016	0.014	0.012	0.011	0.009
Biodiesel (BD100)	0.001	0.001	0.001	0.001	0.001	0.005	0.009	0.013	0.017	0.021	0.021	0.021	0.021	0.021
Medium Duty Trucks														
CNG ICE	0.002	0.002	0.003	0.003	0.003	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001
CNG Bi-fuel	0.002	0.002	0.003	0.003	0.003	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001
LPG ICE	0.055	0.055	0.069	0.043	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034
LPG Bi-fuel	0.055	0.055	0.069	0.043	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034
LNG	0.002	0.002	0.003	0.003	0.003	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Biodiesel (BD100)	0.002	0.002	0.003	0.003	0.003	0.011	0.019	0.027	0.035	0.043	0.043	0.043	0.043	0.043
Heavy-Duty Trucks														
Neat Methanol ICE	0.040	0.040	0.049	0.034	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
Neat Ethanol ICE	0.002	0.040	0.049	0.034	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
CNG ICE	0.045	0.002	0.002	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
LPG ICE	1.229	0.045	0.049	0.032	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026
LPG Bi-fuel	0.002	0.045	0.049	0.032	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026
LNG	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Biodiesel (BD100)	0.040	0.002	0.002	0.002	0.002	0.010	0.018	0.027	0.035	0.043	0.043	0.043	0.043	0.043
Buses														
Neat Methanol ICE	0.045	0.045	0.058	0.040	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032
Neat Ethanol ICE	0.045	0.045	0.058	0.040	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032
CNG ICE	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001
LPG ICE	0.051	0.051	0.058	0.038	0.030	0.028	0.025	0.022	0.020	0.017	0.017	0.017	0.017	0.017
LNG	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001

Biodiesel (BD100)	0.002	0.002	0.002	0.002	0.002	0.011	0.019	0.027	0.035	0.043	0.043	0.043	0.043	0.043

Source: Developed by ICF (Browning 2017) using ANL (2018)

Note: When driven in all-electric mode, plug-in electric vehicles have zero tailpipe emissions. Therefore, emissions factors for battery electric vehicle (BEVs) and the electric portion of plug-in hybrid electric vehicles (PHEVs) are not included in this table.

Table A-98: Emission Factors for CH_4 for Alternative Fuel Vehicles (g/mi)

	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Light-Duty Cars														
Methanol-Flex Fuel ICE	0.034	0.034	0.019	0.015	0.015	0.014	0.013	0.011	0.010	0.009	0.008	0.008	0.008	0.008
Ethanol-Flex Fuel ICE	0.034	0.034	0.019	0.015	0.015	0.014	0.013	0.011	0.010	0.009	0.008	0.008	0.008	0.008
CNG ICE	0.489	0.489	0.249	0.153	0.153	0.139	0.126	0.113	0.100	0.086	0.085	0.083	0.082	0.081
CNG Bi-fuel	0.489	0.489	0.249	0.153	0.153	0.139	0.126	0.113	0.100	0.086	0.085	0.083	0.082	0.081
LPG ICE	0.049	0.049	0.025	0.015	0.015	0.014	0.013	0.011	0.010	0.009	0.008	0.008	0.008	0.008
LPG Bi-fuel	0.049	0.049	0.025	0.015	0.015	0.014	0.013	0.011	0.010	0.009	0.008	0.008	0.008	0.008
Biodiesel (BD100)	0.002	0.002	0.002	0.001	0.001	0.007	0.013	0.018	0.024	0.030	0.019	0.030	0.030	0.030
Light-Duty Trucks														
Ethanol-Flex Fuel ICE	0.051	0.051	0.053	0.033	0.033	0.029	0.025	0.021	0.017	0.013	0.013	0.013	0.012	0.012
CNG ICE	0.728	0.725	0.709	0.349	0.332	0.292	0.251	0.210	0.170	0.129	0.127	0.125	0.123	0.121
CNG Bi-fuel	0.728	0.725	0.709	0.349	0.332	0.292	0.251	0.210	0.170	0.129	0.127	0.125	0.123	0.121
LPG ICE	0.073	0.072	0.071	0.035	0.033	0.029	0.025	0.021	0.017	0.013	0.013	0.013	0.012	0.012
LPG Bi-fuel	0.073	0.072	0.071	0.035	0.033	0.029	0.025	0.021	0.017	0.013	0.013	0.013	0.012	0.012
LNG	0.728	0.725	0.709	0.349	0.332	0.292	0.251	0.210	0.170	0.129	0.127	0.125	0.123	0.121
Biodiesel (BD100)	0.005	0.005	0.005	0.002	0.001	0.007	0.012	0.018	0.023	0.029	0.029	0.029	0.029	0.029
Medium Duty Trucks														
CNG ICE	6.800	6.800	6.800	6.800	6.800	6.280	5.760	5.240	4.720	4.200	4.200	4.200	4.200	4.200
CNG Bi-fuel	6.800	6.800	6.800	6.800	6.800	6.280	5.760	5.240	4.720	4.200	4.200	4.200	4.200	4.200
LPG ICE	0.262	0.262	0.248	0.023	0.021	0.020	0.018	0.017	0.016	0.014	0.014	0.014	0.014	0.014
LPG Bi-fuel	0.262	0.262	0.248	0.023	0.021	0.020	0.018	0.017	0.016	0.014	0.014	0.014	0.014	0.014
LNG	6.800	6.800	6.800	6.800	6.800	6.280	5.760	5.240	4.720	4.200	4.200	4.200	4.200	4.200
Biodiesel (BD100)	0.004	0.004	0.004	0.002	0.002	0.004	0.005	0.006	0.008	0.009	0.009	0.009	0.009	0.009
Heavy-Duty Trucks														
Neat Methanol ICE	0.296	0.296	0.095	0.136	0.151	0.136	0.120	0.105	0.090	0.075	0.075	0.075	0.075	0.075
Neat Ethanol ICE	0.296	0.296	0.095	0.136	0.151	0.136	0.120	0.105	0.090	0.075	0.075	0.075	0.075	0.075
CNG ICE	4.100	4.100	4.100	4.100	4.100	4.020	3.940	3.860	3.780	3.700	3.700	3.700	3.700	3.700
LPG ICE	0.158	0.158	0.149	0.014	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
LPG Bi-fuel	0.158	0.158	0.149	0.014	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
LNG	4.100	4.100	4.100	4.100	4.100	4.020	3.940	3.860	3.780	3.700	3.700	3.700	3.700	3.700
Biodiesel (BD100)	0.012	0.012	0.005	0.005	0.005	0.006	0.007	0.007	0.008	0.009	0.009	0.009	0.009	0.009
Buses														
Neat Methanol ICE	0.086	0.086	0.067	0.068	0.075	0.067	0.060	0.052	0.045	0.037	0.032	0.027	0.022	0.016
Neat Ethanol ICE	0.086	0.086	0.067	0.068	0.075	0.067	0.060	0.052	0.045	0.037	0.032	0.027	0.022	0.016

CNG ICE	18.800	18.800	18.800	18.800	18.800	17.040	15.280	13.520	11.760	10.000	10.000	10.000	10.000	10.000
LPG ICE	0.725	0.725	0.686	0.063	0.058	0.053	0.048	0.044	0.039	0.034	0.034	0.034	0.034	0.034
LNG	18.800	18.800	18.800	18.800	18.800	17.040	15.280	13.520	11.760	10.000	10.000	10.000	10.000	10.000
Biodiesel (BD100)	0.004	0.004	0.003	0.002	0.002	0.004	0.005	0.006	0.008	0.009	0.009	0.009	0.009	0.009

Source: Developed by ICF (Browning 2017) using ANL (2018).

Note: When driven in all-electric mode, plug-in electric vehicles have zero tailpipe emissions. Therefore, emissions factors for battery electric vehicle (BEVs) and the electric portion of plug-in hybrid electric vehicles (PHEVs) are not included in this table.

Table A-99: Emission Factors for N_2O Emissions from Non-Road Mobile Combustion (g/kg fuel)

	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Ships and Boats														
Residual Fuel Oil	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309
Gasoline														
2 Stroke	*0.021*	*0.021*	*0.021*	*0.024*	*0.025*	*0.025*	*0.025*	*0.026*	*0.026*	*0.026*	*0.027*	*0.027*	*0.027*	*0.027*
4 Stroke	*0.002*	*0.003*	*0.003*	*0.003*	*0.003*	*0.003*	*0.003*	*0.003*	*0.003*	*0.003*	*0.003*	*0.003*	*0.003*	*0.003*
Distillate Fuel Oil	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
Rail														
Diesel	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080
Aircraft														
Jet Fuel	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Aviation Gasoline	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040
Agricultural Equipment[a]														
Gasoline-Equipment														
2 Stroke	*0.055*	*0.060*	*0.064*	*0.091*	*0.092*	*0.092*	*0.092*	*0.092*	*0.092*	*0.092*	*0.092*	*0.092*	*0.092*	*0.092*
4 Stroke	*0.543*	*0.550*	*0.558*	*0.618*	*0.624*	*0.629*	*0.634*	*0.638*	*0.642*	*0.644*	*0.647*	*0.650*	*0.653*	*0.656*
Gasoline-Off-road Trucks	0.543	0.550	0.558	0.618	0.624	0.629	0.634	0.638	0.642	0.644	0.647	0.650	0.653	0.656
Diesel-Equipment	0.282	0.282	0.282	0.282	0.282	0.282	0.282	0.282	0.282	0.282	0.282	0.282	0.282	0.282
Diesel-Off-Road Trucks	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288
CNG	0.036	0.036	0.036	0.042	0.043	0.044	0.044	0.044	0.044	0.044	0.044	0.045	0.045	0.045
LPG	0.250	0.250	0.250	0.277	0.281	0.283	0.285	0.287	0.288	0.290	0.291	0.292	0.293	0.293
Construction/Mining Equipment[b]														
Gasoline-Equipment														
2 Stroke	*0.079*	*0.082*	*0.084*	*0.120*	*0.121*	*0.121*	*0.121*	*0.121*	*0.121*	*0.121*	*0.121*	*0.121*	*0.121*	*0.121*
4 Stroke	*0.461*	*0.486*	*0.509*	*0.582*	*0.584*	*0.587*	*0.590*	*0.591*	*0.592*	*0.594*	*0.595*	*0.596*	*0.596*	*0.597*
Gasoline-Off-road Trucks	0.46	0.486	0.509	0.582	0.584	0.587	0.590	0.591	0.592	0.594	0.595	0.596	0.596	0.597

Diesel-Equipment	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274
Diesel-Off-Road Trucks	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288
CNG	0.036	0.036	0.036	0.038	0.038	0.038	0.039	0.039	0.039	0.040	0.040	0.041	0.042	0.042
LPG	0.250	0.250	0.250	0.279	0.283	0.287	0.290	0.293	0.295	0.298	0.300	0.303	0.305	0.306
Lawn and Garden Equipment														
Gasoline-Residential														
2 Stroke	*0.053*	*0.056*	*0.060*	0.084	0.084	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085
4 Stroke	*0.401*	*0.421*	*0.447*	0.526	0.529	0.532	0.534	0.535	0.536	0.537	0.537	0.537	0.538	0.537
Gasoline-Commercial														
2 Stroke	*0.066*	*0.069*	*0.072*	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102
4 Stroke	*0.427*	*0.046*	*0.498*	0.553	0.554	0.555	0.557	0.558	0.558	0.558	0.559	0.559	0.559	0.559
Diesel-Residential														
Diesel-Commercial	0.271	0.271	0.270	0.270	0.270	0.270	0.270	0.270	0.270	0.270	0.270	0.270	0.270	0.270
LPG	0.250	0.250	0.250	0.291	0.297	0.302	0.306	0.307	0.309	0.310	0.311	0.311	0.312	0.312
Airport Equipment														
Gasoline														
4 Stroke	*0.597*	*0.616*	*0.631*	*0.734*	*0.741*	*0.750*	*0.755*	*0.758*	*0.760*	*0.762*	*0.763*	*0.764*	*0.764*	*0.764*
Diesel	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285
LPG	0.250	0.250	0.250	0.295	0.295	0.299	0.304	0.307	0.308	0.310	0.311	0.311	0.312	0.312
Industrial/Commercial Equipment														
Gasoline														
2 Stroke	*0.055*	*0.060*	*0.064*	*0.092*	*0.092*	*0.092*	*0.092*	*0.092*	*0.092*	*0.092*	*0.092*	*0.092*	*0.092*	*0.092*
4 Stroke	*0.457*	*0.485*	*0.510*	*0.583*	*0.587*	*0.590*	*0.593*	*0.594*	*0.595*	*0.596*	*0.597*	*0.598*	*0.599*	*0.600*
Diesel	0.270	0.270	0.270	0.271	0.271	0.272	0.272	0.273	0.273	0.273	0.272	0.272	0.272	0.272
CNG	0.036	0.036	0.036	0.042	0.043	0.043	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044
LPG	0.250	0.250	0.250	0.285	0.291	0.297	0.303	0.305	0.307	0.308	0.309	0.310	0.311	0.311
Logging Equipment														
Gasoline														
2 Stroke	*0.082*	*0.085*	*0.087*	*0.124*	*0.124*	*0.124*	*0.124*	*0.124*	*0.124*	*0.124*	*0.124*	*0.124*	*0.124*	*0.124*
4 Stroke	*0.445*	*0.453*	*0.463*	*0.518*	*0.522*	*0.528*	*0.535*	*0.542*	*0.549*	*0.554*	*0.557*	*0.559*	*0.562*	*0.563*
Diesel	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287
Railroad Equipment														
Gasoline														
4 Stroke	*0.442*	*0.464*	*0.485*	*0.561*	*0.562*	*0.564*	*0.565*	*0.566*	*0.567*	*0.567*	*0.568*	*0.568*	*0.568*	*0.568*
Diesel	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243

LPG	0.250	0.250	0.250	0.283	0.276	0.283	0.287	0.291	0.294	0.297	0.299	0.303	0.305	0.306
Recreational Equipment														
Gasoline														
2 Stroke	*0.059*	*0.060*	*0.060*	*0.063*	*0.064*	*0.064*	*0.065*	*0.066*	*0.067*	*0.068*	*0.069*	*0.070*	*0.071*	*0.072*
4 Stroke	*0.719*	*0.732*	*0.743*	*0.790*	*0.790*	*0.792*	*0.793*	*0.793*	*0.793*	*0.794*	*0.794*	*0.794*	*0.795*	*0.795*
Diesel	0.236	0.236	0.236	0.236	0.236	0.236	0.236	0.236	0.236	0.236	0.236	0.236	0.236	0.236
LPG	0.250	0.250	0.250	0.263	0.265	0.267	0.270	0.272	0.274	0.276	0.278	0.281	0.283	0.285

[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.
Source: IPCC (2006) and Browning, L (2018b), EPA (2018a).

Table A-100: Emission Factors for CH_4 Emissions from Non-Road Mobile Combustion (g/kg fuel)

	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Ships and Boats														
Residual Fuel Oil	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088
Gasoline														
2 Stroke	*1.255*	*1.259*	*1.270*	*1.443*	*1.465*	*1.489*	*1.514*	*1.537*	*1.557*	*1.578*	*1.598*	*1.615*	*1.629*	*1.642*
4 Stroke	*0.718*	*0.721*	*0.725*	*0.757*	*0.760*	*0.764*	*0.769*	*0.773*	*0.778*	*0.783*	*0.789*	*0.794*	*0.798*	*0.802*
Distillate Fuel Oil	2.010	2.010	2.010	2.010	2.010	2.010	2.010	2.010	2.010	2.010	2.010	2.010	2.010	2.010
Rail														
Diesel	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250
Aircraft														
Jet Fuel[c]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Aviation Gasoline	2.640	2.640	2.640	2.640	2.640	2.640	2.640	2.640	2.640	2.640	2.640	2.640	2.640	2.640
Agricultural Equipment[a]														
Gasoline-Equipment														
2 Stroke	*1.993*	*2.141*	*2.284*	*3.288*	*3.294*	*3.294*	*3.294*	*3.294*	*3.294*	*3.294*	*3.294*	*3.294*	*3.294*	*3.293*
4 Stroke	*0.987*	*1.000*	*1.014*	*1.125*	*1.135*	*1.143*	*1.153*	*1.160*	*1.167*	*1.172*	*1.176*	*1.182*	*1.187*	*1.193*
Gasoline-Off-road Trucks	0.987	1.000	1.014	1.125	1.135	1.143	1.153	1.160	1.167	1.172	1.176	1.182	1.187	1.193
Diesel-Equipment	0.303	0.303	0.303	0.303	0.303	0.303	0.303	0.303	0.303	0.303	0.303	0.303	0.303	0.303
Diesel-Off-Road Trucks	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310
CNG	2.293	2.293	2.293	2.698	2.762	2.798	2.819	2.834	2.845	2.853	2.858	2.861	2.861	2.860
LPG	0.175	0.175	0.175	0.194	0.197	0.198	0.200	0.201	0.202	0.203	0.204	0.205	0.205	0.206

Construction/Mining Equipment[b]														
Gasoline-Equipment														
2 Stroke	*2.837*	*2.945*	*3.033*	*4.329*	*4.339*	*4.341*	*4.341*	*4.341*	*4.341*	*4.341*	*4.341*	*4.341*	*4.341*	*4.340*
4 Stroke	*0.839*	*0.885*	*0.926*	*1.058*	*1.063*	*1.068*	*1.073*	*1.075*	*1.077*	*1.080*	*1.082*	*1.083*	*1.085*	*1.085*
Gasoline-Off-road Trucks	0.839	0.885	0.926	1.058	1.063	1.068	1.073	1.075	1.077	1.080	1.082	1.083	1.085	1.085
Diesel-Equipment	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295
Diesel-Off-Road Trucks	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310	0.310
CNG	2.293	2.293	2.293	2.424	2.444	2.468	2.488	2.511	2.531	2.556	2.600	2.653	2.695	2.730
LPG	0.175	0.175	0.175	0.195	0.198	0.201	0.204	0.205	0.207	0.209	0.211	0.213	0.214	0.215
Lawn and Garden Equipment														
Gasoline-Residential														
2 Stroke	*1.91*	*2.01*	*2.14*	*3.01*	*3.03*	*3.05*	*3.06*	*3.06*	*3.06*	*3.06*	*3.06*	*3.06*	*3.06*	*3.06*
4 Stroke	*0.73*	*0.77*	*0.81*	*0.96*	*0.96*	*0.97*	*0.97*	*0.97*	*0.97*	*0.98*	*0.98*	*0.98*	*0.98*	*0.98*
Gasoline-Commercial														
2 Stroke	*2.36*	*2.49*	*2.60*	*3.65*	*3.65*	*3.65*	*3.65*	*3.65*	*3.65*	*3.65*	*3.65*	*3.66*	*3.66*	*3.66*
4 Stroke	*0.78*	*0.84*	*0.91*	*1.01*	*1.01*	*1.01*	*1.01*	*1.01*	*1.01*	*1.02*	*1.02*	*1.02*	*1.02*	*1.02*
Diesel-Commercial	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
LPG	0.18	0.18	0.18	0.20	0.21	0.21	0.21	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Airport Equipment														
Gasoline														
4 Stroke	*1.09*	*1.12*	*1.15*	*1.33*	*1.35*	*1.36*	*1.37*	*1.38*	*1.38*	*1.39*	*1.39*	*1.39*	*1.39*	*1.39*
Diesel	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
LPG	0.18	0.18	0.18	0.21	0.21	0.21	0.21	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Industrial/Commercial Equipment														
Gasoline														
2 Stroke	*1.99*	*2.16*	*2.29*	*3.29*	*3.29*	*3.30*	*3.30*	*3.30*	*3.30*	*3.30*	*3.30*	*3.30*	*3.30*	*3.30*
4 Stroke	*0.83*	*0.88*	*0.93*	*1.06*	*1.07*	*1.07*	*1.08*	*1.08*	*1.08*	*1.08*	*1.09*	*1.09*	*1.09*	*1.09*
Diesel	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
CNG	2.29	2.29	2.29	2.72	2.75	2.78	2.81	2.82	2.83	2.84	2.84	2.84	2.85	2.85
LPG	0.18	0.18	0.18	0.20	0.20	0.21	0.21	0.21	0.22	0.22	0.22	0.22	0.22	0.22
Logging Equipment														
Gasoline														
2 Stroke	*2.95*	*3.05*	*3.13*	*4.47*	*4.47*	*4.47*	*4.47*	*4.47*	*4.47*	*4.47*	*4.47*	*4.47*	*4.47*	*4.47*

4 Stroke	*0.81*	*0.82*	*0.84*	*0.94*	*0.95*	*0.96*	*0.97*	*0.99*	*1.00*	*1.01*	*1.01*	*1.02*	*1.02*	*1.02*
Diesel	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Railroad Equipment														
Gasoline														
4 Stroke	*0.80*	*0.84*	*0.88*	*1.02*	*1.02*	*1.03*	*1.03*	*1.03*	*1.03*	*1.03*	*1.03*	*1.03*	*1.03*	*1.03*
Diesel	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
LPG	0.18	0.18	0.18	0.19	0.19	0.20	0.20	0.20	0.21	0.21	0.21	0.21	0.21	0.21
Recreational Equipment														
Gasoline														
2 Stroke	*1.28*	*1.29*	*1.29*	*1.35*	*1.37*	*1.38*	*1.40*	*1.42*	*1.44*	*1.46*	*1.48*	*1.50*	*1.52*	*1.53*
4 Stroke	*1.13*	*1.15*	*1.17*	*1.24*	*1.24*	*1.24*	*1.25*	*1.25*	*1.25*	*1.25*	*1.25*	*1.25*	*1.25*	*1.54*
Diesel	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
LPG	0.18	0.18	0.18	0.18	0.19	0.19	0.19	0.19	0.19	0.19	0.20	0.20	0.20	0.20

Table A-101: NO_x Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Gasoline On-Road	**5,746**	**4,560**	**3,812**	**2,966**	**2,724**	**2,805**	**2,647**	**2,489**	**2,332**	**2,122**	**1,751**	**1,670**	**1,463**	**1,326**
Passenger Cars	3,847	2,752	2,084	1,618	1,486	1,530	1,444	1,358	1,272	1,158	955	911	798	723
Light-Duty Trucks	1,364	1,325	1,303	1,026	942	970	915	861	806	734	605	578	506	459
Medium- and Heavy-Duty Trucks and Buses	515	469	411	311	286	294	278	261	245	223	184	175	154	139
Motorcycles	20	14	13	11	10	10	10	9	9	8	6	6	5	5
Diesel On-Road	**2,956**	**3,493**	**3,803**	**2,665**	**2,448**	**2,520**	**2,379**	**2,237**	**2,095**	**1,907**	**1,573**	**1,501**	**1,315**	**1,191**
Passenger Cars	39	19	7	5	4	4	4	4	4	3	3	3	2	2
Light-Duty Trucks	20	12	6	4	4	4	4	4	3	3	3	2	2	2
Medium- and Heavy-Duty Trucks and Buses	2,897	3,462	3,791	2,656	2,439	2,512	2,370	2,229	2,088	1,900	1,568	1,495	1,310	1,187
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**	**2,166**	**2,118**	**1,968**	**1,883**	**1,797**	**1,712**	**1,605**	**1,416**	**1,392**	**1,345**	**1,345**
Ships and Boats	402	488	506	448	438	407	389	372	354	332	293	288	278	278
Rail	338	433	451	400	391	363	348	332	316	296	261	257	248	248
Aircraft[b]	25	31	40	32	32	29	28	27	26	24	21	21	20	20
Agricultural Equipment[c]	437	478	484	392	383	356	340	325	309	290	256	252	243	243
Construction/Mining Equipment[d]	641	697	697	563	550	511	489	467	445	417	368	362	349	349
Other[e]	318	357	407	332	324	301	288	275	262	246	217	213	206	206

Total	**10,862**	**10,536**	**10,199**	**7,797**	**7,290**	**7,294**	**6,909**	**6,523**	**6,138**	**5,634**	**4,739**	**4,563**	**4,123**	**3,862**

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.

Notes: The source of this data is the National Emissions Inventory. Updates to estimates from MOVES2014b is a change that affects the emissions time series. Totals may not sum due to independent rounding.

Table A-102: CO Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Gasoline On-Road	**98,328**	**74,673**	**60,657**	**24,515**	**25,235**	**24,442**	**23,573**	**22,704**	**21,834**	**20,864**	**17,995**	**17,435**	**15,898**	**15,070**
Passenger Cars	60,757	42,065	32,867	13,659	14,060	13,618	13,134	12,649	12,165	11,625	10,026	9,714	8,858	8,396
Light-Duty Trucks	29,237	27,048	24,532	9,758	10,044	9,729	9,383	9,037	8,690	8,304	7,162	6,940	6,328	5,998
Medium- and Heavy-Duty Trucks and Buses	8,093	5,404	3,104	1,042	1,073	1,039	1,002	965	928	887	765	741	676	641
Motorcycles	240	155	154	57	58	57	55	53	51	48	42	40	37	35
Diesel On-Road	**1,696**	**1,424**	**1,088**	**376**	**387**	**375**	**361**	**348**	**335**	**320**	**276**	**267**	**244**	**231**
Passenger Cars	35	18	7	3	3	3	2	2	2	2	2	2	2	2
Light-Duty Trucks	22	16	6	2	2	2	2	2	2	2	2	2	1	1
Medium- and Heavy-Duty Trucks and Buses	1,639	1,391	1,075	371	382	370	357	343	330	316	272	264	241	228
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**	**14,365**	**13,853**	**13,488**	**12,981**	**12,474**	**11,966**	**11,451**	**10,518**	**10,421**	**10,448**	**10,448**
Ships and Boats	1,559	1,781	1,825	1,182	1,140	1,109	1,068	1,026	984	942	865	857	859	859
Rail	85	93	90	58	56	54	52	50	48	46	42	42	42	42
Aircraft[b]	217	224	245	151	145	141	136	131	125	120	110	109	110	110
Agricultural Equipment[c]	581	628	626	401	386	376	362	348	334	319	293	291	291	291
Construction/Mining Equipment[d]	1,090	1,132	1,047	672	648	631	607	583	560	535	492	487	489	489
Other[e]	15,805	17,676	17,981	11,903	11,479	11,176	10,756	10,335	9,915	9,488	8,715	8,635	8,657	8,657
Total	**119,360**	**97,630**	**83,559**	**39,256**	**39,475**	**38,305**	**36,915**	**35,525**	**34,135**	**32,635**	**28,789**	**28,124**	**26,590**	**25,749**

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 MOVES2014b is a change that affects the emissions time series. Totals may not sum due to independent rounding.

Table A-103: NMVOCs Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Gasoline On-Road	**8,110**	**5,819**	**4,615**	**2,384**	**2,393**	**2,485**	**2,342**	**2,200**	**2,058**	**1,929**	**1,626**	**1,570**	**1,395**	**1,295**
Passenger Cars	5,120	3,394	2,610	1,332	1,336	1,388	1,308	1,229	1,149	1,077	908	877	779	723
Light-Duty Trucks	2,374	2,019	1,750	926	929	965	910	854	799	749	631	610	542	503
Medium- and Heavy-Duty Trucks and Buses	575	382	232	115	115	120	113	106	99	93	78	76	67	62
Motorcycles	42	24	23	12	12	13	12	11	11	10	8	8	7	7
Diesel On-Road	**406**	**304**	**216**	**115**	**116**	**120**	**113**	**106**	**100**	**93**	**79**	**76**	**68**	**63**
Passenger Cars	16	8	3	2	2	2	2	2	1	1	1	1	1	1
Light-Duty Trucks	14	9	4	2	2	2	2	2	2	2	1	1	1	1
Medium- and Heavy-Duty Trucks and Buses	377	286	209	112	112	116	110	103	96	90	76	74	65	61
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**	**2,150**	**2,082**	**1,957**	**1,837**	**1,717**	**1,597**	**1,435**	**1,168**	**1,112**	**1,080**	**1,080**
Ships and Boats	608	739	744	660	639	600	564	527	490	440	358	341	331	331
Rail	33	36	35	32	31	29	27	26	24	21	17	17	16	16
Aircraft[b]	28	28	24	17	17	16	15	14	13	12	9	9	9	9
Agricultural Equipment[c]	85	86	76	65	63	60	56	52	49	44	36	34	33	33
Construction/Mining Equipment[d]	149	152	130	113	109	103	96	90	84	75	61	58	57	57
Other[e]	1,512	1,580	1,390	1,263	1,223	1,149	1,079	1,008	938	843	686	653	634	634
Total	**10,932**	**8,745**	**7,230**	**4,650**	**4,591**	**4,562**	**4,293**	**4,023**	**3,754**	**3,458**	**2,873**	**2,758**	**2,543**	**2,437**

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 MOVES2014b 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-92 through Table A-95 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, 1999) 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, which 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, a technology used in gasoline passenger cars and light-duty gasoline trucks beginning in the early 1980s which 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 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 expired in 2006. These emission standards 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 andapplied 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.

EPA Tier 3

These standards begin in 2017 and will fully phase-in by 2025, although some Tier 3-compliantvehicles were produced prior to 2017. This emission standard reduces both tailpipe and evaporative emissions from passenger cars, light-duty trucks, medium-duty passenger vehicles, and some heavy-duty vehicles. It is combined with a gasoline sulfur standard that will enable more stringent vehicle emissions standards and will make emissions control systems more effective.

CARB 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). 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.

CARB LEVII

This emission standard builds upon ARB's LEV emission standards. They represent a significant strengthening of the emission standards and require light trucks under 8500 lbs gross vehicle weight meet passenger car standards. It also introduces a super ultra-low vehicle (SULEV) emission standard. The LEVII standards decreased emission requirements for LEV and ULEV vehicles as well as increasing the useful life of the vehicle to 150,000. These standards began with 2004 vehicles. In this analysis, all categories of LEVIIs are treated the same due to the fact that there are very limited CH_4 or N_2O emission factor data for LEVIIs to distinguish among the different types of vehicles. Zero emission vehicles (ZEVs) are incorporated into the alternative fuel and advanced technology vehicle assessments.

CARB LEVIII

These standards begin in 2015 and are fully phased in by 2025, although some LEVIII-compliantvehicles were produced prior to 2017. LEVIII set new vehicle emissions standards and lower the sulfur content of gasoline, considering the vehicle and its fuel as an integrated system. These new tailpipe standards apply to all light-duty vehicles, medium duty and some heavy-duty 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 consolidate all transportation estimates presented throughout the report .

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. 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 industrial and commercial sectors of the Inventory. In order to provide comparable information on transportation and mobile sources, Table A-104 provides estimates of CO_2 from these other mobile sources, developed from the Nonroad component of EPA's MOVES2014b 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 (see Table A-91). Note that the method used to estimate fuel consumption volumes for CO_2 emissions from non-transportation mobile sources for the supplemental information presented in Table A-104, Table A-106, and Table A-107 differs from the method used to estimate fuel consumption volumes for CO_2 in the industrial and commercial sectors in this Inventory, which include CO_2 emissions from all non-transportation mobile sources (see Section 3.1 for a discussion of that methodology).

Table A-104: CO_2 Emissions from Non-Transportation Mobile Sources (MMT CO_2 Eq.)

Fuel Type/ Vehicle Type	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Agricultural Equipment[a]	43.4	43.2	39.8	46.3	46.5	46.7	47.9	45.6	45.8	40.8	39.9	39.5	39.5	39.3
Construction/Mining Equipment[b]	48.9	52.7	57.3	65.8	65.0	63.7	62.6	65.7	60.8	56.6	59.6	64.6	67.6	67.6
Other Sources[c]	69.8	72.7	76.7	84.9	88.0	87.2	87.2	88.3	90.2	88.8	89.7	91.3	92.7	94.6
Total	**162.0**	**168.6**	**173.9**	**196.9**	**199.4**	**197.6**	**197.7**	**199.6**	**196.8**	**186.3**	**189.1**	**195.5**	**199.8**	**203.6**

[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: The method used to estimate CO_2 emissions in this supplementary information table differs from the method used to estimate CO_2 in the industrial and commercial sectors in the Inventory, which include CO_2 emissions from all non-transportation mobile sources (see Section 3.1 for the methodology for estimating CO_2 emissions from fossil fuel combustion in this Inventory). In 2015, EPA incorporated the NONROAD2008 model into MOVES2014a. The current Inventory uses the Nonroad component of MOVES2014b for years 1999 through 2019.

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, light-duty trucks, and heavy-duty vehicles; 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-105 below presents these HFC emissions. Table A-106 presents all transportation and mobile source greenhouse gas emissions, including HFC emissions.

Table A-105: HFC Emissions from Transportation Sources (MMT CO_2 Eq.)

Vehicle Type	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Mobile AC	**+**	**19.4**	**55.2**	**68.2**	**64.7**	**58.6**	**52.7**	**46.7**	**43.4**	**40.5**	**36.9**	**33.3**	**31.0**	**28.8**
Passenger Cars	+	11.2	28.0	29.9	27.5	23.9	20.6	17.2	15.8	14.7	13.2	11.4	10.4	9.3
Light-Duty Trucks	+	7.8	25.6	35.2	34.1	31.6	29.2	26.5	24.7	23.0	21.1	19.2	18.1	16.9
Heavy-Duty Vehicles	+	0.5	1.6	3.0	3.1	3.0	2.9	2.9	2.9	2.8	2.7	2.6	2.6	2.6
Comfort Cooling for Trains and Buses	**+**	**+**	**0.1**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
School and Tour Buses	+	+	0.1	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Transit Buses	+	+	+	+	+	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1
Rail	+	+	+	+	+	+	+	+	+	+	+	+	+	0.1
Refrigerated Transport	**+**	**0.2**	**0.8**	**2.4**	**2.9**	**3.4**	**3.9**	**4.4**	**4.9**	**5.4**	**5.9**	**6.4**	**6.9**	**7.4**
Medium- and Heavy-Duty Trucks	+	0.1	0.4	1.4	1.6	1.8	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5
Rail	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ships and Boats	+	+	0.3	0.9	1.2	1.5	1.7	2.0	2.3	2.6	2.9	3.3	3.6	3.9
Total	**+**	**19.6**	**56.2**	**71.1**	**68.1**	**62.4**	**57.1**	**51.6**	**48.8**	**46.3**	**43.3**	**40.1**	**38.5**	**36.7**

+ 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-106 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 2,118.1 MMT CO_2 Eq. in 2019, an increase of 25 percent from 1990.[58] Transportation sources account for 1,907.1 MMT CO_2 Eq. while non-transportation mobile sources account for 211.0 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 Section 3.1 CO_2 Emissions from Fossil Fuel Combustion, 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 Substitution of Ozone Depleting Substances section of the IPPU chapter; and estimates of CO_2 emitted from non-transportation mobile sources reported in Table A-104 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 2019 and DLA 2019). 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.[59] 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 2017). Carbon dioxide emissions from non-transportation mobile sources are calculated using data from the NONROAD component of EPA's MOVES2014b model (EPA 2019a). 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, emissions 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 1,907.1 MMT CO_2 Eq. in 2019.

On-road vehicles were responsible for about 83 percent of all transportation and non-transportation mobile greenhouse gas emissions in 2019. 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 2019, greenhouse gas emissions from passenger cars increased by 22 percent, while emissions from light-duty trucks increased by less than one percent. Meanwhile, greenhouse gas emissions from

[58] 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 <https://www.epa.gov/regulations-emissions-vehicles-and-engines/organic-gas-speciation-profile-aircraft>).

[59] In 2011 FHWA changed how they defined vehicle types for the purposes of reporting VMT for the years 2007 to 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.

medium- and heavy-duty trucks increased 92 percent between 1990 and 2019, reflecting the increased volume of total freight movement and an increasing share transported by trucks.

Greenhouse gas emissions from aircraft decreased four percent between 1990 and 2019. Emissions from military aircraft decreased 66 percent between 1990 and 2019. Commercial aircraft emissions rose 27 percent between 1990 and 2007 then dropped 7 percent from 2007 to 2019, a change of approximately 18 percent between 1990 and 2019.

Non-transportation mobile sources, such as construction/mining equipment, agricultural equipment, and industrial/commercial equipment, emitted approximately 211 MMT CO_2 Eq. in 2019. Together, these sources emitted more greenhouse gases than ships and boats, and rail combined. Emissions from non-transportation mobile sources increased, growing approximately 26 percent between 1990 and 2019. 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-107 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 2018). Emissions of CO_2 from transportation and mobile sources increased by 414.4 MMT CO_2 Eq. between 1990 and 2019. In contrast, the combined emissions of CH_4 and N_2O decreased by 30.6MMT CO_2 Eq. over the same period, due largely to the introduction of control technologies designed to reduce criteria pollutant emissions.[60] Meanwhile, HFC emissions from mobile air-conditioners and refrigerated transport increased from virtually no emissions in 1990 to 36.7 MMT CO_2 Eq. in 2019 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-108 and Table A-109 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-108. 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-109. 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-106. In addition, estimates of fuel consumption from DOE (1993 through 2017) were used to allocate rail emissions between passenger and freight categories.

In 2019, passenger transportation modes emitted 1,303.9 MMT CO_2 Eq., while freight transportation modes emitted 567.8 MMT CO_2 Eq. Between 1990 and 2019, the percentage growth of greenhouse gas emissions from freight sources was 62 percent, while emissions from passenger sources grew by 15 percent. This difference in growth is due largely to the rapid increase in emissions associated with medium- and heavy-duty trucks.

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

Table A-106: Total U.S. Greenhouse Gas Emissions from Transportation and Mobile Sources (MMT CO_2 Eq.)

Mode / Vehicle Type / Fuel Type	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Percent Change 1990-2019
Transportation Total[a]	**1,530.2**	**1,680.1**	**1,921.5**	**1,828.7**	**1,835.1**	**1,808.8**	**1,782.4**	**1,793.0**	**1,797.2**	**1,829.8**	**1,871.9**	**1,882.3**	**1,887.9**	**1,907.1**	**25%**
On-Road Vehicles	**1,206.8**	**1,351.1**	**1,561.5**	**1,544.8**	**1,543.3**	**1,518.1**	**1,501.7**	**1,501.8**	**1,521.3**	**1,541.8**	**1,571.4**	**1,571.1**	**1,569.1**	**1,580.8**	**31%**
Passenger Cars	639.6	635.3	688.1	792.5	784.3	775.4	768.3	761.6	760.3	775.8	787.6	784.9	777.5	782.1	**22%**
Gasoline[b]	631.7	616.3	656.4	758.9	753.1	747.3	743.5	740.0	739.9	756.3	769.5	768.3	761.6	767.0	**21%**
Diesel[b]	7.9	7.8	3.7	3.6	3.7	4.1	4.1	4.1	4.1	4.3	4.3	4.3	4.4	4.4	**-44%**
AFVs[c]	+	+	+	+	+	0.1	0.1	0.2	0.4	0.5	0.7	0.8	1.2	1.4	**NA**
HFCs from Mobile AC	-	11.2	28.0	29.9	27.5	23.9	20.6	17.2	15.8	14.7	13.2	11.4	10.4	9.3	**NA**
Light-Duty Trucks	326.7	428.8	508.3	350.9	348.1	331.1	324.3	320.7	334.7	329.8	339.7	333.7	328.3	329.5	**1%**
Gasoline[b]	315.1	406.0	462.3	303.1	301.3	286.3	282.2	281.1	296.2	292.9	304.3	300.2	295.8	297.9	**-5%**
Diesel[b]	11.5	14.9	20.3	12.1	12.5	13.1	12.9	13.0	13.8	13.9	14.3	14.0	14.1	14.3	**25%**
AFVs[c]	0.2	0.2	0.1	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.3	**60%**
HFCs from Mobile AC	-	7.8	25.6	35.2	34.1	31.6	29.2	26.5	24.7	23.0	21.1	19.2	18.1	16.9	**NA**
Medium- and Heavy-Duty Trucks	230.3	276.0	352.1	380.9	391.3	391.2	387.3	397.7	403.4	412.9	420.8	428.2	437.5	443.1	**92%**
Gasoline[b]	38.5	36.1	36.5	43.4	43.2	39.6	39.3	40.0	40.3	40.6	41.7	42.6	42.6	43.0	**12%**
Diesel[b]	190.7	238.4	312.9	332.1	343.2	346.4	342.6	352.1	357.3	366.4	373.1	379.5	388.5	393.6	**106%**
AFVs[c]	1.2	0.9	0.6	1.0	0.3	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	**-57%**
HFCs from Refrigerated Transport and Mobile AC[e]	-	0.6	2.0	4.4	4.7	4.8	5.0	5.2	5.3	5.5	5.5	5.7	5.9	6.1	**NA**
Buses	8.5	9.2	11.1	16.3	15.9	16.8	17.7	18.0	19.1	19.5	19.2	20.4	21.9	22.2	**162%**
Gasoline[b]	0.3	0.4	0.4	0.8	0.7	0.7	0.8	0.9	0.9	0.9	0.9	1.0	1.0	1.0	**203%**
Diesel[b]	8.0	8.7	10.3	13.7	13.5	14.5	15.3	15.6	16.7	17.0	16.8	17.8	19.2	19.4	**142%**
AFVs[c]	0.1	0.1	0.3	1.4	1.2	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.3	1.3	**1257%**
HFCs from Comfort Cooling	-	+	0.1	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	**NA**
Motorcycles	1.7	1.8	1.9	4.2	3.7	3.6	4.2	3.9	3.8	3.8	4.0	3.9	3.9	3.9	**126%**
Gasoline[b]	1.7	1.8	1.9	4.2	3.7	3.6	4.2	3.9	3.8	3.8	4.0	3.9	3.9	3.9	**126%**
Aircraft	**189.2**	**176.7**	**199.4**	**157.4**	**154.8**	**149.9**	**146.5**	**150.1**	**151.3**	**160.5**	**169.0**	**174.8**	**175.5**	**181.0**	**-4%**
General Aviation Aircraft	42.9	35.8	35.9	21.2	26.7	22.5	19.9	23.6	20.9	26.8	35.1	33.3	32.8	38.4	**-11%**
Jet Fuel[f]	39.8	33.0	33.4	19.4	24.8	20.6	18.2	22.0	19.4	25.3	33.7	31.8	31.2	36.7	**-8%**
Aviation Gasoline	3.2	2.8	2.6	1.9	1.9	1.9	1.8	1.6	1.5	1.5	1.5	1.5	1.6	1.7	**-48%**
Commercial Aircraft	110.9	116.3	140.6	120.6	114.4	115.7	114.3	115.4	116.3	120.1	121.5	129.2	130.8	130.8	**18%**
Jet Fuel[f]	110.9	116.3	140.6	120.6	114.4	115.7	114.3	115.4	116.3	120.1	121.5	129.2	130.8	130.8	**18%**
Military Aircraft	35.3	24.5	22.9	15.5	13.7	11.7	12.2	11.1	14.1	13.6	12.4	12.3	11.9	11.9	**-66%**
Jet Fuel[f]	35.3	24.5	22.9	15.5	13.7	11.7	12.2	11.1	14.1	13.6	12.4	12.3	11.9	11.9	**-66%**
Ships and Boats[d]	**47.4**	**59.5**	**66.5**	**39.7**	**45.6**	**47.3**	**40.9**	**40.4**	**29.2**	**34.1**	**41.4**	**44.4**	**41.4**	**42.4**	**-11%**

Gasoline	14.4	14.5	14.5	12.7	12.1	11.7	11.5	11.2	10.8	11.0	11.1	11.1	11.0	11.0	**-24%**
Distillate Fuel	9.7	15.0	17.4	11.7	11.2	14.1	11.3	11.6	10.1	16.1	14.1	13.0	12.4	12.3	**27%**
Residual Fuel[e]	23.2	30.0	34.3	14.4	21.1	20.0	16.3	15.6	6.0	4.4	13.4	17.0	14.4	15.2	**-35%**
HFCs from Refrigerated Transport[e]	+	+	0.3	0.9	1.2	1.5	1.7	2.0	2.3	2.6	2.9	3.3	3.6	3.9	**NA**
Rail	**39.0**	**43.1**	**46.6**	**41.2**	**43.7**	**45.4**	**43.6**	**44.9**	**46.0**	**43.9**	**40.5**	**41.1**	**42.8**	**40.3**	**3%**
Distillate Fuel[f]	35.8	40.0	42.9	36.4	38.9	40.9	39.5	40.6	41.7	39.9	36.8	37.5	39.2	37.0	**3%**
Electricity	3.1	3.1	3.5	4.5	4.5	4.3	3.9	4.1	4.1	3.8	3.5	3.4	3.4	3.1	**2%**
Other Emissions from Rail Electricity Use[g]	0.1	0.1	+	+	+	+	+	+	+	+	+	0.1	0.1	+	**-100%**
HFCs from Comfort Cooling	-	+	+	+	+	+	+	+	+	+	+	+	+	0.1	**NA**
HFCs from Refrigerated Transport[e]	-	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	**NA**
Pipelines[h]	**36.0**	**38.4**	**35.5**	**37.1**	**37.3**	**38.1**	**40.6**	**46.2**	**39.4**	**38.5**	**39.2**	**41.3**	**49.9**	**53.7**	**49%**
Natural Gas	36.0	38.4	35.5	37.1	37.3	38.1	40.6	46.2	39.4	38.5	39.2	41.3	49.9	53.7	**49%**
Other Transportation	**11.8**	**11.3**	**12.1**	**8.5**	**10.4**	**10.0**	**9.1**	**9.6**	**10.0**	**11.0**	**10.4**	**9.6**	**9.2**	**8.9**	**-25%**
Lubricants	11.8	11.3	12.1	8.5	10.4	10.0	9.1	9.6	10.0	11.0	10.4	9.6	9.2	8.9	**-25%**
Non-Transportation Mobile[i] Total	**167.5**	**174.4**	**179.9**	**204.3**	**207.0**	**205.1**	**205.2**	**207.3**	**203.1**	**193.1**	**196.1**	**202.6**	**207.1**	**211.0**	**26%**
Agricultural Equipment[i,j]	**44.8**	**44.7**	**41.1**	**47.8**	**48.0**	**48.3**	**49.6**	**47.2**	**47.2**	**42.1**	**41.1**	**40.7**	**40.7**	**40.5**	**-10%**
Gasoline	7.7	8.7	6.1	6.4	6.5	7.5	8.3	6.2	5.9	1.5	1.6	1.6	1.5	1.2	**-84%**
Diesel	37.1	35.8	34.9	41.4	41.4	40.6	41.2	40.9	41.2	40.5	39.4	39.0	39.1	39.2	**6%**
CNG	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	**-13%**
LPG	+	+	+	+	+	+	+	+	+	+	+	+	+	+	**-9%**
Construction/Mining Equipment[i,k]	**50.3**	**54.2**	**59.0**	**67.8**	**67.0**	**65.7**	**64.6**	**67.9**	**62.6**	**58.3**	**61.4**	**66.5**	**69.6**	**71.7**	**43%**
Gasoline	4.4	4.1	3.3	5.5	6.4	6.0	6.1	10.3	6.5	3.4	3.5	3.5	3.5	3.5	**-20%**
Diesel	45.5	49.7	55.1	61.8	60.1	59.2	58.0	57.1	55.7	54.5	57.4	62.5	65.6	67.7	**49%**
CNG	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	**26%**
LPG	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	**21%**
Other Equipment[i,l]	**72.3**	**75.5**	**79.7**	**88.7**	**92.0**	**91.1**	**91.1**	**92.3**	**93.3**	**92.7**	**93.6**	**95.4**	**96.8**	**98.8**	**37%**
Gasoline	40.6	41.5	43.4	49.5	51.6	49.8	48.3	48.3	48.0	47.1	47.7	48.1	47.6	48.1	**18%**
Diesel	22.1	21.8	21.8	24.9	25.7	26.4	27.6	28.6	29.4	29.7	29.8	30.5	31.7	32.6	**47%**
CNG	1.2	1.3	1.4	1.6	1.7	1.8	2.0	2.1	2.2	2.2	2.1	2.2	2.3	2.4	**101%**
LPG	8.5	10.9	13.2	12.7	13.0	13.0	13.1	13.3	13.5	13.7	14.0	14.5	15.3	15.8	**86%**
Transportation and Non-Transportation Mobile Total[l]	**1,697.7**	**1,854.5**	**2,101.4**	**2,032.9**	**2,042.1**	**2,013.9**	**1,987.6**	**2,000.3**	**2,000.3**	**2,022.9**	**2,068.0**	**2,084.9**	**2,095.0**	**2,118.1**	**25%**

+ 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 2019). Data from Table VM-1 are used to estimate the share of fuel consumption between each on-road vehicle class. 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 2019). 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 2018). TEDB data for 2018 has not been published yet, therefore 2017 data are used as a proxy.

[c] In 2017, 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 incorporated into this year's Inventory and apply to the 2005 to 2019 time period.

[d] 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.

[e] 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.

[f] Class II and Class III diesel consumption data for 2014 to 2019 is not available. Diesel consumption data for 2014-2019 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[g] 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).

[h] 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.

[i] Note that the method used to estimate CO_2 emissions from non-transportation mobile sources in this supplementary information table differs from the method used to estimate CO_2 in the industrial and commercial sectors in the Inventory, which include CO_2 emissions from all non-transportation mobile sources (see Section 3.1 for the methodology for estimating CO_2 emissions from fossil fuel combustion in this Inventory).

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

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

[l] "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 (MOVES2014b) model that is used to estimate on-road gasoline vehicle distribution and mileage across the time series, as well as non-transportation mobile fuel consumption. 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 MOVES2014b for years 1999 through 2019. In 2016, historical confidential vehicle sales data were 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, the 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 not included in the engine technology breakouts. For this Inventory, HEVs are classified as gasoline vehicles across the entire time series.

Table A-107: Transportation and Mobile Source Emissions by Gas (MMT CO_2 Eq.)

	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Percent Change 1990-2019
CO_2 [a]	1,646.0	1,773.0	1,985.4	1,926.1	1,939.1	1,918.0	1,899.7	1,919.8	1,924.9	1,952.0	2,000.9	2,021.9	2,034.9	2,060.4	**25%**
N_2O	45.2	55.8	55.0	32.3	31.5	30.1	27.7	25.9	23.8	21.9	21.1	20.2	19.1	18.6	**-59%**
CH_4	6.4	6.0	4.8	3.3	3.3	3.2	3.0	2.9	2.7	2.6	2.5	2.5	2.4	2.4	**-63%**
HFC	+	19.6	56.2	71.1	68.1	62.4	57.1	51.6	48.8	46.3	43.3	40.1	38.5	36.7	**NA**
Total[b]	**1,697.6**	**1,854.4**	**2,101.3**	**2,032.8**	**2,042.0**	**2,013.8**	**1,987.5**	**2,000.2**	**2,000.2**	**2,022.8**	**2,067.9**	**2,084.8**	**2,094.9**	**2,118.1**	**25%**

[a] 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.

[b] The method used to estimate CO_2 emissions from non-transportation mobile sources in this supplementary information table differs from the method used to estimate CO_2 in the industrial and commercial sectors in the Inventory, which include CO_2 emissions from all non-transportation mobile sources (see Section 3.1 for the methodology for estimating CO_2 emissions from fossil fuel combustion in this Inventory).

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

Note: 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 2018). Data from Table VM-1 is used to estimate the share of fuel consumption between each on-road vehicle class. 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 2019). 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 2018). TEDB data for 2018 has not been published yet, therefore 2017 data are used 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, the 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 not included in the engine technology breakouts. For this Inventory, HEVs are classified as gasoline vehicles across the entire time series.

Figure A-4: Domestic Greenhouse Gas Emissions by Mode and Vehicle Type, 1990 to 2019

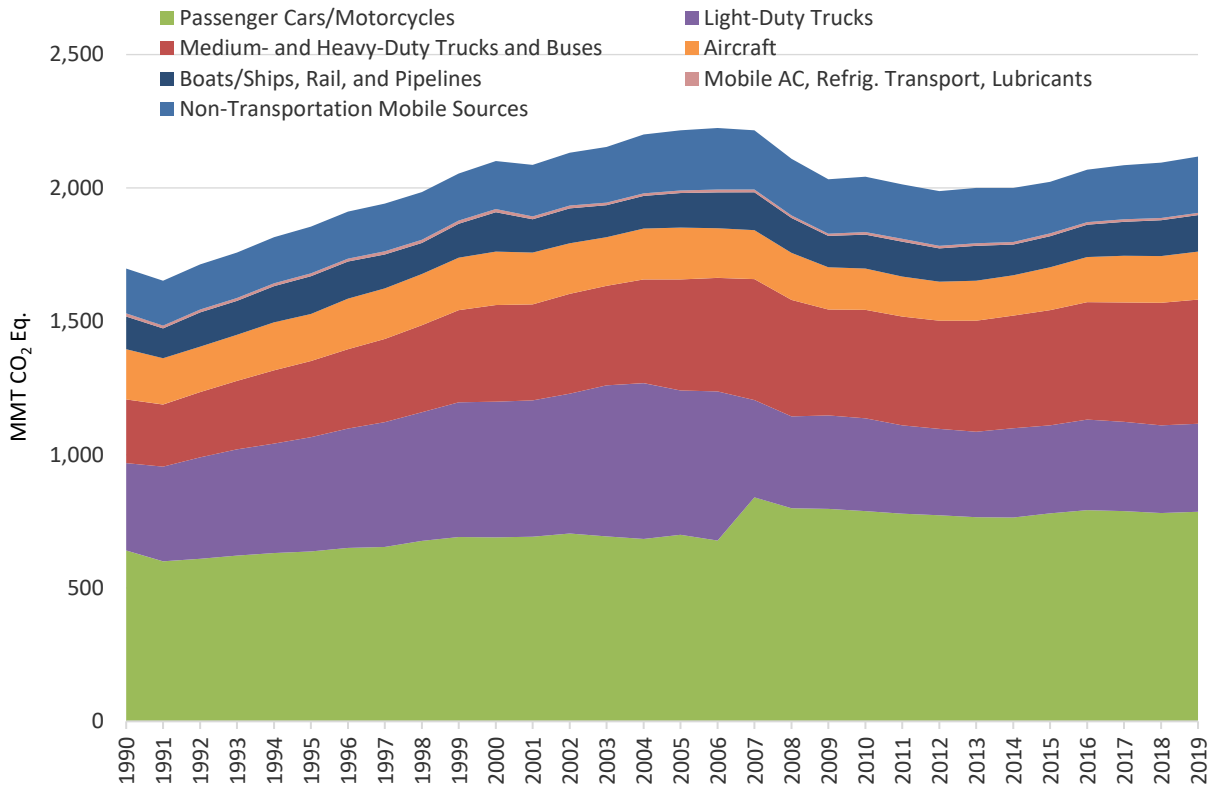


Table A-108: Greenhouse Gas Emissions from Passenger Transportation (MMT CO_2 Eq.)

Vehicle Type	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Percent Change 1990-2019
On-Road Vehicles[a,b]	**976.5**	**1,075.1**	**1,209.4**	**1,163.8**	**1,152.0**	**1,126.9**	**1,114.4**	**1,104.2**	**1,141.2**	**1,128.9**	**1,150.6**	**1,143.0**	**1,131.5**	**1,137.6**	**17%**
Passenger Cars	639.6	635.3	688.1	792.5	784.3	775.4	768.3	761.6	776.8	775.8	787.6	784.9	777.5	782.1	22%
Light-Duty Trucks	326.7	428.8	508.3	350.9	348.1	331.1	324.3	320.7	341.4	329.8	339.7	333.7	328.3	329.5	1%
Buses	8.5	9.2	11.1	16.3	15.9	16.8	17.7	18.0	19.1	19.5	19.2	20.4	21.9	22.2	162%
Motorcycles	1.7	1.8	1.9	4.2	3.7	3.6	4.2	3.9	3.9	3.8	4.0	3.9	3.9	3.9	126%
Aircraft	**134.6**	**132.0**	**152.2**	**125.2**	**124.8**	**122.1**	**118.5**	**123.1**	**120.9**	**130.5**	**139.8**	**144.1**	**144.9**	**150.5**	**12%**
General Aviation	42.9	35.8	35.9	21.2	26.7	22.5	19.9	23.6	20.9	26.8	35.1	33.3	32.8	38.4	-11%
Commercial Aircraft	91.7	96.2	116.3	103.9	98.0	99.6	98.6	99.5	100.0	103.6	104.7	110.7	112.1	112.1	22%
Recreational Boats	**17.2**	**17.2**	**17.3**	**15.5**	**14.8**	**14.4**	**14.0**	**13.8**	**(3.3)**	**13.9**	**11.1**	**11.1**	**11.0**	**11.0**	**-36%**
Passenger Rail	**4.4**	**4.5**	**5.2**	**6.2**	**6.2**	**6.0**	**5.5**	**5.8**	**5.7**	**5.4**	**5.2**	**5.1**	**5.0**	**4.8**	**9%**
Total	**1,132.7**	**1,228.8**	**1,384.2**	**1,310.7**	**1,297.8**	**1,269.4**	**1,252.5**	**1,246.9**	**1,264.6**	**1,278.6**	**1,306.7**	**1,303.2**	**1,292.4**	**1,303.9**	**15%**

[a] The current Inventory includes updated vehicle population data based on the MOVES2014b 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 2018). Data from Table VM-1 is used to estimate the share of fuel consumption between each on-road vehicle class. 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 2018). 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 2017). TEDB data for 2018 has not been published yet, therefore 2017 data are used as a proxy.

Notes: Data from DOE (1993 through 2017) 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 MOVES2014b for years 1999 through 2018. In 2017, 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 incorporated into this year's Inventory and apply to the 2005 to 2018 time period.

In 2016, historical confidential vehicle sales data were 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, the 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 not included in the engine technology breakouts. For this Inventory, HEVs are classified as gasoline vehicles across the entire time series.

Table A-109: Greenhouse Gas Emissions from Domestic Freight Transportation (MMT CO_2 Eq.)

By Mode	1990	1995	2000	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Percent Change 1990-2019
Trucking[a,b]	230.3	275.5	350.5	377.9	388.3	388.2	384.4	394.7	400.5	410.1	418.1	425.6	434.9	440.5	**91%**
Freight Rail	34.5	38.6	41.3	34.9	37.4	39.4	38.0	39.0	40.2	38.4	35.3	36.0	37.7	35.5	**3%**

Ships and Non-Recreational Boats	30.2	42.3	49.2	24.2	30.8	32.9	26.9	31.0	19.6	16.6	16.7	20.6	18.3	19.4	**-36%**
Pipelines[c]	36.0	38.4	35.5	37.1	37.3	38.1	40.6	46.2	39.4	38.5	39.2	41.3	49.9	53.7	**49%**
Commercial Aircraft	19.2	20.1	24.3	16.7	16.3	16.0	15.8	15.9	16.2	16.5	16.8	18.4	18.7	18.7	**-3%**
Total	**350.3**	**414.9**	**500.8**	**490.8**	**510.1**	**514.7**	**505.6**	**526.9**	**515.9**	**520.0**	**526.0**	**541.8**	**559.6**	**567.8**	**62%**

[a] The current Inventory includes updated vehicle population data based on the MOVES2014b 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 2018). Data from Table VM-1 is used to estimate the share of fuel consumption between each on-road vehicle class. 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 2018). 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 2017). TEDB data for 2018 has not been published yet, therefore 2017 data are as a proxy.

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

Notes: Data from DOE (1993 through 2017) 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 MOVES2014b for years 1999 through 2018. In 2017, 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 incorporated into this year's Inventory and apply to the 2005 to 2018 time period.

In 2016, historical confidential vehicle sales data were 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, the 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 not included in the engine technology breakouts. For this Inventory, HEVs are classified as gasoline vehicles across the entire time series.

References

AAR (2008 through 2019) *Railroad Facts.* Policy and Economics Department, Association of American Railroads, Washington, D.C.

ANL (2019) *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET 2018)*. Argonne National Laboratory. October 2017. Available at <https://greet.es.anl.gov>.

APTA (2007 through 2019) *Public Transportation Fact Book.* American Public Transportation Association, Washington, D.C. Available online at: <http://www.apta.com/resources/statistics/Pages/transitstats.aspx>.

APTA (2006) *Commuter Rail National Totals.* American Public Transportation Association, Washington, D.C. Available online at: <http://www.apta.com/research/stats/rail/crsum.cfm>.

BEA (2019) *Table 1.1.6. Real Gross Domestic Product, Chained 2009 Dollars*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. March 2017. Available online at: <http://www.bea.gov/iTable/iTable.cfm?ReqID=9&step=1#reqid=9&step=3&isuri=1&904=1990&903=6&906=a&905=2013&910=x&911=0>.

Benson, D. (2002 through 2004) Unpublished data. Upper Great Plains Transportation Institute, North Dakota State University and American Short Line & Regional Railroad Association.

Browning (2019) *Updated On-highway CH_4 and N_2O Emission Factors for GHG Inventory*. Memorandum from ICF to Sarah Roberts and Justine Geidosch, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2019.

Browning, L. (2018a). *Updated Methodology for Estimating Electricity Use from Highway Plug-In Electric Vehicles*. Technical Memo, October 2018.

Browning, L. (2018b). *Updated Non-Highway CH_4 and N_2O Emission Factors for U.S. GHG Inventory*. Technical Memo, November 2018.

Browning, L. (2017) "Updated Methodology for Estimating CH_4 and N_2O Emissions from Highway Vehicle Alternative Fuel Vehicles". Technical Memo, October 2017.

Browning, L. (2005) Personal communication with Lou Browning, Emission control technologies for diesel highway vehicles specialist, ICF.

DHS (2008) Email Communication. Elissa Kay, Department of Homeland Security and Joe Aamidor, ICF International. January 11, 2008.

DLA Energy (2019) 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.

DOC (1991 through 2019) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, D.C.

DOE (1993 through 2018) *Transportation Energy Data Book Edition 36*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. ORNL-6978.

DOT (1991 through 2019) Airline *Fuel Cost and Consumption*. U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, D.C. DAI-10. Available online at: <http://www.transtats.bts.gov/fuel.asp>.

EEA (2009*) EMEP/EAA Air Pollutant Emission Inventory Guidebook*. European Environment Agency, Copenhagen, Denmark. Available online at: <https://www.eea.europa.eu/themes/air/emep-eea-air-pollutant-emission-inventory-guidebook/emep>EIA (2017a) *Monthly Energy Review, October 2017,* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2017/10).

EIA (2019a) *Monthly Energy Review, November 2019,* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2019/11).

EIA (2019f) *Natural Gas Annual 2018.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0131(06).

EIA (2019h) *Alternative Fuels Data Tables*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: <http://www.eia.doe.gov/fuelalternate.html>.

EIA (1991 through 2019) *Fuel Oil and Kerosene Sales.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: <http://www.eia.gov/petroleum/fueloilkerosene/>.

EPA (2019a*). Motor Vehicle Emissions Simulator (MOVES) 2014b*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: <https://www.epa.gov/moves>.

EPA (2020b) "1970 - 2019 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards. Available online at: <https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data >.

EPA (2019c) Confidential Engine Family Sales Data Submitted to EPA By Manufacturers. Office of Transportation and Air Quality, U.S. Environmental Protection Agency.

EPA (2018d) Annual Certification Test Results Report. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: <https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-test-data-vehicles-and-engines>.

EPA (2000) *Mobile6 Vehicle Emission Modeling Software*. Office of Mobile Sources, U.S. Environmental Protection Agency, Ann Arbor, Michigan.

EPA (1999) Regulatory Announcement: EPA's Program for Cleaner Vehicles and Cleaner Gasoline. Office of Mobile Sources. December 1999. EPA420-F-99-051. Available online at: <https://nepis.epa.gov/Exe/ZyPDF.cgi/P1001Z9W.PDF?Dockey=P1001Z9W.PDF>.

EPA (1998) *Emissions of Nitrous Oxide from Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–1996*. Office of Mobile Sources, Assessment and Modeling Division, U.S. Environmental Protection Agency. August 1998. EPA420-R-98-009.

FAA (2019) Personal Communication between FAA and John Steller, Mausami Desai, and Vincent Camobreco for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). January 2019.

FHWA (1996 through 2019) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report FHWA-PL-96-023-annual. Available online at: <http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.htm>.

FHWA (2015) *Off-Highway and Public-Use Gasoline Consumption Estimation Models Used in the Federal Highway Administration*, Publication Number FHWA-PL-17-012. Available online at: <https://www.fhwa.dot.gov/policyinformation/pubs/pl17012.pdf>.

Gaffney, J. (2007) Email Communication. John Gaffney, American Public Transportation Association and Joe Aamidor, ICF International. December 17, 2007.

HybridCars.com (2020). Monthly Plug-In Electric Vehicle Sales Dashboard, 2010-2019. Available online at <https://www.hybridcars.com/december-2017-dashboard/>.

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.

ICF (2004) *Update of Methane and Nitrous Oxide Emission Factors for On-Highway Vehicles*. Final Report to U.S. Environmental Protection Agency. February 2004.

RailInc (2014 through 2019) *RailInc Short line and Regional Traffic Index.* Carloads Originated Year-to-Date. December 2019. Available online at: < https://www.railinc.com/rportal/railinc-indexes>.

Santoni, G., B. Lee, E. Wood, S. Herndon, R. Miake-Lye, S Wofsy, J. McManus, D. Nelson, M. Zahniser (2011) Aircraft emissions of methane and nitrous oxide during the alternative aviation fuel experiment. Environ Sci Technol. 2011 Aug 15; 45(16):7075-82.

Wards Intelligence (2019-2020) U.S. Light Vehicle Sales Report. August 2020

Whorton, D. (2006 through 2014) Personal communication, Class II and III Rail energy consumption, American Short Line and Regional Railroad Association.

3.3. Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption[61] – TO BE UPDATED FOR THE FINAL INVENTORY REPORT

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 2018 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*.

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 2018 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, 2015, 2016, 2017 and 2018 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 Tier 3B 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 additional 1995-1999 emissions estimates, which were established using previously available trends. International consumption estimates for 1991-1999 and domestic consumption estimates for 1991-1994 are calculated using fuel consumption estimates from the Bureau of Transportation Statistics (DOT 1991 through 2013), adjusted based on the ratio of DOT to AEDT data.

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 2018 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

[61] Estimates for 2019 were not available for Public Review and were proxied to 2018 values.

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 inventory is approximately 15.2 percent lower than the 2018 CO_2 emissions inventory. It is important to note that the distance flown increased by 58 percent over this 28-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.[62]

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 (*Aircraft Emissions of Methane and Nitrous Oxide during the Alternative Aviation Fuel Experiment*, Santoni et al., Environ. Sci. Technol., 2011, 45, 7075-7082). As a result, the U.S. Environmental Protection Agency 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."*[63] In accordance with the following statements in the 2006 IPCC Guidelines (IPCC 2006), the FAA does not calculate CH4 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)

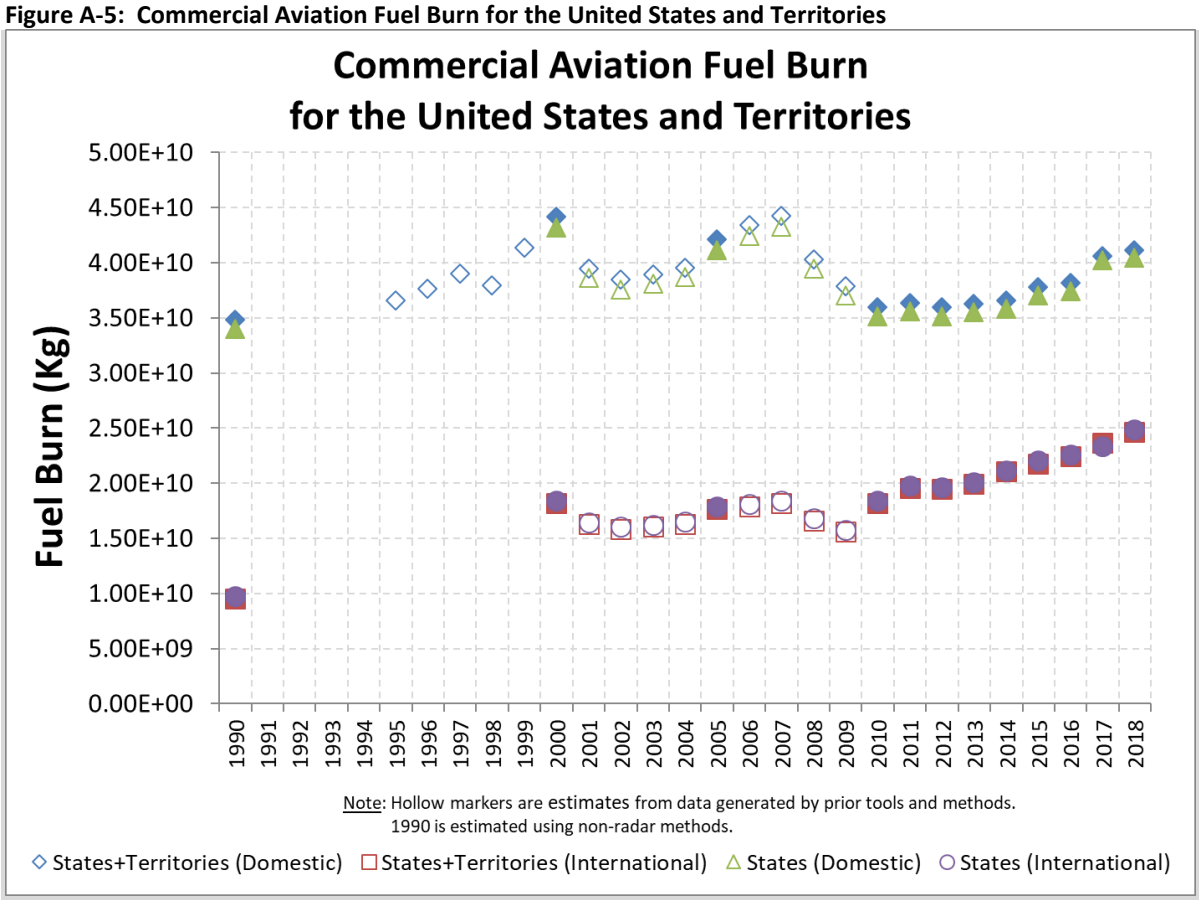
Results: For each inventory calendar year the graph and table below include four jet fuel burn values. These values are comprised of domestic and international fuel burn totals for the U.S. 50 States and the U.S. 50 States + Territories. Data are presented for domestic defined as jet fuel burn from any 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.

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

[63] 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, http://www.epa.gov/otaq/aviation.htm

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 method.

Table A-110: 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[a]	Domestic U.S. 50 States and U.S. Territories	NA	12,136	1,638	36,528,990,675	115.2
1996[a]	Domestic U.S. 50 States and U.S. Territories	NA	12,492	1,686	37,600,624,534	118.6
1997[a]	Domestic U.S. 50 States and U.S. Territories	NA	12,937	1,747	38,940,896,854	122.9
1998[a]	Domestic U.S. 50 States and U.S. Territories	NA	12,601	1,701	37,930,582,643	119.7
1999[a]	Domestic U.S. 50 States and U.S. Territories	NA	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[a]	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[a]	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[a]	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[a]	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[a]	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[a]	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[a]	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[a]	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
2015	Domestic U.S. 50 States and U.S. Territories	5,900,440,363	12,534	1,692	37,727,860,796	119.0
	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
2016	Domestic U.S. 50 States and U.S. Territories	5,929,429,373	12,674	1,711	38,148,578,811	120.4
	International U.S. 50 States and U.S. Territories	1,817,739,570	7,453	1006	22,434,619,940	70.8
	Domestic U.S 50 States	5,827,141,640	12,422	1,677	37,391,339,601	118.0
	International U.S. 50 States	1,839,651,091	7,504	1013	22,588,366,704	71.3
2017	Domestic U.S. 50 States and U.S. Territories	6,264,650,997	13,475	1,819	40,560,206,261	128.0
	International U.S. 50 States and U.S. Territories	1,944,104,275	7,841	1,059	23,602,935,694	74.5
	Domestic U.S. 50 States	6,214,083,068	13,358	1,803	40,207,759,885	126.9
	International U.S. 50 States	1,912,096,739	7,755	1,047	23,343,627,689	73.6
2018	Domestic U.S. 50 States and U.S. Territories	6,408,870,104	13,650	1,843	41,085,494,597	129.6
	International U.S. 50 States and U.S. Territories	2,037,055,865	8,178	1,104	24,616,382,063	77.7
	Domestic U.S. 50 States	6,318,774,158	13,425	1,812	40,410,478,534	127.5
	International U.S. 50 States	2,066,756,708	8,254	1,114	24,843,232,462	78.4

NA (Not Applicable)

[a] Estimates for these years were derived from previously reported tools and methods.

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.

IPCC (1999) *Aviation and the Global Atmosphere. Intergovernmental Panel on Climate Change*. [J.E. Penner, et al. (eds.)]. Cambridge University Press. Cambridge, United Kingdom.

Santoni, G., B. Lee, E. Wood, S. Herndon, R. Miake-Lye, S Wofsy, J. McManus, D. Nelson, M. Zahniser (2011) *Aircraft emissions of methane and nitrous oxide during the alternative aviation fuel experiment*. Environ Sci Technol. 2011 Aug 15; 45(16):7075-82.

3.4. Methodology for Estimating CH_4 Emissions from Coal Mining

EPA uses an IPCC Tier 3 method for estimating CH_4 emissions from underground mining and an IPCC Tier 2 method for estimating CH_4 emissions from surface mining and post-mining activities (for both coal production from underground mines and surface mines). 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 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 concentration 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 2020).[64] 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 2019, 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 17,525 MT CO_2 Eq.)—have been required to report to EPA's GHGRP (EPA 2020).[65] Mines that report to EPA's GHGRP must report quarterly measurements of CH_4 emissions from ventilation systems; 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 United States with detectable CH_4 concentrations.

Since 2013, ventilation emission estimates have been calculated based on both EPA's GHGRP[66] data submitted by underground mines, and on mine-specific CH_4 measurement data obtained directly from MSHA for the remaining mines. The MSHA measurement data are used to determine the average daily emission rate for all mines in the reporting year. The CH_4 liberated from ventilation systems was estimated by summing the emissions from the mines reporting to EPA's GHGRP and emissions based on MSHA measurements for the remaining mines not reporting to EPA's GHGRP.

[64] 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.

[65] Underground coal mines report to EPA under subpart FF of EPA's GHGRP (40 CFR part 98). In 2019, 65 underground coal mines reported to the program.

[66] In implementing improvements and integrating data from EPA's GHGRP, the EPA followed the latest guidance from the IPCC on the use of facility-level data in national inventories (IPCC 2011).

Table A-111: 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)[a]
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) [a]
1994	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) [a]
1995	All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total) [a]
1996	All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total) [a]
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) [a]
1999	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) [a]
2000	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) [a]
2001	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) [a]
2002	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) [a]
2003	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) [a]
2004	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) [a]
2005	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) [a]
2006	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) [a]
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) [b]
2009	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total) [b]
2010	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total) [b]
2011	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total) [b]
2012	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total) [b]
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)
2016	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2017	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2018	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2019	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)

[a] Factor derived from a complete set of individual mine data collected for 1997.
[b] 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).

Nineteen mines employed degasification systems in 2019, and 17 of these mines reported the CH_4 liberated through these systems to the EPA's GHGRP (EPA 2020). Thirteen of the 19 mines with degasification systems had operational CH_4 recovery and use projects, and the other six 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 exclusively to estimate CH_4 liberated from degasification systems at 14 of the 19 mines that used degasification systems in 2019.

Degasification volumes for the life of mined-through, pre-mining wells are attributed to the mine as emissions in the year in which the well is mined through.[67] 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 five mines with degasification systems that include pre-mining wells that were mined through in 2019, EPA's GHGRP information was supplemented with historical data from state gas well production databases and mine-specific information regarding the dates on which pre-mining wells were mined through (GSA 2020; DMME 2020; WVGES 2020; JWR 2010; El Paso 2009; ERG 2020). For pre-mining wells, the cumulative CH_4 production from the well is totaled using gas sales data and is considered liberated from the mine's degasification system the year in which the well is mined through.

Reports to EPA's GHGRP with CH_4 liberated from degasification systems are reviewed for errors in reporting. For some mines, 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 GHGRP data are inaccurate and gas sales data are 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)

There were 13 active coal mines with operational CH_4 recovery and use projects in 2019. Twelve of these projects involved degasification systems and one involved ventilation air methane (VAM). Eleven of these mines sold the recovered CH_4 to a pipeline, including one mine that used CH_4 to fuel a thermal coal dryer. One mine used CH_4 to heat mine ventilation air (data was unavailable for estimating CH_4 recovery at this mine). One mine destroyed the recovered CH_4 (VAM) using Regenerative Thermal Oxidation (RTO) without energy recovery.

The CH_4 recovered and used (or destroyed) at the thirteen coal mines described above for which data were available were estimated using the following methods:

- EPA's GHGRP data was exclusively used to estimate the CH_4 recovered and used from seven mines that deployed degasification systems in 2019. 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. Reports to EPA's GHGRP are reviewed for errors in reporting. For some mines, GHGRP data are corrected for the Inventory based on expert judgment (see further discussion in Step 1.2).
- For the single mine that employed VAM for CH_4 recovery and use, the estimates of CH_4 recovered and used were obtained from the mine's offset verification statement (OVS) submitted to the California Air Resources Board (CARB) (McElroy OVS 2020). State sales data were used to estimate CH_4 recovered and used from the remaining five mines that deployed degasification systems in 2019 (DMME 2020; GSA 20). These five mines intersected pre-mining wells in 2019. Supplemental information was used for these mines because estimating CH_4 recovery and use from pre-mining wells requires additional data (data not reported under subpart FF of EPA's GHGRP; see discussion in step 1.2 above) to account for the emissions avoided prior to the well being mined through. The 2019 data came from state gas production databases (DMME 2020; GSA 2020; WVGES 2020), as well as mine-specific information on the timing of mined-through, pre-mining wells (JWR 2010; El Paso 2009, ERG 2019-2020). For pre-mining wells, the cumulative CH_4 production from the wells was totaled using gas sales data, and was considered to be CH_4 recovered and used from the mine's degasification system in the year in which the well was mined through.

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 (King 1994; Saghafi 2013). For post-mining activities, basin-

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

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-112, which presents coal basin definitions by basin and by state.

The Energy Information Administration's *Annual Coal Report* (EIA 2020) 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-112. 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-113 presents the coal production data aggregated by basin.

Step 2.2: Estimate Emission 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 United States (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-114 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-112 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-113 shows annual underground, surface, and total coal production (in short tons) for each coal basin. Table A-114 shows the surface, post-surface, and post-underground emission factors used for estimating CH_4 emissions for each of the categories. For underground mines,

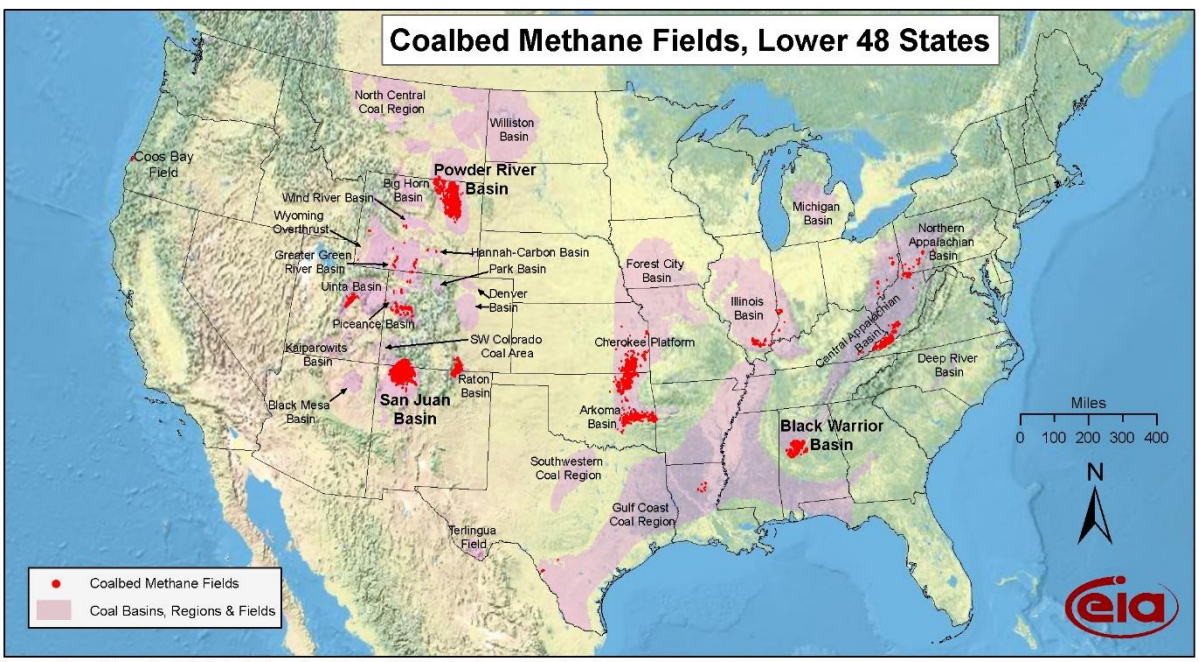
Table A-115 presents annual estimates of CH_4 emissions for ventilation and degasification systems, and CH_4 recovered and used. Table A-116 presents annual estimates of total CH_4 emissions from underground, post-underground, surface, and post-surface activities.

Table A-112: 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-113: Annual Coal Production (Thousand Short Tons)

Basin	1990	2005	2015	2016	2017	2018	2019
Underground Coal Production	**423,556**	**368,612**	**306,821**	**252,106**	**273,129**	**275,361**	**267,373**
N. Appalachia	103,865	111,151	103,579	94,685	97,741	97,070	97,905
Cent. Appalachia	198,412	123,082	53,230	39,800	46,053	45,306	39,957
Warrior	17,531	13,295	9,897	7,434	10,491	12,199	11,980
Illinois	69,167	59,180	96,361	76,578	80,855	85,416	81,061
S. West/Rockies	32,754	60,866	33,762	26,413	30,047	25,387	27,257
N. Great Plains	1,722	572	9,510	6,776	7,600	9,777	9,213
West Interior	105	465	482	420	343	206	0
Northwest	0	0	0	0	0	0	0
Surface Coal Production	**602,753**	**762,190**	**588,736**	**475,407**	**500,782**	**480,080**	**438,445**
N. Appalachia	60,761	81,439	31,704	23,989	29,341	31,111	8,476
Cent. Appalachia	94,343	59,656	19,027	11,509	11,850	11,907	32,742
Warrior	11,413	11,599	6,437	5,079	4,974	5,523	4,841
Illinois	72,000	33,703	27,359	21,707	22,427	21,405	18,591
S. West/Rockies	43,863	42,756	26,019	18,951	19,390	19,599	18,394
N. Great Plains	249,356	474,056	436,929	350,898	372,874	362,664	329,164
West Interior	64,310	52,262	40,084	42,342	38,966	26,969	25,261
Northwest	6,707	6,720	1,177	932	959	902	975
Total Coal Production	**1,026,309**	**1,130,802**	**895,557**	**727,514**	**773,911**	**755,442**	**705,818**
N. Appalachia	164,626	192,589	135,283	118,674	127,082	128,181	106,381
Cent. Appalachia	292,755	182,739	72,257	51,308	57,903	57,213	72,700
Warrior	28,944	24,894	16,334	12,513	15,464	17,723	16,822
Illinois	141,167	92,883	123,720	98,285	103,282	106,821	99,652
S. West/Rockies	76,617	103,622	59,781	45,364	49,437	44,987	45,652
N. Great Plains	251,078	474,629	446,438	357,675	380,474	372,441	338,376
West Interior	64,415	52,727	40,566	42,763	39,309	27,175	25,261
Northwest	6,707	6,720	1,177	932	959	902	975

Notes: Totals may not sum due to independent rounding.

Table A-114: 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 Factors
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	5.2	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-115: Underground Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	2005	2015	2016	2017	2018	2019
Ventilation Output	112	75	84	76	78	73	62
Adjustment Factor for Mine Data	98%	98%	100%	100%	100%	100%	100%
Adjusted Ventilation Output	114	77	84	76	78	73	62
Degasification System Liberated	54	47	43	42	42	47	42
Total Underground Liberated	168	124	127	119	121	120	104
Recovered & Used	(14)	(37)	(34)	(34)	(36)	(39)	(33)
Total	**154**	**87**	**93**	**85**	**84**	**81**	**72**

Table A-116: Total Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	2005	2015	2016	2017	2018	2019
Underground Mining	154	87	93	85	84	81	72
Surface Mining	22	27	19	15	16	16	13
Post-Mining (Underground)	19	16	12	10	11	11	11
Post-Mining (Surface)	5	6	4	3	3	3	3
Total	**200**	**137**	**128**	**113**	**115**	**111**	**98**

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

Table A-117: Total Coal Mining CH_4 Emissions by State (Million Cubic Feet)

State	1990	2005	2015	2016	2017	2018	2019
Alabama	32,097	15,789	12,675	10,752	11,044	12,119	9,494
Alaska	50	42	34	27	28	26	28
Arizona	151	161	91	72	83	87	51
Arkansas	5	+	559	247	770	71	0
California	1	0	0	0	0	0	0
Colorado	10,187	13,441	3,248	2,272	1,940	1,616	1,730
Illinois	10,180	6,488	10,547	11,034	8,513	6,530	5,661
Indiana	2,232	3,303	6,891	6,713	6,036	6,729	6,807
Iowa	24	0	0	0	0	0	0
Kansas	45	11	12	2	0	0	0
Kentucky	10,018	6,898	6,378	4,880	4,636	4,636	2,264
Louisiana	64	84	69	56	42	129	36
Maryland	474	361	171	131	152	113	119
Mississippi	0	199	176	161	146	165	151
Missouri	166	37	9	15	15	16	12
Montana	1,373	1,468	1,353	1,004	1,102	1,172	1,038
New Mexico	363	2,926	2,648	1,954	1,728	1,360	1,446
North Dakota	299	306	294	287	294	303	276
Ohio	4,406	3,120	2,718	1,998	1,473	1,342	1,283
Oklahoma	226	825	736	867	2,407	2,317	116
Pennsylvania	21,864	18,605	19,554	17,932	19,662	20,695	23,528
Tennessee	276	115	40	27	14	23	17
Texas	1,119	922	721	783	730	498	468
Utah	3,587	4,787	1,737	788	678	629	811
Virginia	46,041	8,649	6,396	6,692	7,663	7,051	6,959
Washington	146	154	0	0	0	0	0

West Virginia	48,335	33,064	37,628	33,272	34,382	30,068	25,711
Wyoming	6,671	14,745	13,624	10,812	11,497	13,201	10,409
Total	**200,399**	**136,501**	**128,307**	**112,778**	**115,036**	**110,897**	**98,416**

+ 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.

References

AAPG (1984) Coalbed Methane Resources of the United States. AAPG Studies in Geology Series #17.

Creedy, D.P. (1993) Chemosphere. Vol. 26, pp. 419-440.

DMME (2020) *DGO Data Information System*. Department of Mines, Minerals and Energy of Virginia. Available online at <https://www.dmme.virginia.gov/dgoinquiry/frmmain.aspx>.

EIA (2020) Annual Coal Report 2019. Table 1. Energy Information Administration, U.S. Department of Energy.

El Paso (2009) Shoal Creek Mine Plan, El Paso Exploration & Production.

EPA (2020) Greenhouse Gas Reporting Program (GHGRP) 2018 Envirofacts. Subpart FF: Underground Coal Mines. Available online at <http://www.epa.gov/ghgreporting/ghgdata/reported/coalmines.html>.

EPA (2005) Surface Mines Emissions Assessment. Draft. U.S. Environmental Protection Agency.

EPA (1996) Evaluation and Analysis of Gas Content and Coal Properties of Major Coal Bearing Regions of the United States. U.S. Environmental Protection Agency. EPA/600/R-96-065.

ERG (2019-2020). Correspondence between ERG and Buchanan Mine.

Geological Survey of Alabama State Oil and Gas Board (GSA) (2020) Well Records Database. Available online at <http://www.gsa.state.al.us/ogb/database.aspx>.

IPCC (2011) Use of Models and Facility-Level Data in Greenhouse Gas Inventories. Report of IPCC Expert Meeting on Use of Models and Measurements in Greenhouse Gas Inventories 9-11 August 2010, Sydney, Australia. Eds: Eggleston H.S., Srivastava N., Tanabe K., Baasansuren J., Fukuda M. IGES.

JWR (2010) No. 4 & 7 Mines General Area Maps. Walter Energy: Jim Walter Resources.

King, B. (1994) Management of Methane Emissions from Coal Mines: Environmental, Engineering, Economic and Institutional Implication of Options, Neil and Gunter Ltd., Halifax, March 1994.

McElroy OVS (2020) Marshall County VAM Abatement Project Offset Verification Statement submitted to California Air Resources Board, July 2019.

MSHA (2020) Data Transparency at MSHA. Mine Safety and Health Administration. Available online at <http://www.msha.gov/>.

Mutmansky, Jan M., and Yanbei Wang (2000) Analysis of Potential Errors in Determination of Coal Mine Annual Methane Emissions. Department of Energy and Geo-Environmental Engineering, Pennsylvania State University. University Park, PA.

Saghafi, Abouna (2013) Estimation of fugitive emissions from open cut coal mining and measurable gas content, 13th Coal Operators' Conference, University of Wollongong, The Australian Institute of Mining and Metallurgy & Mine Managers Association of Australia, 2013, 306-313.

USBM (1986) Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins. Circular 9067, U.S. Bureau of Mines.

West Virginia Geological & Economic Survey (WVGES) (2020) Oil & Gas Production Data. Available online at <http://www.wvgs.wvnet.edu/www/datastat/datastat.htm>.

3.5. Methodology for Estimating CH_4, CO_2, and N_2O Emissions from Petroleum Systems - TO BE UPDATED FOR FINAL INVENTORY REPORT

For details on the emissions, emission factors, activity data, data sources, and methodologies for each year from 1990 to 2019 please see the spreadsheet file annexes for the current (i.e., 1990 to 2019) Inventory, available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

As described in the main body text on Petroleum Systems, the Inventory methodology involves the calculation of CH_4, CO_2, and N_2O emissions for approximately 100 emissions sources, and then the summation of emissions for each petroleum systems segment. The approach for calculating emissions for petroleum systems generally involves the application of emission factors to activity data.

Emission Factors

Table 3.5-2, Table 3.5-7, and Table 3.5-10 show CH_4, CO_2, and N_2O emissions, respectively, for all sources in Petroleum Systems, for all time series years. Table 3.5-3, Table 3.5-8, and Table 3.5-11 show the CH_4, CO_2, and N_2O average emission factors, respectively, for all sources in Petroleum Systems, for all time series years. These emission factors are calculated by dividing net emissions by activity. Therefore, in a given year, these emission factors reflect the estimated contribution from controlled and uncontrolled fractions of the source population.

Additional detail on the basis for emission factors used across the time series is provided in Table 3.5-4, Table 3.5-9, Table 3.5-12, and below.

In addition to the Greenhouse Gas Reporting Program (GHGRP), key references for emission factors for CH_4 and non-combustion-related CO_2 emissions from the U.S. petroleum industry include a 1999 EPA/Radian report *Methane Emissions from the U.S. Petroleum Industry* (EPA/Radian 1999), which contained the most recent and comprehensive determination of CH_4 emission factors for CH_4-emitting activities in the oil industry at that time, a 1999 EPA/ICF draft report *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA/ICF 1999) which is largely based on the 1999 EPA/Radian report, and a detailed study by the Gas Research Institute and EPA *Methane Emissions from the Natural Gas Industry* (EPA/GRI 1996). These studies still represent best available data in many cases—in particular, for the early years of the time series.

In recent Inventories, EPA has revised the emission estimation methodology for many sources in Petroleum Systems. New data from studies and EPA's GHGRP (EPA 2019b) allows for emission factors to be calculated that account for adoption of control technologies and emission reduction practices. For several sources, EPA has developed control category-specific emission factors from recent data that are used over the time series (paired with control category-specific activity data that fluctuates to reflect control adoption over time).

For oil well completions with hydraulic fracturing, controlled and uncontrolled emission factors were developed using GHGRP data. For associated gas, separate emission estimates are developed from GHGRP data for venting and flaring. For oil tanks, emissions estimates were developed for large and small tanks with flaring or VRU control, without control devices, and with upstream malfunctioning separator dump valves. For pneumatic controllers, separate estimates are developed for low bleed, high bleed, and intermittent controllers. For chemical injection pumps, the estimate is calculated with an emission factor developed with GHGRP data, which is based on the previous GRI/EPA factor but takes into account operating hours. Some sources in Petroleum Systems that use methodologies based on GHGRP data use a basin-level aggregation approach, wherein EPA calculates basin-specific emissions and/or activity factors for basins that contribute at least 10 percent of total annual emissions (on a CO_2 Eq. basis) from the source in any year—and combines all other basins into one grouping. This methodology is currently applied for associated gas venting and flaring and miscellaneous production flaring.

For the refining segment, EPA has directly used the GHGRP data for all emission sources for recent years (2010 forward) (EPA 2019b) and developed source level throughput-based emission factors from GHGRP data to estimate emissions in earlier time series years (1990-2009). For some sources, EPA continues to apply the historical emission factors for all time series years. All refineries have been required to report CH_4, CO_2, and N_2O emissions for all major activities since 2010. The national totals of these emissions for each activity were used for the 2010 to 2018 emissions. The national emission totals for each activity were divided by refinery feed rates for those four Inventory years to

develop average activity-specific emission factors, which were used to estimate national emissions for each refinery activity from 1990 to 2009 based on national refinery feed rates for each year (EPA 2015b).

Offshore emissions are taken from analysis of the *Gulfwide Emission Inventory Studies* and GHGRP data (BOEM 2019a-d; EPA 2019b; EPA 2020). Emission factors are calculated for offshore facilities located in the Gulf of Mexico, Pacific, and Alaska regions.

When a CO_2-specific emission factor is not available for a source, the CO_2 emission factors were derived from the corresponding source CH_4 emission factors. The amount of CO_2 in the crude oil stream changes as it passes through various equipment in petroleum production operations. As a result, four distinct stages/streams with varying CO_2 contents exist. The four streams that are used to estimate the emissions factors are the associated gas stream separated from crude oil, hydrocarbons flashed out from crude oil (such as in storage tanks), whole crude oil itself when it leaks downstream, and gas emissions from offshore oil platforms. For this approach, CO_2 emission factors are estimated by multiplying the existing CH_4 emissions factors by a conversion factor, which is the ratio of CO_2 content to methane content for the particular stream. Ratios of CO_2 to CH_4 volume in emissions are presented in Table 3.5-1.

N_2O emission factors were calculated using GHGRP data. For each flaring emission source calculation methodology that uses GHGRP data, the existing source-specific methodology was applied to calculate N_2O emission factors.

<u>1990-2018 Inventory updates to emission factors</u>

Summary information for emission factors for sources with revisions in this year's Inventory is below. The details are presented in a memorandum,[68] *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Update for Offshore Production Emissions* (EPA 2020), as well as the "Recalculations Discussion" section of the main body text.

In the production segment, EPA updated the methodology for Gulf of Mexico (GOM) federal waters offshore oil production to use vent and leak emission factors for major complexes and minor complexes using BOEM Gulfwide Emissions Inventory (GEI) emissions data. EPA developed production-based emission factors for offshore facilities in GOM state waters using GOM federal waters emissions and regional gas production in each year. EPA also calculated production-based emission factors for offshore facilities in the Pacific and Alaska using GHGRP data from that region.

In the refining segment, EPA updated the methodology for delayed cokers. The subpart Y calculation methodology for delayed cokers was updated for reporting year 2018 to use more accurate methods to quantify emissions for delayed cokers. The update to the calculation methodology resulted in higher reported emissions from delayed cokers in 2018 compared to previous years of reporting. The update did not impact all facilities in subpart Y as some facilities had already been reporting using the more accurate methods. For time-series consistency across 1990 to 2018 in the Inventory, emission estimates were updated for 1990 through 2017 using a ratio of reported emissions for 2018 to 2017, comparing facilities that used different methods for those years.

Activity Data

Table 3.5-5 shows the activity data for all sources in Petroleum Systems, for all time series years. Additional detail on the basis for activity data used across the time series is provided in Table 3.5-6, and below.

For many sources, complete activity data were not available for all years of the time series. In such cases, one of three approaches was employed. Where appropriate, the activity data were calculated from related statistics using ratios developed based on EPA 1996, and/or GHGRP data. For major equipment, pneumatic controllers, and chemical injection pumps, GHGRP subpart W data were used to develop activity factors (i.e., count per well) that are applied to calculated activity in recent years; to populate earlier years of the time series, linear interpolation is used to connect GHGRP-based estimates with existing estimates in years 1990 to 1995. In other cases, the activity data were held constant from 1990 through 2014 based on EPA (1999). Lastly, the previous year's data were used when data for the current year were unavailable. For offshore production in the GOM, the number of active major and minor complexes are used as activity data. For offshore production in the Pacific and Alaska region, the activity data are region-specific production. The activity data for the total crude transported in the transportation segment is not available, therefore the activity data for the refining sector (i.e., refinery feed in 1000 bbl/year) was used also for the transportation sector, applying an assumption that all crude transported is received at refineries. In the few cases where no data were located,

[68] Stakeholder materials including EPA memoranda for the current (i.e., 1990 to 2018) Inventory are available at < https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

oil industry data based on expert judgment was used. In the case of non-combustion CO_2 and N_2O emission sources, the activity factors are the same as for CH_4 emission sources. In some instances, where recent time series data (e.g., year 2018) are not yet available, year 2017 or prior data has been used as proxy.

Methodology for well counts and events

EPA used DI Desktop, a production database maintained by Enverus DrillingInfo, Inc. (Enverus DrillingInfo 2019), covering U.S. oil and natural gas wells to populate time series activity data for active oil wells, oil wells drilled, and oil well completions and workovers with hydraulic fracturing. For more information on the DrillingInfo data processing, please see Annex 3.6 Methodology for Estimating CH_4, CO_2, and N_2O from Natural Gas Systems.

1990-2018 Inventory updates to activity data

Summary information for activity data for sources with revisions in this year's Inventory is below. The details are presented in a memorandum,[69] *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Update for Offshore Production Emissions* (EPA 2020), as well as the "Recalculations Discussion" section of the main body text.

In the production segment, EPA made several improvements to the offshore gas production methodology. EPA updated GOM federal waters facility emissions to use active major and minor complex counts over the time series. EPA developed GOM federal waters flaring emissions to use flaring volumes reported in Oil and Gas Operations Reports (OGOR), Part B (OROR-B). EPA expanded the Inventory beyond the GOM federal waters to include GOM state waters, Alaskan, and Pacific offshore facilities using region-specific annual production over the time series.

Methane, Carbon Dioxide, and Nitrous Oxide Emissions by Emission Source for Each Year

Annual CH_4, CO_2, and N_2O emissions for each source were estimated by multiplying the activity data for each year by the corresponding emission factor. These annual emissions for each activity were then summed to estimate the total annual CH_4, CO_2, and N_2O emissions, respectively. Emissions at a segment level are shown in Table 3.5-2, Table 3.5-7, and Table 3.5-10.

Refer to the 1990-2018 Inventory section at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems for the following data tables, in spreadsheet format:

- Table 3.5-1: Ratios of CO_2 to CH_4 Volume in Emissions from Petroleum Production Field Operations
- Table 3.5-2: CH_4 Emissions (kt) for Petroleum Systems, by Segment and Source, for All Years
- Table 3.5-3: Average CH_4 Emission Factors (kg/unit activity) for Petroleum Systems Sources, for All Years
- Table 3.5-4: CH_4 Emission Factors for Petroleum Systems, Data Sources/Methodology
- Table 3.5-5: Activity Data for Petroleum Systems Sources, for All Years
- Table 3.5-6: Activity Data for Petroleum Systems, Data Sources/Methodology
- Table 3.5-7: CO_2 Emissions (kt) for Petroleum Systems, by Segment and Source, for All Years
- Table 3.5-8: Average CO_2 Emission Factors (kg/unit activity) for Petroleum Systems Sources, for All Years
- Table 3.5-9: CO_2 Emission Factors for Petroleum Systems, Data Sources/Methodology
- Table 3.5-10: N_2O Emissions (kt) for Natural Gas Systems, by Segment and Source, for All Years
- Table 3.5-11: Average N_2O Emission Factors (kg/unit activity) for Natural Gas Systems Sources, for All Years
- Table 3.5-12: N_2O Emission Factors for Natural Gas Systems, Data Sources/Methodology
- Table 3.5-13: Annex 3.5 Electronic Tables – References

[69] Stakeholder materials including EPA memoranda for the current (i.e., 1990 to 2018) Inventory are available at < https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

References

AL/OGB (2019) Alabama Oil and Gas Board. Production Data. Available online at: https://www.gsa.state.al.us/ogb/production

AOGCC (2019a) List of wells. Alaska Oil and Gas Conservation Commission (AOGCC). Available online at: http://aogweb.state.ak.us/DataMiner3/Forms/WellList.aspx

AOGCC (2019b) Oil and Gas Production. Alaska Oil and Gas Conservation Commission (AOGCC). Available online at: http://aogweb.state.ak.us/DataMiner3/Forms/Production.aspx

API (1989) Aboveground Storage Tank Survey report prepared by Entropy Limited for American Petroleum Institute, April 1989.

API (1995) API 4615: Emission Factors For Oil and Gas Production Operations. American Petroleum Institute. Washington, DC.

API (1996) API 4638: Calculation Workbook For Oil And Gas Production Equipment Fugitive Emissions. American Petroleum Institute. Washington, DC.

API (2000) API 4697: Production Tank Emissions Model - A Program For Estimating Emissions From Hydrocarbon Production Tanks - E&P Tank Version 2.0. American Petroleum Institute. Washington, DC.

API (2003) Basic Petroleum Data Book, 1990-2003. American Petroleum Institute. Washington, DC.

BOEM (2005) Year 2005 Gulfwide Emission Inventory Study. Each GEI study is available online: https://www.boem.gov/Gulfwide-Offshore-Activity-Data-System-GOADS/

BOEM (2008) Year 2008 Gulfwide Emission Inventory Study. Each GEI study is available online: https://www.boem.gov/Gulfwide-Offshore-Activity-Data-System-GOADS/

BOEM (2011) Year 2011 Gulfwide Emission Inventory Study. Each GEI study is available online: https://www.boem.gov/Gulfwide-Offshore-Activity-Data-System-GOADS/

BOEM (2014) Year 2014 Gulfwide Emission Inventory Study. Each GEI study is available online: https://www.boem.gov/Gulfwide-Offshore-Activity-Data-System-GOADS/

BOEM (2019a) BOEM Platform Structures Online Query. Available online at: https://www.data.boem.gov/Platform/PlatformStructures/Default.aspx

BOEM (2019b) BOEM Oil and Gas Operations Reports - Part A (OGOR-A). Production Data for 1947 to 2018. Download "Production Data" online at: https://www.data.boem.gov/Main/RawData.aspx

BOEM (2019c) BOEM Oil and Gas Operations Reports - Part A (OGOR-A). Production Data for 1996 to 2018. Available online at: https://www.data.boem.gov/Main/OGOR-A.aspx

BOEM (2019d) BOEM Oil and Gas Operations Reports - Part B (OGOR-B). Flaring volumes for 1996 to 2018. Available online at: https://www.data.boem.gov/Main/OGOR-B.aspx

CA/DOC (2019) Annual Oil and Gas Reports for 1990-2018. State Oil and Gas Supervisor, California Department of Conservation. Available online at: https://www.conservation.ca.gov/calgem/pubs_stats/annual_reports/Pages/annual_reports.aspx

CAPP (1992) Canadian Association of Petroleum Producers (CAPP), A Detailed Inventory of CH_4 and VOC Emissions from Upstream Oil & Gas Operations in Alberta. March 1992.

Enverus DrillingInfo (2019) March 2019 Download. DI Desktop® Enverus DrillingInfo, Inc.

EIA (2019a) Monthly Energy Review, 1995-2019 editions. Energy Information Administration, U.S. Department of Energy. Washington, DC. Available online at: <http://www.eia.gov/totalenergy/data/monthly/index.cfm>.

EIA (2019b) Petroleum Supply Annual. 2001-2019 editions. U.S Department of Energy Washington, DC. Available online at: <http://www.eia.gov/petroleum/supply/annual/volume1/>.

EIA (2019c) Refinery Capacity Report, 2005-2019 editions. Energy Information Administration, U.S. Department of Energy. Washington, DC. Available online at: <http://www.eia.gov/petroleum/refinerycapacity/>.

EIA (2019d) 1981-Current: Energy Information Administration estimates published in the Petroleum Supply Annual and Petroleum Supply Monthly reports. Energy Information Administration, U.S. Department of Energy. Washington, DC. Available online at: <https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_a.htm>.

EPA (1997) Compilation of Air Pollutant Emission Factors, AP-42. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

EPA (2015a) Inventory of U.S. GHG Emissions and Sinks 1990-2013: Revision to Well Counts Data. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-updates-1990-2013-inventory-published>.

EPA (2015b) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Refineries Emissions Estimate. Available online at: <https://www.epa.gov/ghgemissions/additional-information-oil-and-gas-estimates-1990-2013-ghg-inventory-published-april>.

EPA (2016a) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014: Revisions to Natural Gas and Petroleum Production Emissions. Available online at: <https://www.epa.gov/ghgemissions/additional-information-oil-and-gas-estimates-1990-2014-ghg-inventory-published-april>.

EPA (2017a) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2015: Revisions to Natural Gas and Petroleum Production Emissions. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2015-ghg>.

EPA (2018a) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Additional Revisions Under Consideration. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2016-ghg>.

EPA (2018b) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Revisions to Create Year-Specific Emissions and Activity Factors. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2016-ghg>.

EPA (2018c) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Revisions to CO2 Emissions Estimation Methodologies. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2016-ghg>.

EPA (2019a) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2017: Other Updates Considered for 2019 and Future GHGIs. Available online at: https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems

EPA (2019b) Greenhouse Gas Reporting Program. U.S. Environmental Protection Agency. Data reported as of August 4, 2019.

EPA (2020) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Update for Offshore Production Emissions. Available online at: https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems

EPA/GRI (1996) Methane Emissions from the Natural Gas Industry. Prepared by Harrison, M., T. Shires, J. Wessels, and R. Cowgill, eds., Radian International LLC for National Risk Management Research Laboratory, Air Pollution Prevention and Control Division, Research Triangle Park, NC. EPA-600/R-96-080a.

LA/DNR (2019) Production Data. Louisiana Department of Natural Resources. Available online at: http://www.dnr.louisiana.gov/index.cfm?md=pagebuilder&tmp=home&pid=206

EPA/ICF (1999) Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report). Prepared by ICF International. Office of Air and Radiation, U.S. Environmental Protection Agency. October 1999.

EPA/Radian (1999) Methane Emissions from the U.S. Petroleum Industry. Prepared by Radian International. U.S. Environmental Protection Agency. February 1999.

OGJ (2019) Special Report: Pipeline Economics, 2005-2019 Editions. *Oil & Gas Journal,* PennWell Corporation, Tulsa, OK. Available online at: <http:// http://www.ogj.com/>.

Radian/API (1992) "Global Emissions of Methane from Petroleum Sources." American Petroleum Institute, Health and Environmental Affairs Department, Report No. DR140, February 1992.

TRC (2019) Oil & Gas Production Data Query. Texas Railroad Commission. Available online at: http://webapps.rrc.state.tx.us/PDQ/generalReportAction.do

WCUS (2016) Waterborne Commerce of the United States, Part 5: National Summaries, 2000-2016 Editions. United States Army Corps of Engineers. Washington, DC, July 20, 2015. Latest edition available online at: <http://www.navigationdatacenter.us/wcsc/pdf/wcusnatl14.pdf>.

3.6. Methodology for Estimating CH_4, CO_2, and N_2O Emissions from Natural Gas Systems - TO BE UPDATED FOR FINAL INVENTORY REPORT

For details on the emissions, emission factors, activity data, data sources, and methodologies for each year from 1990 to 2019 please see the spreadsheet file annexes for the current (i.e., 1990 to 2019) Inventory, available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

As described in the main body text on Natural Gas Systems, the Inventory methodology involves the calculation of CH_4, CO_2, and N_2O emissions for over 100 emissions sources, and the summation of emissions for each natural gas sector stage. The approach for calculating emissions for natural gas systems generally involves the application of emission factors to activity data. For many sources, the approach uses technology-specific emission factors or emission factors that vary over time and take into account changes to technologies and practices, which are used to calculate net emissions directly. For others, the approach uses what are considered "potential methane factors" and reduction data to calculate net emissions.

Emission Factors

Table 3.6-1, Table 3.6-10, and Table 3.6-14 show CH_4, CO_2, and N_2O emissions, respectively, for all sources in Natural Gas Systems, for all time series years. Table 3.6-2, Table 3.6-12, and Table 3.6-15 show the CH_4, CO_2, and N_2O average emission factors, respectively, for all sources in Natural Gas Systems, for all time series years. These emission factors are calculated by dividing net emissions by activity. Therefore, in a given year, these emission factors reflect the estimated contribution from controlled and uncontrolled fractions of the source population and any source-specific reductions (see below section "Reductions Data"); additionally, for sources based on the GRI/EPA study, the values take into account methane compositions from GTI 2001 adjusted year to year using gross production for National Energy Modeling System (NEMS) oil and gas supply module regions from the EIA. These adjusted region-specific annual CH_4 compositions are presented in Table 3.6-3 (for general sources), Table 3.6-4 (for gas wells without hydraulic fracturing), and Table 3.6-5 (for gas wells with hydraulic fracturing).

Additional detail on the basis for the CH_4, CO_2, and N_2O emission factors used across the time series is provided in Table 3.6-6, Table 3.6-13, Table 3.6-16, and below.

Key references for emission factors for CH_4 and non-combustion-related CO_2 emissions from the U.S. natural gas industry include the 1996 Gas Research Institute (GRI) and EPA study (EPA/GRI 1996), the Greenhouse Gas Reporting Program (GHGRP) (EPA 2018d), and others.

The EPA/GRI study developed over 80 CH_4 emission factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system for base year 1992. Since the time of this study, practices and technologies have changed. This study still represents best available data in many cases—in particular, for early years of the time series.

In recent Inventories, EPA has revised the CH_4 and CO_2 emission estimation methodology for many sources in Natural Gas Systems. New data from studies and EPA's GHGRP (EPA 2019d) allows for emission factors to be calculated that account for adoption of control technologies and emission reduction practices. For some sources, EPA has developed control category-specific emission factors from recent data that are used over the time series (paired with control category-specific activity data that fluctuates to reflect control adoption over time). In other cases, EPA retains emission factors from the EPA/GRI study for early time series years (1990 to 1992), applies updated emission factors in recent years (e.g., 2011 forward), and uses interpolation to calculate emission factors for intermediate years. For some sources, EPA continues to apply the EPA/GRI emission factors for all time series years, and accounts for emission reductions through data reported to Gas STAR or estimated based on regulations (see below section "Reductions Data"). For many sources in the exploration and production segments, EPA has used GHGRP data to calculate net emission factors and establish source type and/or control type subcategories. For example: for gas well completions and workovers with hydraulic fracturing, separate emissions estimates were developed for hydraulically fractured completions and workovers that vent, flared hydraulic fracturing completions and workovers, hydraulic fracturing completions and workovers with reduced emissions completions (RECs), and hydraulic fracturing completions and workovers with RECs that flare; for gas well completions without hydraulic fracturing, separate emissions estimates were developed for completions that event and completions that flare; for liquids unloading, separate emissions estimates

were developed for wells with plunger lifts and wells without plunger lifts; for condensate tanks, emissions estimates were developed for large and small tanks with flaring or VRU control, without control devices, and with upstream malfunctioning separator dump valves; for pneumatic controllers, separate estimates are developed for low bleed, high bleed, and intermittent controllers; and chemical injection pumps estimates are calculated with an emission factor developed with GHGRP data, which is based on the previous GRI/EPA factor but takes into account operating hours. For most sources in the processing, transmission and storage, and distribution segments, net emission factors have been developed for application in recent years of the time series, while the existing emission factors are applied in early time series years. When a CO_2-specific emission factor is not available for a source, the CO_2 emission factors were derived from the corresponding source CH_4 emission factors using default gas composition data. CO_2 emission factors are estimated by multiplying the CH_4 emission factors by the ratio of the CO_2-to-CH_4 gas content. This approach is applied for certain sources in the natural gas production, gas processing (only for early time series years), transmission and storage, and distribution segments. The default gas composition data are specific to segment and are provided in Table 3.6-11. The default values were derived from EPA/GRI (1996), EIA (1994), and GTI (2001).

N_2O emission factors were calculated using GHGRP data. For each flaring emission source calculation methodology that uses GHGRP data, the existing source-specific methodology was applied to calculate N_2O emission factors.

1990-2018 Inventory updates to emission factors

Summary information for emission factors for sources with revisions in this year's Inventory is below. The details are presented in memoranda,[70] *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Update for Natural Gas Gathering & Boosting Station Emissions* (EPA 2020b) and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Update for Offshore Production Emissions* (EPA 2020a), as well as the "Recalculations Discussion" section of the main body text.

In the production segment, EPA updated the methodology for gathering and boosting stations to supplement reported GHGRP data with emissions data from a Zimmerle et al. 2019 study. EPA also updated the offshore production methodology to estimate emissions for the Gulf of Mexico (GOM) and Alaska regions. EPA updated the methodology for GOM federal waters offshore gas production to use vent and leak emission factors for major complexes and minor complexes using BOEM Gulfwide Emissions Inventory (GEI) emissions data. EPA developed production-based emission factors for offshore facilities in GOM state waters using GOM federal waters emissions and regional gas production in each year. EPA also calculated production-based emission factors for offshore facilities in Alaska using GHGRP data from that region.

Activity Data

Table 3.6-7 shows the activity data for all sources in Natural Gas Systems, for all time series years. Additional detail on the basis for activity data used across the time series is provided in Table 3.6-8, and below.

For a few sources, recent direct activity data were not available. For these sources, either 2017 data were used as proxy for 2018 data or a set of industry activity data drivers was developed and was used to update activity data. Key drivers include statistics on gas production, number of wells, system throughput, miles of various kinds of pipe, and other statistics that characterize the changes in the U.S. natural gas system infrastructure and operations.

Methodology for well counts and events

EPA used DI Desktop, a production database maintained by Enverus DrillingInfo, Inc. (Enverus DrillingInfo 2019), covering U.S. oil and natural gas wells to populate time series activity data for active gas wells, gas wells drilled, and gas well completions and workovers with hydraulic fracturing (for 1990 to 2010). EPA queried DI Desktop for relevant data on an individual well basis—including location, natural gas and liquids (i.e., oil and condensate) production by year, drill type (e.g., horizontal or vertical), and date of completion or first production. Non-associated gas wells were classified as any well within DI Desktop that had non-zero gas production in a given year, and with a gas-to-oil ratio (GOR) of greater than 100 mcf/bbl in that year. Oil wells were classified as any well that had non-zero liquids production in a given year, and with a GOR of less than or equal to 100 mcf/bbl in that year. Gas wells with hydraulic fracturing were assumed to be the subset of the non-associated gas wells that were horizontally drilled and/or located in an unconventional formation

[70] Stakeholder materials including EPA memoranda for the current (i.e., 1990 to 2018) Inventory are available at <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

(i.e., shale, tight sands, or coalbed). Unconventional formations were identified based on well basin, reservoir, and field data reported in DI Desktop referenced against a formation type crosswalk developed by EIA (EIA 2012a).

For 1990 through 2010, gas well completions with hydraulic fracturing were identified as a subset of the gas wells with hydraulic fracturing that had a date of completion or first production in the specified year. To calculate workovers for all time series years, EPA applied a refracture rate of 1 percent (i.e., 1 percent of all wells with hydraulic fracturing are assumed to be refractured in a given year) to the total counts of wells with hydraulic fracturing from the DrillingInfo data. For 2011 forward, EPA used GHGRP data for the total number of well completions. The GHGRP data represents a subset of the national completions, due to the reporting threshold, and therefore using this data without scaling it up to national level results in an underestimate. However, because EPA's GHGRP counts of completions were higher than national counts of completions (estimated using DI Desktop data), EPA directly used the GHGRP data to estimate national activity for years 2011 forward.

EPA calculated the percentage of gas well completions and workovers with hydraulic fracturing in each of the four control categories using year-specific GHGRP data (applying year 2011 factors to earlier years). EPA assumed no REC use from 1990 through 2000, used a REC use percentage calculated from GHGRP data for 2011 forward, and then used linear interpolation between the 2000 and 2011 percentages. For flaring, EPA used an assumption of 10 percent (the average of the percent of completions and workovers that were flared in 2011 through 2013 GHGRP data) flaring from 1990 through 2010 to recognize that some flaring has occurred over that time period. For 2011 forward, EPA used a flaring percentage calculated from GHGRP data.

<u>1990-2018 Inventory updates to activity data</u>

Summary information for activity data for sources with revisions in this year's Inventory is below. The details are presented in memoranda,[71] *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Update for Natural Gas Gathering & Boosting Station Emissions* (EPA 2020b) and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Update for Offshore Production Emissions*, as well as the "Recalculations Discussion" section of the main body text.

In the production segment, EPA developed a new methodology for gathering and boosting station emissions. EPA used activity data from a Zimmerle et al. 2019 study and subpart W activity data across the time series. EPA also updated the offshore production methodology to estimate emissions for the Gulf of Mexico (GOM) and Alaska regions. EPA updated the GOM federal waters methodology to use active major and minor complex counts over the time series. EPA developed GOM federal waters flaring emissions to use flaring volumes reported in Oil and Gas Operations Reports (OGOR), Part B (OROR-B). EPA expanded the Inventory beyond the GOM federal waters to include GOM state waters and Alaskan offshore facilities using region-specific annual production over the time series.

Reductions Data

As described under "Emission Factors" above, some sources in Natural Gas Systems rely on CH_4 emission factors developed from the 1996 EPA/GRI study. Application of these emission factors across the time series represents potential emissions and does not take into account any use of technologies or practices that reduce emissions. To take into account use of such technologies for emission sources that use potential factors, data were collected on relevant voluntary and regulatory reductions.

Voluntary and regulatory emission reductions by segment, for all time series years, are included in Table 3.6-1. Reductions by emission source, for all time series years, are shown in Table 3.6-9.

<u>Voluntary reductions</u>

Voluntary reductions included in the Inventory were those reported to Gas STAR for activities such as replacing gas engines with electric compressor drivers and installing automated air-to-fuel ratio controls for engines.

Most Gas STAR reductions in the production segment are not classified as applicable to specific emission sources. As many sources in production are now calculated with net factor approaches, to address potential double-counting of reductions, a scaling factor was applied to the "other voluntary reductions" to reduce this reported amount

[71] Stakeholder materials including EPA memoranda for the current (i.e., 1990 to 2017) Inventory are available at <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

based on an estimate of the fraction of those reductions that occur in the sources that are now calculated using net emissions approaches. This fraction was developed by dividing the net emissions from sources with net approaches, by the total production segment emissions (without deducting the Gas STAR reductions). The result for 2018, is that around 80 percent of the reductions were estimated to occur in sources for which net emissions are now calculated, which yields an adjusted "other reductions" estimate of 3 MMT CO_2 Eq.

Federal regulations

Regulatory actions reducing emissions in the current Inventory include National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents in the production segment. In regards to the oil and natural gas industry, the NESHAP regulation addresses HAPs from the oil and natural gas production sectors and the natural gas transmission and storage sectors of the industry. Though the regulation deals specifically with HAPs reductions, methane emissions are also incidentally reduced.

The NESHAP regulation requires that glycol dehydration unit vents that have HAP emissions and exceed a gas throughput threshold be connected to a closed loop emission control system that reduces emissions by 95 percent. The emissions reductions achieved as a result of NESHAP regulations for glycol dehydrators in the production segment were calculated using data provided in the Federal Register Background Information Document (BID) for this regulation. The BID provides the levels of control measures in place before the enactment of regulation. The emissions reductions were estimated by analyzing the portion of the industry without control measures already in place that would be impacted by the regulation.

NESHAP driven reductions from storage tanks and from dehydrators in the processing segment are estimated with net emission methodologies that take into account controls implemented due to regulations. In addition to the NESHAP applicable to natural gas, the Inventory reflects the New Source Performance Standards (NSPS) for oil and gas, through the use of a net factor approach that captures shifts to lower emitting technologies required by the regulation. Examples include separating gas well completions and workovers with hydraulic fracturing into four categories and developing control technology-specific methane emission factors and year-specific activity data for each category; establishing control category-specific emission factors and associated year-specific activity data for condensate tanks; calculating year-specific activity data for pneumatic controller bleed categories; and estimating year-specific activity data for wet versus dry seal centrifugal compressors.

Methane, Carbon Dioxide, and Nitrous Oxide Emissions by Emission Source for Each Year

Annual CH_4, CO_2, and N_2O emissions for each source were estimated by multiplying the activity data for each year by the corresponding emission factor. These annual emissions for each activity were then summed to estimate the total annual CH_4, CO_2, and N_2O emissions, respectively. As a final step for CH_4 emissions, any relevant reductions data from each segment is summed for each year and deducted from the total calculated emissions in that segment to estimate net CH_4 emissions for the Inventory. CH_4 potential emissions, reductions, and net emissions at a segment level are shown in Table 3.6-1. CO_2 emissions by segment and source are summarized in Table 3.6-10. N_2O emissions by segment and source are summarized in Table 3.6-14.

Refer to the 1990-2018 Inventory section at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems for the following data tables, in spreadsheet format:

- Table 3.6-1: CH_4 Emissions (kt) for Natural Gas Systems, by Segment and Source, for All Years
- Table 3.6-2: Average CH_4 Emission Factors (kg/unit activity) for Natural Gas Systems Sources, for All Years
- Table 3.6-3: U.S. Production Sector CH_4 Content in Natural Gas by NEMS Region (General Sources)
- Table 3.6-4: U.S. Production Sector CH_4 Content in Natural Gas by NEMS Region (Gas Wells Without Hydraulic Fracturing)
- Table 3.6-5: U.S. Production Sector CH_4 Content in Natural Gas by NEMS Region (Gas Wells With Hydraulic Fracturing)
- Table 3.6-6: CH_4 Emission Factors for Natural Gas Systems, Data Sources/Methodology
- Table 3.6-7: Activity Data for Natural Gas Systems Sources, for All Years
- Table3.6-8: Activity Data for Natural Gas Systems, Data Sources/Methodology
- Table 3.6-9: Voluntary and Regulatory CH_4 Reductions for Natural Gas Systems (kt)
- Table 3.6-10: CO_2 Emissions (kt) for Natural Gas Systems, by Segment and Source, for All Years

- Table 3.6-11: Default Gas Content by Segment, for All Years
- Table 3.6-12: Average CO_2 Emission Factors (kg/unit activity) for Natural Gas Systems Sources, for All Years
- Table 3.6-13: CO_2 Emission Factors for Natural Gas Systems, Data Sources/Methodology
- Table 3.6-14: N_2O Emissions (kt) for Natural Gas Systems, by Segment and Source, for All Years
- Table 3.6-15: Average N_2O Emission Factors (kg/unit activity) for Natural Gas Systems Sources, for All Years
- Table 3.6-16: N_2O Emission Factors for Natural Gas Systems, Data Sources/Methodology
- Annex 3.6-17: Electronic Tables – References

References

Alabama (2013) Alabama State Oil and Gas Board. Available online at <http://www.ogb.state.al.us>.

AL/OGB (2019) *Alabama Oil and Gas Board. Production Data. Available online at: <https://www.gsa.state.al.us/ogb/production>*.

AOGCC (2019a) *List of wells. Alaska Oil and Gas Conservation Commission (AOGCC). Available online at: <http://aogweb.state.ak.us/DataMiner3/Forms/WellList.aspx>*.

AOGCC (2019b) *Oil and Gas Production. Alaska Oil and Gas Conservation Commission (AOGCC). Available online at: <http://aogweb.state.ak.us/DataMiner3/Forms/Production.aspx>*.

API/ANGA (2012) *Characterizing Pivotal Sources of Methane Emissions from Natural Gas Production – Summary and Analysis of API and ANGA Survey Responses*. Final Report. American Petroleum Institute and America's Natural Gas Alliance. September 21.

BOEM (2005) Year 2005 Gulfwide Emission Inventory Study. Each GEI study is available online: https://www.boem.gov/Gulfwide-Offshore-Activity-Data-System-GOADS/.

BOEM (2008) Year 2008 Gulfwide Emission Inventory Study. Each GEI study is available online: https://www.boem.gov/Gulfwide-Offshore-Activity-Data-System-GOADS/.

BOEM (2011) Year 2011 Gulfwide Emission Inventory Study. Each GEI study is available online: https://www.boem.gov/Gulfwide-Offshore-Activity-Data-System-GOADS/.

BOEM (2014) Year 2014 Gulfwide Emission Inventory Study. Each GEI study is available online: https://www.boem.gov/Gulfwide-Offshore-Activity-Data-System-GOADS/.

BOEM (2019a) BOEM Platform Structures Online Query. Available online at: <https://www.data.boem.gov/Platform/PlatformStructures/Default.aspx>.

BOEM (2019b) BOEM Oil and Gas Operations Reports - Part A (OGOR-A). Production Data for 1947 to 2018. Download "Production Data" online at: <https://www.data.boem.gov/Main/RawData.aspx>.

BOEM (2019c) BOEM Oil and Gas Operations Reports - Part A (OGOR-A). Production Data for 1996 to 2018. Available online at: <https://www.data.boem.gov/Main/OGOR-A.aspx>.

BOEM (2019d) BOEM Oil and Gas Operations Reports - Part B (OGOR-B). Flaring volumes for 1996 to 2018. Available online at: <https://www.data.boem.gov/Main/OGOR-B.aspx>.

CA/DOC (2019) Annual Oil and Gas Reports for 1990-2018. State Oil and Gas Supervisor, California Department of Conservation. Available online at: <https://www.conservation.ca.gov/calgem/pubs_stats/annual_reports/Pages/annual_reports.aspx>.

Clearstone (2011) Clearstone Engineering, Development of Updated Emission Factors for Residential Meters, May 2011.

DOE (2019) LNG Annual Reports, 2004-2018. U.S. Department of Energy, Washington, DC. Available online at: <https://www.energy.gov/fe/listings/lng-reports>

EIA (1994) "Emissions of Greenhouse Gases in the United States: 1987-1992." Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA (1996) "Emissions of Greenhouse Gases in the United States: 1987-1994." Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA (2004) *U.S. LNG Markets and Uses*. Energy Information Administration, U.S. Department of Energy, Washington, DC. June 2004. Available online at: <http://www.eia.doe.gov/pub/oil_gas/natural_gas/feature_articles/2004/lng/lng2004.pdf>.

EIA (2011) "Monthly Energy Review" Table 5.2, Crude Oil and Natural Gas Resource Development. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at: < https://www.eia.gov/totalenergy/data/monthly/previous.php>.

EIA (2012) Formation crosswalk. Energy Information Administration, U.S. Department of Energy, Washington, DC. Provided July 7.

EIA (2019a) “Natural Gas Gross Withdrawals and Production: Marketed Production.” Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at: <http://www.eia.doe.gov>.

EIA (2019b) Lease Condensate Production, Natural Gas Navigator. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.gov/dnav/ng/ng_prod_lc_s1_a.htm >.

EIA (2019c) “Table 1—Summary of natural gas supply and disposition in the United States 2013-2018.” Natural Gas Monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at < https://www.eia.gov/naturalgas/monthly/>.

EIA (2019d) “Table 2—Natural Gas Consumption in the United States 2013-2018.” Natural Gas Monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at < https://www.eia.gov/naturalgas/monthly/>.

EIA (2019e) “Natural Gas Annual Respondent Query System. Report 191 Field Level Storage Data (Annual).” Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at < https://www.eia.gov/cfapps/ngqs/ngqs.cfm?f_report=RP7>.

EIA (2019f) "U.S. Natural Gas Imports, 2016-2018." Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.gov/naturalgas/monthly/pdf/table_04.pdf>.

EIA (2019g) Number of Natural Gas Consumers. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at: <https://www.eia.gov/dnav/ng/ng_cons_num_dcu_nus_a.htm>.

EIA (2019h) "Monthly Energy Review" Table A4, Approximate Heat Content of Natural Gas. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at: <https://www.eia.gov/totalenergy/data/monthly/previous.php>.

Enverus DrillingInfo (2019) March 2019 Download. DI Desktop®ad Enverus DrillingInfo, Inc.

EPA (2013) Updating GHG Inventory Estimate for Hydraulically Fractured Gas Well Completions and Workovers. Available online at: <http://www.epa.gov/climatechange/Downloads/ghgemissions/memo-update-emissions-for-hydraulically-workovers.pdf>.

EPA (2015a) Inventory of U.S. GHG Emissions and Sinks 1990-2013: Revision to Well Counts Data. Available online at: <https://www.epa.gov/sites/production/files/2015-12/documents/revision-data-source-well-counts-4-10-2015.pdf>.

EPA (2015b) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Offshore Oil and Gas Platforms Emissions Estimate. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-updates-1990-2013-inventory-published>.

EPA (2016a) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014: Revisions to Natural Gas and Petroleum Production Emissions. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2014-ghg>.

EPA (2016b) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014: Revisions to Natural Gas Gathering and Boosting Emissions. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2014-ghg>.

EPA (2016c) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014: Revisions to Natural Gas Transmission and Storage Emissions. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2014-ghg>.

EPA (2016d) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014: Revisions to Natural Gas Distribution Emissions. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2014-ghg>.

EPA (2017a) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2015: Revisions to Natural Gas and Petroleum Production Emissions. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2015-ghg>.

EPA (2017b) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2015: Revisions to Natural Gas Processing Emissions. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2015-ghg>.

EPA (2017c) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2015: Incorporating an Estimate for the Aliso Canyon Leak. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2015-ghg>.

EPA (2018a) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Additional Revisions Under Consideration. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2016-ghg>.

EPA (2018b) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Revisions to Create Year-Specific Emissions and Activity Factors. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2016-ghg>.

EPA (2018c) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Revisions to CO_2 Emissions Estimation Methodologies. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2016-ghg>.

EPA (2019a) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2017: Updates to Natural Gas Gathering & Boosting Pipeline Emissions. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

EPA (2019b) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2017: Updates to Liquefied Natural Gas Segment. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

EPA (2019c) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2017: Other Updates Considered for 2019 and Future GHGIs. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

EPA (2019d) *Greenhouse Gas Reporting Program- Subpart W – Petroleum and Natural Gas Systems*. Environmental Protection Agency. Data reported as of August 4, 2019.

EPA (2020a) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990- 2018: Update for Offshore Production Emissions. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

EPA (2020b) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018: Update for Natural Gas Gathering & Boosting Station Emissions. Available online at: <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

FERC (2017) *North American LNG Terminals*. Federal Energy Regulatory Commission, Washington, DC. Available online at: <https://www.ferc.gov/industries/gas/indus-act/lng/lng-existing.pdf>

EPA/GRI (1996) *Methane Emissions from the Natural Gas Industry*. Prepared by Harrison, M., T. Shires, J. Wessels, and R. Cowgill, eds., Radian International LLC for National Risk Management Research Laboratory, Air Pollution Prevention and Control Division, Research Triangle Park, NC. EPA-600/R-96-080a.

GTI (2001) Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. GRI-01/0136.

GTI (2009) Gas Technology Institute and Innovative Environmental Solutions, Field Measurement Program to Improve Uncertainties for Key Greenhouse Gas Emission Factors for Distribution Sources, November 2009. GTI Project Number 20497. OTD Project Number 7.7.b.

ICF (1997) "Additional Changes to Activity Factors for Portions of the Gas Industry."September 18, 1997.

ICF (2008) "Natural Gas Model Activity Factor Basis Change."January 7, 2008.

ICF (2010) "Emissions from Centrifugal Compressors." December, 2010.

LA/DNR (2019) Production Data. Louisiana Department of Natural Resources. Available online at: <http://www.dnr.louisiana.gov/index.cfm?md=pagebuilder&tmp=home&pid=206>.

Lamb, et al. (2015) Direct Measurements Show Decreasing Methane Emissions from Natural Gas Local Distribution Systems in the United States. Environmental Science & Technology, Vol. 49 5161-5169.

Marchese, et al. (2015) Methane Emissions from United States Natural Gas Gathering and Processing. Environmental Science and Technology, Vol. 49 10718−10727.

OGJ (1997-2014) "Worldwide Gas Processing." *Oil & Gas Journal,* PennWell Corporation, Tulsa, OK. Available online at: <http:// http://www.ogj.com/>.

PHMSA (2019a) "Annual Report Mileage for Natural Gas Transmission and Gathering Systems." Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, Washington, DC. Available online at: <http://phmsa.dot.gov/pipeline/library/data-stats >.

PHMSA (2019b) "Annual Report Mileage for Natural Gas Distribution Systems." Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, Washington, DC. Available online at: <http://phmsa.dot.gov/pipeline/library/data-stats>.

PHMSA (2019c) LNG Annual Data, Pipeline and Hazardous Materials Safety Administration (PHMSA), Washington, DC. Available online at: <https://www.phmsa.dot.gov/pipeline/liquified-natural-gas/lng-data-and-maps>.

Radian/API (1992) "Global Emissions of Methane from Petroleum Sources." American Petroleum Institute, Health and Environmental Affairs Department, Report No. DR140, February 1992.

TRC (2019) Oil & Gas Production Data Query. Texas Railroad Commission. Available online at: <http://webapps.rrc.state.tx.us/PDQ/generalReportAction.do>.

Wyoming (2013) Wyoming Oil and Gas Conservation Commission. Available online at: <http://wogcc.state.wy.us/coalbedchart.cfm>.

Zimmerle, et al. (2015) "Methane Emissions from the Natural Gas Transmission and Storage System in the United States." Environmental Science and Technology, Vol. 49 9374−9383.

Zimmerle, et al. (2019) "Characterization of Methane Emissions from Gathering Compressor Stations." Available at https://mountainscholar.org/handle/10217/195489. October 2019.

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 MSW include CO_2 generated by the incineration of plastics, textiles, and other non-durable and durable goods. Using a combination of moisture content and carbon content for each category of waste, EPA estimated an annual carbon content for each material and calculated the overall carbon content for incinerated waste using a weighted average of carbon contents for each waste category and applied this factor to the total municipal solid waste (MSW) incinerated. 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) also result in CO_2 emissions.

Incineration of MSW and tires also results in emissions of CH_4 and N_2O. The methodology for calculating emissions from each of these waste incineration sources is described in this Annex.

Carbon Content of Municipal Solid Waste

Carbon content per ton of waste incinerated is based material specific discard tonnages, fossil and biogenic carbon contents, and moisture content of MSW. MSW discard tonnage data were obtained from *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* (EPA 2000 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; EPA 2016; EPA 2018a; EPA 2019; EPA 2020a). Data on the quantity of MSW discarded by material are shown in Table A-118.

Table A-118: Municipal Solid Waste Discarded (Thousands Short Tons)

Material	1990	2005	2015	2016	2017	2018	2019[a]
Paper and Paperboard	52,500	42,880	22,730	21,960	22,840	21,420	21,420
Glass	10,470	9,950	8,280	8,320	8,350	9,190	9,190
Ferrous Metals	10,410	10,190	12,120	12,520	12,720	12,840	12,840
Aluminum	1,800	2,640	3,000	3,150	3,210	3,220	3,220
Other Nonferrous Metals	370	580	720	750	790	820	820
Plastics	16,760	27,600	31,360	31,630	32,410	32,660	32,660
PET	*1,239*	*2,349*	*4,160*	*4,090*	*4,100*	*4,100*	*4,100*
HDPE	*2,935*	*5,437*	*5,420*	*5,390*	*5,570*	*5,570*	*5,570*
PVC	*1,397*	*1,660*	*890*	*930*	*960*	*960*	*960*
LDPE/LLDPE	*4,695*	*6,338*	*7,440*	*7,450*	*7,740*	*7,740*	*7,740*
PP	*2,590*	*4,040*	*7,660*	*7,730*	*7,950*	*7,950*	*7,950*
PS	*2,078*	*2,622*	*2,340*	*2,320*	*2,340*	*2,340*	*2,340*
Other	*1,826*	*5,153*	*3,450*	*3,720*	*3,750*	*3,750*	*3,750*
Rubber and Leather	5,420	6,240	7,010	7,440	7,440	7,490	7,490
Tires	*3,170*	*3,210*	*3,560*	*4,080*	*3,930*	*3,920*	*3,920*
Other (dur. & non-dur.)	*2,250*	*3,030*	*3,450*	*3,360*	*3,510*	*3,570*	*3,570*
Textiles	5,150	9,680	13,600	14,370	14,320	14,520	14,520
Wood	12,080	12,960	13,640	15,110	14,990	14,990	14,990
Other	2,510	3,080	3,650	3,660	3,650	3,590	3,590
Food Wastes	23,860	32,240	37,630	38,160	38,100	60,540	60,540
Yard Trimming	30,800	12,210	13,430	11,990	10,760	13,100	13,100
Miscellaneous Inorganic Wastes	2,900	3,690	3,990	4,020	4,040	4,070	4,070
Total MSW Discarded	**175,030**	**173,940**	**171,160**	**173,080**	**173,620**	**180,740**	**180,740**
Total Minus Tires	*171,860*	*170,730*	*167,600*	*169,000*	*169,690*	*176,820*	*176,820*

[a] Proxied from 2018.

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).

Carbon emitted from each material was derived by removal of moisture content and application of fossil carbon content included in each material. The carbon content of other plastics is assumed to be an average of the carbon contents of the six plastic types, weighted by tonnage discarded each year. Table A-119 displays the moisture content and fossil carbon content of each material in 2019. The fraction oxidized was assumed to be 98 percent.

Table A-119: 2019 MSW Moisture Content (%) and Fossil Carbon Content

Material	Moisture Content (percent)	Fossil Carbon Content (dry mass fraction)
Paper and Paperboard	6%	0.00
Glass	2%	0.00
Ferrous Metals	3%	0.00
Aluminum	3%	0.00
Other Nonferrous Metals	3%	0.00
Plastics	0%	0.00
PET	2%	0.63
HDPE	2%	0.86
PVC	2%	0.38
LDPE/LLDPE	2%	0.86
PP	2%	0.86
PS	2%	0.92
Other	2%	0.81
Rubber and Leather	0%	0.00
Tires	0%	0.00
Other (dur. & non-dur.)	7%	0.60
Textiles	10%	0.39
Wood	20%	0.00
Other	2%	0.00
Food Wastes	70%	0.00
Yard Trimming	60%	0.00
Miscellaneous Inorganic Wastes	7%	0.00

Sources: Staley and Barlaz (2009), Barlaz (1998).

These data were used to calculate and aggregate fossil carbon content per ton of waste incinerated in kilograms of CO_2 per short ton of MSW, which was applied to the mass flow of waste incinerated to calculate CO_2 emissions.

CO_2 from Incineration of Synthetic Rubber and Carbon Black in Tires

Emissions from tire incineration require two pieces of information: the amount (tons) of tires incinerated and the C content of the tires. "2019 U.S. Scrap Tire Management Summary" (RMA 2020) reports that 1,594.3 thousand tons of the 3,241.1 thousand tons of scrap tires generated in 2019 (approximately 51 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.[72] Table A-120 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-121. 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-120 (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 2019 were taken from RMA 2006; RMA 2009; RMA 2011; RMA 2014a; RMA 2016; RMA 2018; RMA 2020, 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

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

convert the previous years from millions of tires to thousands of short tons (STMC 1990 through 1997; RMA 2002 through RMA 2006; RMA 2014b; RMA 2016; RMA 2018; RMA 2020).

Table A-120: 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[a]	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**

NA (Not Applicable)

[a] Used to calculate C content of non-tire rubber products in municipal solid waste.

Note: Totals may not sum due to independent rounding.

Table A-121: Scrap Tire Constituents and CO_2 Emissions from Scrap Tire Incineration in 2019

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%	1.5
Total	**0.7**	**NA**	**NA**	**2.6**

NA (Not Applicable)

Mass of MSW Incinerated for CO_2 and Non-CO_2 emissions

As outlined above, the carbon content of MSW used to calculate CO_2 emissions does not incorporate tire carbon content in the aggregate CO_2 emission factor. Therefore, the MSW mass flow for the CO_2 calculations also does not include tires. The emissions from incineration from tires is added in after calculating emissions from MSW. The methodology for calculating tire emissions is outlined in the CO_2 from Incineration of Synthetic Rubber and Carbon Black in Tires section.

Emissions from methane and nitrous oxide are calculated using the emission factor of 0.20 kg CH_4/kt MSW and 50 g N_2O/metric ton MSW respectively, 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). Tire data are considered in both emission factors and therefore are included in the MSW mass flow for CH_4 and N_2O emissions. Table A-122 shows the MSW mass flow used to calculate emissions for CO_2 and non-CO_2 emissions.

Table A-122: U.S. Waste Incinerated for CO_2 and Non-CO_2 Emissions (Short Tons)

Year	CO_2 MSW Tonnage	CO_2 Tire Tonnage	Non-CO_2 MSW & Tire Tonnage
1990	33,344,095	421,400	33,765,495
1995	30,813,300	1,857,600	32,670,900
2000	26,639,962	1,992,068	28,632,030
2001	26,617,719	1,978,000	28,595,719
2002	26,399,232	2,043,137	28,442,369
2003	26,474,775	2,108,274	28,583,049
2004	26,574,847	2,126,457	28,701,304
2005	26,485,783	2,144,640	28,630,423
2006	28,727,371	2,314,500	31,041,871
2007	27,727,107	2,484,360	30,211,467
2008	27,688,414	2,284,555	29,972,969
2009	27,600,139	2,084,750	29,684,889
2010	27,593,089	1,755,890	29,348,979
2011	28,897,784	1,427,030	30,324,814
2012	29,000,686	1,773,660	30,774,346
2013	29,036,427	2,120,290	31,156,717
2014	29,025,071	2,021,480	31,046,551
2015	29,053,560	1,922,670	30,976,230
2016	29,704,817	1,829,505	31,534,322
2017	28,574,258	1,736,340	30,310,598
2018	29,162,364	1,691,585	30,853,949
2019	28,174,311	1,646,830	29,821,141

References

ArSova, Ljupka, Rob van Haaren, Nora Goldstein, Scott M. Kaufman, and Nickolas J. Themelis (2008) "16th Annual BioCycle Nationwide Survey: The State of Garbage in America" Biocycle, JG Press, Emmaus, PA. December.

Bahor, B (2009) Covanta Energy's public review comments re: *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007.* Submitted via email on April 9, 2009 to Leif Hockstad, U.S. EPA.

Barlaz, M. A. (1998). Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills. Global biogeochemical cycles, 12(2), 373-380.

De Soete, G.G. (1993) "Nitrous Oxide from Combustion and Industry: Chemistry, Emissions and Control." In A. R. Van Amstel, (ed) Proc. of the International Workshop Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control, Amersfoort, NL. February 3-5, 1993.

DeZan, D. (2000) Personal Communication between Diane DeZan, Fiber Economics Bureau and Joe Casola, ICF Consulting. 4 August 2000.

Energy Recovery Council (2009) "2007 Directory of Waste-to-Energy Plants in the United States." Accessed September 29, 2009.

EPA (2019) *Advancing Sustainable Materials Management: 2016 and 2017 Data Tables*. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: <https://www.epa.gov/sites/production/files/2019-11/documents/2016_and_2017_facts_and_figures_data_tables_0.pdf>.

EPA (2018) *Advancing Sustainable Materials Management: 2015 Data Tables*. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: <https://www.epa.gov/sites/production/files/2018-07/documents/smm_2015_tables_and_figures_07252018_fnl_508_0.pdf>.

EPA (2016) Advancing Sustainable Materials Management: 2014 Fact Sheet – Assessing Trends in Material Generation, Recycling and Disposal in the United States. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: <https://www.epa.gov/sites/production/files/2016-11/documents/2014_smmfactsheet_508.pdf>.

EPA (2015) Advancing Sustainable Materials Management: Facts and Figures 2013 – Assessing Trends in Material Generation, Recycling and Disposal in the United States. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. Available online at <https://www.epa.gov/sites/production/files/2015-09/documents/2013_advncng_smm_rpt.pdf>.

EPA (1999 through 2003, 2005 through 2014Municipal Solid Waste in the United States: Facts and Figures. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. Available online at < https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management >.

EPA (2006) Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C.

EPA (2000) Characterization of Municipal Solid Waste in the United States: Source Data on the 1999 Update. Office of Solid Waste, U.S. Environmental Protection Agency. Washington, D.C. EPA530-F-00-024.

EPA (1995) AP 42, Fifth Edition Compilation of Air Pollutant Emission Factors. Office of Air Quality Planning and Standards, Office of Air and Radiation. U.S. Environmental Protection Agency. Washington, D.C. Available online at: <https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emission-factors>.

FEB (2009) Fiber Economics Bureau, as cited in C&EN (2009) Chemical Output Slipped In Most Regions Chemical & Engineering News, American Chemical Society, 6 July. Available online at <http://www.cen-online.org/>.

Goldstein, N. and C. Madtes (2001) 13th Annual BioCycle Nationwide Survey: The State of Garbage in America. BioCycle, JG Press, Emmaus, PA. December 2001.

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.

Kaufman, et al. (2004) "14th Annual BioCycle Nationwide Survey: The State of Garbage in America 2004" Biocycle, JG Press, Emmaus, PA. January, 2004.RMA (2018) 2017 U.S. Scrap Tire Management Summary. Rubber Manufacturers Association, Washington, D.C. July 2018. https://www.ustires.org/system/files/USTMA_scraptire_summ_2017_072018.pdf. September 27, 2018

RMA (2020) "2019 U.S. Scrap Tire Management Summary". Rubber Manufacturers Association, Washington, D.C. October 2020. Available online at: <https://www.ustires.org/sites/default/files/2019%20USTMA%20Scrap%20Tire%20Management%20Summary%20Report.pdf>.

RMA (2018) "2017 U.S. Scrap Tire Management Summary". Rubber Manufacturers Association, Washington, D.C. July 2018. Available online at: <https://www.ustires.org/system/files/USTMA_scraptire_summ_2017_072018.pdf>.

RMA (2016) "2015 U.S. Scrap Tire Management Summary." Rubber Manufacturers Association. August 2016. Available online at: < https://www.ustires.org/sites/default/files/MAR_028_USTMA.pdf>.

RMA (2014a) "2013 U.S. Scrap Tire Management Summary." Rubber Manufacturers Association. November 2014. Available online at: <http://www.rma.org/download/scrap-tires/market-reports/US_STMarket2013.pdf>. Accessed 17 November 2014.

RMA (2014b) "Scrap Tire Markets: Facts and Figures – Scrap Tire Characteristics." Available online at: <https://www.ustires.org/sites/default/files/MAR_027_USTMA.pdf>. Accessed 17 November 2014.

RMA (2012) "Rubber FAQs." Rubber Manufacturers Association. Available online at <http://www.rma.org/about-rma/rubber-faqs/>. Accessed 19 November 2014.

RMA (2011) "U.S. Scrap Tire Management Summary 2005-2009." Rubber Manufacturers Association. October 2011. Available online at: <http://www.rma.org/scrap_tires/scrap_tire_markets/2009_summary.pdf>.

RMA (2009) "Scrap Tire Markets in the United States: 9th Biennial Report." Rubber Manufacturers Association. Washington, D.C. May 2009.

RMA (2002 through 2006) "U.S. Scrap Tire Markets." Rubber Manufacturers Association. Washington, D.C. Available online at: <https://www.ustires.org/publications_bulletins?publication_categories=398>.

Schneider, S. (2007) E-mail between Shelly Schneider of Franklin Associates (a division of ERG) and Sarah Shapiro of ICF International, January 10, 2007.

Shin, D. (2014) Generation and Disposition of Municipal Solid Waste (MSW) in the United States–A National Survey. Thesis. Columbia University, Department of Earth and Environmental Engineering, January 3, 2014.

Simmons, et al. (2006) "15th Nationwide Survey of Municipal Solid Waste Management in the United States: The State of Garbage in America" BioCycle, JG Press, Emmaus, PA. April 2006.

Staley, B. F., and Barlaz, M. A. (2009) Composition of municipal solid waste in the United States and implications for carbon sequestration and methane yield. Journal of Environmental Engineering, 135(10), 901-909.

STMC (1990 through 1997) "Scrap Tire Use/Disposal Study". Rubber Manufacturers Association: Scrap Tire Management Council. Available online at: <https://www.ustires.org/publications_bulletins?publication_categories=398>.

Themelis and Shin (2014) U.S. Survey of Generation and Disposition of Municipal Solid Waste. Waste Management. Columbia University. January 2014. <http://www.seas.columbia.edu/earth/wtert/sofos/Dolly_Shin_Thesis.pdf>.

van Haaren, Rob, Thermelis, N., and Goldstein, N. (2010) "The State of Garbage in America." BioCycle, October 2010. Volume 51, Number 10, pg. 16-23.

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 2019fuel sales in the Continental United States (CONUS).[73] 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 Jet Fuel between Aviation and Land-based Vehicles

As a result of DoD[74] and NATO[75] policies on implementing the Single Fuel For the Battlefield concept, DoD activities have been increasingly replacing diesel fuel with 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 jet fuel consumption should be attributed to ground vehicle use. Based on available Military Service data and expert judgment, a small fraction of jet fuel 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 jet fuel use reported for aviation was reduced and the fuel use for land-based equipment increased. DoD's total fuel use did not change. DoD has been undergoing a transition from JP-8 jet fuel to commercial specification Jet A fuel with additives (JAA) for non-naval aviation and ground assets. To account for this transition jet fuel used for ground-based vehicles was reallocated from JP8 prior to 2014 and from JAA in 2014 and subsequent years. The transition was completed in 2016.

Table A-123 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).

[73] FAS contains data for 1995 through 2019, 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.
[74] DoD Directive 4140.25-M-V1, Fuel Standardization and Cataloging, 2013; DoD Instruction 4140.25, DoD Management Policy for Energy Commodities and Related Services, 2015.
[75] NATO Standard Agreement NATO STANAG 4362, Fuels for Future Ground Equipment Using Compression Ignition or Turbine Engines, 2012.

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.
- 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.[76]

Table A-124 and Table A-125 display DoD bunker fuel use totals for the Navy and Air Force.

[76] 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.

Step 6: Calculate Emissions from International Bunker Fuels

Bunker fuel totals were multiplied by appropriate emission factors to determine greenhouse gas (GHG) emissions. CO_2 emissions from Aviation Bunkers and distillate Marine Bunkers are the total of military aviation and marine bunker fuels, respectively.

The rows labeled "U.S. Military" and "U.S. Military Naval Fuels" in the tables in the International Bunker Fuels section of the Energy chapter were based on the totals provided in Table A-124 and Table A-125, below. CO_2 emissions from aviation bunkers and distillate marine bunkers are presented in Table A-129, and are based on emissions from fuels tallied in Table A-124 and Table A-125.

Table A-123: Transportation Fuels from Domestic Fuel Deliveries[a] (Million Gallons)

Vehicle Type/Fuel	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Aviation	**4,598.4**	**3,099.9**	**2,664.4**	**2,338.1**	**1,814.5**	**1,663.9**	**1,405.0**	**1,449.7**	**1,336.4**	**1,679.5**	**1,663.7**	**1,558.0**	**1,537.7**	**1,482.2**	**1,487.6**
Total Jet Fuels	**4,598.4**	**3,099.9**	**2,664.4**	**2,338.0**	**1,814.3**	**1,663.7**	**1,404.8**	**1,449.5**	**1,336.2**	**1,679.2**	**1,663.5**	**1,557.7**	**1,537.5**	**1,481.9**	**1,487.4**
JP8	285.7	2,182.8	2,122.7	1,838.8	1,358.2	1,100.1	882.8	865.2	718.0	546.6	126.6	(9.52)	(11.38)	1.92	4.71
JP5	1,025.4	691.2	472.1	421.6	361.2	399.3	372.3	362.5	316.4	311.0	316.4	320.4	316.3	304.1	314.4
Other Jet Fuels	3,287.3	225.9	69.6	77.6	94.8	164.3	149.7	221.8	301.7	821.6	1,220.5	1,246.9	1,232.7	1,175.9	1,168.2
Aviation Gasoline	**+**	**+**	**+**	**0.1**	**0.2**	**0.2**	**0.2**	**0.3**	**0.2**	**0.3**	**0.3**	**0.3**	**0.2**	**0.3**	**0.2**
Marine	**686.8**	**438.9**	**454.4**	**604.9**	**485.8**	**578.8**	**489.9**	**490.4**	**390.4**	**427.9**	**421.7**	**412.4**	**395.2**	**370.9**	**365.4**
Middle Distillate (MGO)	0.0	0.0	48.3	54.0	56.8	48.4	37.3	52.9	40.9	62.0	56.0	23.1	24.4	19.9	23.2
Naval Distillate (F76)	686.8	438.9	398.0	525.9	399.0	513.7	440.0	428.4	345.7	362.7	363.3	389.1	370.8	351.0	342.2
Intermediate Fuel Oil (IFO)[b]	0.0	0.0	8.1	25.0	30.0	16.7	12.5	9.1	3.8	3.2	2.4	0.1	0.0	0.0	0.0
Other[c]	**717.1**	**310.9**	**248.2**	**205.6**	**206.8**	**224.0**	**208.6**	**193.8**	**180.6**	**190.7**	**181.1**	**178.3**	**165.8**	**170.4**	**161.4**
Diesel	93.0	119.9	126.6	56.8	58.3	64.1	60.9	57.9	54.9	57.5	54.8	54.7	50.4	51.8	48.7
Gasoline	624.1	191.1	74.8	24.3	25.2	25.5	22.0	19.6	16.9	16.5	16.2	15.9	15.6	14.7	14.9
Jet Fuel[d]	0.0	0.0	46.7	124.4	123.3	134.4	125.6	116.2	108.8	116.7	110.1	107.6	99.9	104.0	97.7
Total (Including Bunkers)	**6,002.4**	**3,849.8**	**3,367.0**	**3,148.6**	**2,507.1**	**2,466.7**	**2,103.5**	**2,133.9**	**1,907.5**	**2,298.2**	**2,266.5**	**2,148.7**	**2,098.7**	**2,023.4**	**2,014.3**

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values. The negative values in this table represent returned products.

+ Indicates value does not exceed 0.05 million gallons.

Includes fuel distributed in the United States and U.S. Territories.

Intermediate fuel oil (IFO 180 and IFO 380) is a blend of distillate and residual fuels. IFO is used by the Military Sealift Command.

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.

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.

Table A-124: Total U.S. Military Aviation Bunker Fuel (Million Gallons)

Fuel Type/Service	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Jet Fuels															
JP8	**56.7**	**300.4**	**307.6**	**285.6**	**211.4**	**182.5**	**143.4**	**141.2**	**122.0**	**88.0**	**17.2**	**2.4**	**2.5**	**2.9**	**1.2**
Navy	56.7	38.3	53.4	70.9	55.4	60.8	47.1	50.4	48.9	31.2	0.8	5.5	6.4	4.8	2.5
Air Force	+	262.2	254.2	214.7	156.0	121.7	96.2	90.8	73.0	56.7	16.4	(3.1)	(3.9)	(1.9)	(1.3)
JP5	**370.5**	**249.8**	**160.3**	**160.6**	**137.0**	**152.5**	**144.9**	**141.2**	**124.9**	**121.9**	**124.1**	**126.1**	**124.7**	**120.1**	**123.9**
Navy	365.3	246.3	155.6	156.9	133.5	149.7	143.0	139.5	123.6	120.2	122.6	124.7	123.4	118.9	122.5
Air Force	5.3	3.5	4.7	3.7	3.5	2.8	1.8	1.7	1.3	1.6	1.5	1.4	1.3	1.2	1.4
JP4	**420.8**	**21.5**	**+**	**+**	**+**	**0.1**	**0.0**	**0.0**	**+**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Navy	+	+	0.0	+	+	+	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Air Force	420.8	21.5	+	+	+	0.1	0.0	0.0	+	0.0	0.0	0.0	0.0	0.0	0.0
JAA	**13.7**	**9.2**	**12.5**	**15.5**	**18.1**	**31.4**	**31.1**	**38.6**	**46.5**	**128.0**	**199.8**	**203.7**	**198.9**	**191.8**	**192.5**
Navy	8.5	5.7	7.9	11.6	12.3	13.7	14.6	14.8	13.4	36.1	71.7	72.9	67.8	68.1	71.2
Air Force	5.3	3.5	4.5	3.9	5.9	17.7	16.5	23.8	33.1	91.9	128.1	130.8	131.1	123.7	121.4
JA1	**+**	**+**	**+**	**0.5**	**0.6**	**0.3**	**(0.5)**	**(0.3)**	**0.6**	**1.1**	**0.3**	**0.5**	**0.2**	**0.5**	**0.3**
Navy	+	+	+	+	0.1	0.1	(0.5)	(0.3)	0.6	0.7	+	0.1	(+)	(+)	(+)
Air Force	+	+	+	0.5	0.5	0.1	(0.1)	(+)	+	0.5	0.3	0.5	0.2	0.5	0.3
JAB	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
Navy	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Air Force	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Navy Subtotal	**430.5**	**290.2**	**216.9**	**239.4**	**201.3**	**224.4**	**204.3**	**204.5**	**186.5**	**188.2**	**195.0**	**203.2**	**197.5**	**191.8**	**196.1**
Air Force Subtotal	**431.3**	**290.7**	**263.5**	**222.9**	**165.9**	**142.4**	**114.5**	**116.3**	**107.4**	**150.7**	**146.4**	**129.5**	**128.8**	**123.5**	**121.8**
Total	**861.8**	**580.9**	**480.4**	**462.3**	**367.2**	**366.7**	**318.8**	**320.8**	**293.9**	**339.0**	**341.4**	**332.8**	**326.3**	**315.3**	**317.9**

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values. The negative values in this table represent returned products.
+ Does not exceed 0.05 million gallons.
NO (Not Occurring)

Table A-125: Total U.S. DoD Maritime Bunker Fuel (Million Gallons)

Marine Distillates	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Navy – MGO	0.0	0.0	23.8	38.0	39.9	32.9	25.5	36.5	32.3	43.3	37.8	5.7	13.2	8.5	10.6
Navy – F76	522.4	333.8	298.6	413.1	311.4	402.2	346.6	337.9	273.1	286.2	286.7	307.8	293.3	276.9	270.0
Navy – IFO	0.0	0.0	6.4	19.7	23.1	12.9	9.5	6.1	3.0	1.5	1.9	+	0.0	0.0	0.0
Total	**522.4**	**333.8**	**328.8**	**470.7**	**374.4**	**448.0**	**381.5**	**380.6**	**308.5**	**331.0**	**326.3**	**313.6**	**306.5**	**285.4**	**280.6**

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

Table A-126: 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)	Variable	1.00
Marine (Residual)	20.48	1.00

Source: EPA (2010) and IPCC (2006).

Table A-127: Annual Variable Carbon Content Coefficient for Jet Fuel (MMT Carbon/QBtu)

Fuel	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
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

Source: EPA (2010).

Table A-128: Annual Variable Carbon Content Coefficient for Distillate Fuel Oil (MMT Carbon/QBtu)

Fuel	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Distillate Fuel Oil	20.17	20.17	20.39	20.37	20.23	20.24	20.22	20.22	20.23	20.23	20.22	20.21	20.20	20.22	20.22

Source: EPA (2020).

Table A-129: Total U.S. DoD CO_2 Emissions from Bunker Fuels (MMT CO_2 Eq.)

Mode	1990	1995	2000	2005	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Aviation	8.1	5.5	4.7	4.5	3.6	3.6	3.1	3.1	2.9	3.3	3.3	3.3	3.2	3.1	3.1
Marine	5.4	3.4	3.4	4.8	3.8	4.6	3.9	3.9	3.1	3.4	3.3	3.2	3.1	2.9	2.9
Total	**13.4**	**9.0**	**8.1**	**9.3**	**7.4**	**8.1**	**7.0**	**7.0**	**6.0**	**6.7**	**6.7**	**6.4**	**6.3**	**6.0**	**6.0**

Note: Totals may not sum due to independent rounding.

References

DLA Energy (2020) 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.

EPA (2010) *Carbon Content Coefficients Developed for EPA's Inventory of Greenhouse Gases and Sinks*. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2020) EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Updated Gasoline and Diesel Fuel CO_2 Emission Factors – Memo.

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 (i.e., HFC-emitting) end-use sectors: refrigeration and air-conditioning, foams, aerosols, solvents, and fire-extinguishing. Within these sectors, there are 78 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. In addition, emissions of certain gases (including HFC-152a, HFC-227ea, HFC-245fa, HFC 365mfc, HFC-43-10mee, HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications) are marked as confidential because they are produced or imported by a small number of chemical providers and in such small quantities or for such discrete applications that reporting national data would effectively be reporting the chemical provider's output, which is considered confidential business information. These gases are modeled individually in the Vintaging Model, but are aggregated and reported as an unspecified mix of HFCs and PFCs.

The Vintaging Model is regularly updated to incorporate up-to-date market information, including equipment stock estimates, leak rates, and sector transitions. In addition, comparisons against published emission and consumption

sources are performed when available. Independent peer reviews of the Vintaging Model are periodically performed, including one conducted in 2017 (EPA 2018), to confirm Vintaging Model estimates and identify updates.

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 three categories: emissions at first-fill, which arise during manufacture or installation, emissions during equipment lifetime, which arise from annual leakage and service losses, and disposal emissions, which occur at the time of discard. This methodology is consistent to the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, where the total refrigerant emissions from Ref/AC equipment is the sum of first-fill emissions, annual operational and servicing emissions, and disposal emissions under the Tier 2a emission factor approach (IPCC 2006). Three separate steps are required to calculate the lifetime emissions from installation, leakage and service, and the emissions resulting from disposal of the equipment. The model assumes that equipment is serviced annually so that the amount equivalent to average annual emissions for each product (and hence for the total of what was added to the bank in a previous year in equipment that has not yet reached end-of-life) is replaced/applied to the starting charge size (or chemical bank). For any given year, these first-fill emissions (for new equipment), 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.

At disposal, refrigerant that is recovered from discarded equipment is assumed to be reused to the extent necessary in the following calendar year. The Vintaging Model does not make any explicit assumption whether recovered refrigerant is reused as-is (allowed under U.S. regulations if the refrigerant is reused in the same owner's equipment), recycled (commonly practiced even when re-used directly), or reclaimed (brought to new refrigerant purity standards and available to be sold on the open market).

Step 1: Calculate first-fill emissions

The first-fill emission equation assumes that a certain percentage of the chemical charge will be emitted to the atmosphere when the equipment is charged with refrigerant during manufacture or installation. First-fill emissions are

considered for all Ref/AC equipment that are charged with refrigerant within the United States, including those which are produced for export, and excluding those that are imported pre-charged. First-fill emissions are thus a function of the quantity of chemical contained in new equipment and the proportion of equipment that are filled with refrigerant in the United States:

$$Ef_j = Qc_j \times I_f \times A_j$$

where:

Ef	=	Emissions from Equipment First-fill. Emissions in year j from filling new equipment.
Qc	=	Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in year j, by weight.
I_f	=	First-fill Leak Rate. Average leak rate during installation or manufacture of new equipment (expressed as a percentage of total chemical charge).
A	=	Applicability of First-fill Leak Rate. Percentage of new equipment that are filled with refrigerant in the United States in year j.
j	=	Year of emission.

Step 2: 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:

$$Es_j = (I_a + I_s) \times \sum Qc_{j-i+1} \quad for\ i = 1 \rightarrow k$$

where:

Es	=	Emissions from Equipment Serviced. Emissions in year j from normal leakage and servicing (including recharging) of equipment.
I_a	=	Annual Leak Rate. Average annual leak rate during normal equipment operation (expressed as a percentage of total chemical charge).
I_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 3: 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, while remaining refrigerant is assumed to be recovered and reused. 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 4: Calculate total emissions

Finally, first-fill, lifetime, and disposal emissions are summed to provide an estimate of total emissions.

$$E_j = Ef_j + Es_j + Ed_j$$

where:

E = Total Emissions. Emissions from refrigeration and air conditioning equipment in year *j.*

Ef = Emissions from first Equipment Fill. Emissions in year *j* from filling new equipment.

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-130, 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-130: Refrigeration and Air-Conditioning Market Transition Assumptions

	Primary Substitute				Secondary Substitute				Tertiary Substitute				
Initial Market Segment	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Growth Rate[7]
Centrifugal Chillers													
CFC-11	HCFC-123	1993	1993	45%	HCFO-1233zd(E)	2016	2016	1%	None				1.6%
					R-514A	2017	2017	1%	None				
					HCFO-1233zd(E)	2017	2020	49%	None				
					R-514A	2018	2020	49%	None				
	HCFC-22	1991	1993	16%	HFC-134a	2000	2010	100%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	HFC-134a	1992	1993	39%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
CFC-12	HFC-134a	1992	1994	53%	R-450A	2017	2017	1%	None				1.5%
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
	HCFC-22	1991	1994	16%	HFC-134a	2000	2010	100%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	HCFC-123	1993	1994	31%	HCFO-1233zd(E)	2016	2016	1%	None				
					R-514A	2017	2017	1%	None				
					HCFO-1233zd(E)	2017	2020	49%	None				
					R-514A	2018	2020	49%	None				
R-500	HFC-134a	1992	1994	53%	R-450A	2017	2017	1%	None				1.5%
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
	HCFC-22	1991	1994	16%	HFC-134a	2000	2010	100%	R-450A	2017	2017	1%	

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate[7]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	HCFC-123	1993	1994	31%	HCFO-1233zd(E)	2016	2016	1%	None				
					R-514A	2017	2017	1%	None				
					HCFO-1233zd(E)	2017	2020	49%	None				
					R-514A	2018	2020	49%	None				
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%	R-407F	2017	2023	100%	3.1%
					R-507	1996	2010	25%	R-407F	2017	2023	100%	
	R-404A	1994	1996	26%	R-407F	2017	2023	100%	None				
	R-507	1994	1996	9%	R-407F	2017	2023	100%	None				
HCFC-22	HCFC-22	1992	1993	100%	R-404A	1996	2009	8%	R-407F	2017	2023	100%	3.0%
					R-507	1996	2009	3%	R-407F	2017	2023	100%	
					R-404A	2009	2010	68%	R-407F	2017	2023	100%	
					R-507	2009	2010	23%	R-407F	2017	2023	100%	
R-502	HCFC-22	1990	1993	40%	R-404A	1996	2010	38%	R-407F	2017	2023	100%	2.6%
					R-507	1996	2010	12%	R-407F	2017	2023	100%	
					Non-ODP/GWP	1996	2010	50%	None				
	R-404A	1993	1996	45%	R-407F	2017	2023	100%	None				
	R-507	1994	1996	15%	R-407F	2017	2023	100%	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				

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate[7]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
					R-410A	2006	2009	8%	None				
					R-410A	2009	2010	71%	None				
Dehumidifiers													
HCFC-22	HFC-134a	1997	1997	89%	None								1.3%
	R-410A	2007	2010	11%	None								
Ice Makers													
CFC-12	HFC-134a	1993	1995	27%	None								2.1%
	R-404A	1993	1995	73%	R-410A	2013	2019	32%	None				
Industrial Process Refrigeration													
CFC-11	HCFC-123	1992	1994	70%	HCFO-1233zd(E)	2016	2016	2%	None				3.2%
					HCFO-1233zd(E)	2017	2020	98%	None				
	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%	HCFO-1233zd(E)	2016	2016	2%	None				
					HCFO-1233zd(E)	2017	2020	98%	None				
	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%

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate[7]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
					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 (Heavy Duty Vehicles)													
CFC-12	HFC-134a	1993	1994	100%	None								0.8%
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	1994	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								
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 (Reciprocating and Screw)													
CFC-12 HCFC-22[2]	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	R-450A	2017	2017	1%	2.5%
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
					R-410A	2010	2020	40%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	R-407C	2000	2009	1%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
	HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
					R-410A	2010	2020	40%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate[7]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	R-407C	2009	2010	9%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
HCFC-22	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	R-450A	2017	2017	1%	2.5%
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
					R-410A	2010	2020	40%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	R-407C	2000	2009	1%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
	HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
					R-410A	2010	2020	40%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	R-407C	2009	2010	9%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
Positive Displacement Chillers (Scroll)													
HCFC-22	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	R-452B	2024	2024	100%	2.5%
					R-410A	2010	2020	40%	R-452B	2024	2024	100%	
	R-407C	2000	2009	1%	R-452B	2024	2024	100%	None				
	HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	R-452B	2024	2024	100%	
					R-410A	2010	2020	40%	R-452B	2024	2024	100%	

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate[7]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
	R-407C	2009	2010	9%	R-452B	2024	2024	100%	None				
Refrigerated Appliances													
CFC-12	HFC-134a	1994	1995	100%	Non-ODP/GWP	2019	2021	86%	None				1.7%
					R-450A	2021	2021	7%	None				
					R-513A	2021	2021	7%	None				
Refrigerated Food Processing and Dispensing Equipment													
CFC-12	HCFC-22	1990	1994	100%	HFC-134a	1995	1998	70%	None				2.1%
					R-404A	1995	1998	30%	R-448A	2021	2021	50%	
									R-449A	2021	2021	50%	
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[3]	DX	2001	2006	67.5%	DX	2006	2015	62%	None				1.7%
					DR[4]	2000	2015	23%	None				
					SLS[5]	2000	2015	15%	None				
	DR	2000	2006	22.5%	None								
	SLS	2000	2006	10%	None								
Retail Food (Large; Refrigerant Transition)													
CFC-12 R-502[6]	R-404A	1995	2000	17.5%	R-404A	2000	2000	3.3%	R-407A	2017	2017	100%	1.7%
					R-407A	2011	2015	63.3%	None				
					R-407A	2017	2017	33.3%	None				
	R-507	1995	2000	7.5%	R-404A	2006	2010	71%	R-407A	2017	2017	100%	
					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%	R-407A	2017	2017	100%	
					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%	R-407A	2017	2017	100%	
					R-407A	2006	2010	25.3%	None				
Retail Food (Large Condensing Units)													

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate[7]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
HCFC-22	R-402A	1995	2005	5%	R-404A	2006	2006	100%	R-407A	2018	2018	100%	1.5%
	R-404A	1995	2005	25%	R-407A	2018	2018	100%	None				
	R-507	1995	2005	10%	R-407A	2018	2018	100%	None				
	R-404A	2008	2010	45%	R-407A	2018	2018	100%	None				
	R-507	2008	2010	15%	R-407A	2018	2018	100%	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%	None								
	R-404A	1995	2005	30%	R-407A	2018	2018	100%					
	R-404A	2008	2010	30%	R-407A	2018	2018	100%					
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%	
									Non-ODP/GWP	2014	2019	31%	
									Non-ODP/GWP	2016	2016	17.3%	
									R-450A	2016	2020	23%	
									R-513A	2016	2020	23%	
					HFC-134a	2000	2009	9%	Non-ODP/GWP	2014	2019	30%	
									R-450A	2016	2020	35%	
									R-513A	2016	2020	35%	
	R-404A	1990	1993	9%	Non-ODP/GWP	2016	2016	30%	None				
					R-448A	2019	2020	35%	None				
					R-449A	2019	2020	35%	None				
Transport Refrigeration (Road Transport)													
CFC-12	HFC-134a	1993	1995	10%	None								5.5%
	R-404A	1993	1995	60%	R-452A	2017	2021	5%					
					R-452A	2021	2030	95%					
	HCFC-22	1993	1995	30%	R-410A	2000	2003	5%	None				
					R-404A	2006	2010	95%	R-452A	2017	2021	5%	
									R-452A	2021	2030	95%	

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate[7]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	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	100%	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-404A	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								
Vending Machines													
CFC-12	HFC-134a	1995	1998	90%	CO_2	2012	2012	1%	Propane	100%	2019	2019	-0.03%
					Propane	2013	2017	39%	None				
					Propane	2014	2014	1%	None				
					Propane	2019	2019	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				
Water-Source and Ground-Source Heat Pumps													
HCFC-22	R-407C	2000	2006	5%	None								1.3%
	R-410A	2000	2006	5%	None								

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate[7]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
	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								

[1] Transitions between the start year and date of full penetration in new equipment are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.
[2] The CFC-12 reciprocating chillers market for new systems transitioned to HCFC-22 overnight in 1993. This transition is not shown in the table in order to provide the HFC transitions in greater detail.
[3] 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.
[4] 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.
[5] 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.
[6] The CFC-12 large retail food market for new systems transitioned to R-502 from 1988 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.
[7] Growth Rate is the average annual growth rate for individual market sectors from the base year to 2030.

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Table A-131 presents the average equipment lifetimes and annual HFC emission rates (for first-fill, servicing, leaks, and disposal) for each end-use assumed by the Vintaging Model.

Table A-131: Refrigeration and Air-Conditioning Lifetime Assumptions

End-Use	Lifetime (Years)	HFC Emission Rates (First-fill)[a] (%)	HFC Emission Rates (Servicing and Leaks) (%)	HFC Emission Rates (Disposal)[b] (%)
Centrifugal Chillers	20 – 27	0.2 – 0.5	2.0 – 10.9	10
Cold Storage	20 – 25	1	15.0	10
Commercial Unitary A/C	15	0.5 – 1	7.9 – 8.6	18 – 40
Condensing Units (Medium Retail Food)	10 – 20	0.5 – 3	8 – 15	10 – 20
Dehumidifiers	11	0.5 – 1	0.5	50
Ice Makers	8	0.5 – 2	3.0	49
Industrial Process Refrigeration	25	1	3.6 – 12.3	10
Large Retail Food	18	2	17 – 33	10
Mobile Air Conditioners	5 –16	0.2 – 0.5	2.3 – 18.0	43 – 50
Positive Displacement Chillers	20	0.2 – 0.5	0.5 – 1.5	10
PTAC/PTHP	12	1	3.9	40
Refrigerated Appliances	14	0.6	0.6	42
Refrigerated Food Processing and Dispensing Equipment	10	1	1	68
Residential Unitary A/C	15	0.2 – 1	5.3 – 10.6	20 – 40
Small Retail Food	10	1	1	19 – 65
Transport Refrigeration	9 – 40	0.2 – 1	19.4 – 36.4	10 – 65
Vending Machines	10	0.5	1	68– 79
Water & Ground Source Heat Pumps	20	1	3.9	43
Window Units	12	0.5 – 1	0.6	50

[a] For some equipment, first-fill emissions are adjusted to account for equipment that are produced in the United States, including those which are produced for export, and excluding those that are imported pre-charged estimate.
[b] Disposal emissions rates are developed based on consideration of the original charge size, the percentage of refrigerant likely to remain in equipment at the time of disposal, and recovery practices assumed to vary by gas type. Because equipment lifetime emissions are annualized, equipment is assumed to reach the end of its lifetime with a full charge. Therefore, recovery rate is equal to 100 percent - Disposal Loss Rate (%).

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. Three types of aerosol products are modeled: metered dose inhalers (MDI), consumer aerosols, and technical 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 and certain technical aerosols continued to use CFCs and HCFCs 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. Under the Clean Air Act, the use of CFCs and HCFCs was also exempted in technical aerosols for several applications, including industrial cleaners, pesticides, mold release agents, certain dusters, and lubricants.

All HFCs 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-132.

Table A-132: Aerosol Product Transition Assumptions

	Primary Substitute				Secondary Substitute				Tertiary Substitute				
Initial Market Segment	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Growth Rate[4]
MDIs													
CFC Mix[2]	HFC-134a	1997	1997	6%	None								2.1%
	Non-ODP/GWP	1998	2007	7%	None								
	CFC Mix[a]	2000	2000	87%	HFC-134a	2001	2011	28%	Non-ODP/GWP	2012	2018	64%	
					Non-ODP/GWP	2001	2014	67%	None				
					HFC-227ea	2007	2013	5%	Non-ODP/GWP	2015	2018	44%	
Consumer Aerosols (Non-MDIs)													
NA[3]	HFC-152a	1990	1991	50%	None								4.2%
	HFC-134a	1995	1995	50%	HFC-152a	1997	1998	44%	None				
					HFC-152a	2001	2005	38%	None				
					HFO-1234ze(E)	2016	2018	16%	None				
Technical Aerosols (Non-MDIs)													
CFC-12	HCFC-142b	1994	1994	10%	HFC-152a	2001	2010	90%	None				4.2%
					HFC-134a	2001	2010	10%	None				
	Non-ODP/GWP	1994	1994	5%	None								
	HCFC-22	1994	1994	50%	HFC-134a	2001	2010	100%	HFO-1234ze(E)	2012	2016	10%	
	HFC-152a	1994	1994	10%	None								
	HFC-134a	1994	1994	25%	None								

[1] Transitions between the start year and date of full penetration in new products are assumed to be linear so that in total 100% of the market is assigned to the original ODS or the various ODS substitutes.

[2] 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. It is assumed that CFC mix was stockpiled in the United States and used in new products through 2013.

[3] 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.

[4] Growth Rate is the average annual growth rate for individual market sectors from the base year to 2030.

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 solvent is assumed to be recycled or continuously reused through a distilling and cleaning process until it is eventually almost entirely emitted. The remainder of the consumed solvent is assumed to be entrained in sludge or wastes and disposed of by incineration or other destruction technologies without being released to the atmosphere (U.S. EPA 2004). 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-133.

Table A-133: Solvent Market Transition Assumptions

	Primary Substitute				Secondary Substitute				
Initial Market Segment	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment[1]**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment[1]**	**Maximum Market Penetration**	**Growth Rate[3]**
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	2013[2]	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	2013[2]	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%

Initial Market Segment	Primary Substitute				Secondary Substitute				Growth Rate[3]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
	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	2013[2]	90%	None				2.0%
	Methyl Siloxanes	1995	1996	6%					
	HCFC-225ca/cb	1995	1996	1%	Unknown				
	HFE-7100	1995	1996	3%	None				

Note: 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.

[1] Transitions between the start year and date of full penetration in new equipment or chemical supply are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.

[2] Transition assumed to be completed in 2013 to mimic CFC-113 stockpile use.

[3] Growth Rate is the average annual growth rate for individual market sectors from the base year to 2030.

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 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. The model assumes that equipment is serviced annually so that the amount equivalent to average annual emissions for each product (and hence for the total of what was added to the bank in a previous year in equipment that has not yet reached end-of-life) is replaced/applied to the starting charge size (or chemical bank). Each fire protection agent is modeled separately. In the Vintaging Model, streaming applications have a 24-year lifetime and flooding applications have a 33-year lifetime. At end-of-life, remaining agent is recovered from equipment being disposed and is reused.

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

where:

E = Emissions. Total emissions of a specific chemical in year *j* for 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-134.

Table A-134: Fire Extinguishing Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Growth Rate[3]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
Flooding Agents									
Halon-1301	Halon-1301[2]	1994	1994	4%	Unknown				2.2%
	HFC-23	1994	1999	0.2%	None				
	HFC-227ea	1994	1999	50.2%	FK-5-1-12	2003	2020	35%	
					HFC-125	2001	2012	10%	
					Non-ODP/GWP	2005	2020	13%	
	Non-ODP/GWP	1994	1994	22%	FK-5-1-12	2003	2020	7%	
	Non-ODP/GWP	1995	2003	7%	None				
	CO_2	1998	2006	7%	None				
	C_4F_{10}	1994	1999	0.5%	FK-5-1-12	2003	2003	100%	
	HFC-125	1997	2006	9.1%	FK-5-1-12	2003	2020	35%	
					Non-ODP/GWP	2005	2020	10%	
					Non-ODP/GWP	2005	2019	3%	
Streaming Agents									
Halon-1211	Halon-1211[2]	1992	1992	5%	Unknown				3.0%
	HFC-236fa	1997	1999	3%	None				
	Halotron	1994	1995	0.1%	Unknown				
	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				

[1] Transitions between the start year and date of full penetration in new equipment are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.
[2] 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.
[3] Growth Rate is the average annual growth rate for individual market sectors from the base year to 2030.

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. Manufacturing emissions are considered for all foam equipment that are filled with foam within the United States, including those which are produced for export, and excluding those that are imported pre-filled.

$$Em_j = Im \times Qc_j$$

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_j	=	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-135. The emission profiles of these thirteen foam types are shown in Table A-136.

Table A-135: Foam Blowing Market Transition Assumptions

	Primary Substitute				Secondary Substitute				Tertiary Substitute				
Initial Market Segment	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Growth Rate[3]
Vending Machine Foam													
CFC-11	HCFC-141b	1993	1995	100%	HFC-245fa	2001	2004	100%	Non-ODP/GWP	2004	2006	45%	-0.03%
									Non-ODP/GWP	2007	2009	5%	
									Non-ODP/GWP	2007	2009	25%	
									Non-ODP/GWP	2010	2010	10%	
									Non-ODP/GWP	2017	2017	2%	
									Non-ODP/GWP	2017	2017	8%	
Stand-alone Equipment Foam													
CFC-11	HCFC-141b	1990	1995	40%	HFC-245fa	2003	2005	80%	HCFO-1233zd(E)	2019	2020	25%	2.2%
					HFC-134a	2003	2005	40%	None				
					Non-ODP/GWP	2003	2005	40%	None				
	HCFC-22	1990	1995	56%	HFC-134a	2004	2008	46%	Non-ODP/GWP	2010	2018	32%	
									HCFO-1233zd(E)	2019	2020	36%	
					Non-ODP/GWP	2004	2008	54%	None				
Ice Machine Foam													
CFC-11	HCFC-141b	1989	1996	40%	CO_2	2002	2003	69%	None				2.1%
					HFC-134a	2002	2003	31%	CO_2	2017	2020	47%	
									HCFO-1233zd(E)	2017	2020	20%	
	HCFC-142b	1989	1996	8%	CO_2	2002	2003	69%	None				
					HFC-134a	2002	2003	31%	CO_2	2017	2020	47%	
									HCFO-1233zd(E)	2017	2020	20%	
	HCFC-22	1989	1996	52%	CO_2	2002	2003	69%	None				
					HFC-134a	2002	2003	31%	CO_2	2017	2020	47%	
									HCFO-1233zd(E)	2017	2020	20%	
Refrigerated Food Processing and Dispensing Equipment Foam													
CFC-11	HCFC-22	1989	1997	100%	HFC-134a	2004	2008	75%	Non-ODP/GWP	2015	2021	30%	2.1%
						2009	2010	20%	HCFO-1233zd(E)	2020	2021	3%	
									HFO-1234ze	2020	2021	3%	
					Non-ODP/GWP	2004	2008	25%	None				
Small Walk-in Cooler Foam													
CFC-11	HCFC-141b	1990	1995	50%	HFC-245fa	2001	2003	100%	None				1.6%

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate[3]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
	HCFC-22	1990	1995	50%	HFC-134a	2000	2001	10%	None				
					HFC-245fa	2009	2010	50%	HCFO-1233zd(E)	2020	2020	20%	
					HFC-134a	2009	2010	40%	None				
Large Walk-in Cooler Foam													
CFC-11	HCFC-141b	1990	1995	50%	HFC-245fa	2001	2003	100%	None				1.5%
	HCFC-22	1990	1995	50%	HFC-134a	2000	2001	10%	None				
					HFC-245fa	2009	2010	50%	HCFO-1233zd(E)	2020	2020	20%	
					HFC-134a	2009	2010	40%	None				
Display Case Foam													
CFC-11	HCFC-141b	1991	1992	50%	HFC-245fa	2003	2003	100%	None				1.7%
	HCFC-142b	1991	1992	50%	HFC-245fa	2004	2004	100%	None				
CFC-12	HCFC-22	1991	1993	100%	HFC-134a	2003	2007	100%	HCFO-1233zd(E)	2015	2020	60%	
Road Transport Foam													
CFC-11	HCFC-141b	1989	1996	19%	HCFC-22	1999	2001	37%	HFC-245fa	2005	2007	100%	5.5%
					CO2	1999	2001	11%	None				
					Non-ODP/GWP	1999	2001	53%	None				
	HCFC-22	1989	1996	81%	HFC-134a	2005	2007	37%	None				
					HFC-245fa	2005	2007	63%	HCFO-1233zd	2020	2020	76%	
Intermodal Container Foam													
CFC-11	HCFC-141b	1989	1996	19%	HCFC-22	1999	2001	37%	HFC-245fa	2005	2007	100%	7.3%
					CO2	1999	2001	11%	None				
					Non-ODP/GWP	1999	2001	53%	None				
	HCFC-22	1989	1996	81%	HFC-134a	2005	2007	37%	None				
					HFC-245fa	2005	2007	63%	HCFO-1233zd	2020	2020	76%	
Flexible PU Foam: Integral Skin Foam													
HCFC-141b[4]	HFC-134a	1996	2000	50%	HFC-245fa	2003	2010	96%	HCFO-1233zd(E)	2017	2017	83%	2.0%
									Non-ODP/GWP	2017	2017	6%	
									HFO-1336mzz(Z)	2017	2017	10%	
					Non-ODP/GWP	2003	2010	4%	None				
	CO_2	1996	2000	50%	None								
Flexible PU Foam: Slabstock Foam, Moulded Foam													

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate[3]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
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				4.8%
					HC/HFC-245fa Blend	2000	2003	5%	Non-ODP/GWP	2017	2017	100%	
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	2020	50%	
									HCFO-1233zd(E)	2015	2020	50%	
					HFC-245fa	2006	2009	10%	Non-ODP/GWP	2015	2020	50%	
									HCFO-1233zd(E)	2015	2020	50%	
					Non-ODP/GWP	2002	2005	10%	None				
					Non-ODP/GWP	2006	2009	3%	None				
					Non-ODP/GWP	2009	2014	20%	None				
PU Rigid: One Component Foam													
CFC-12	HCFC-142b/22 Blend	1989	1996	70%	Non-ODP/GWP	2009	2010	80%	None				4.0%
					HFC-134a	2009	2010	10%	HFO-1234ze(E)	2018	2020	100%	
					HFC-152a	2009	2010	10%	None				

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate[3]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
	HCFC-22	1989	1996	30%	Non-ODP/GWP	2009	2010	80%	None				
					HFC-134a	2009	2010	10%	HFO-1234ze(E)	2018	2020	100%	
					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													
HCFC-141b[2]	HCFC-22/Water Blend	2001	2003	20%	HFC-245fa/CO_2 Blend	2009	2010	50%	HCFO-1233zd(E)	2015	2020	100%	6.0%
					Non-ODP/GWP	2009	2010	50%	None				
	HFC-245fa/CO_2 Blend	2002	2004	20%	HCFO-1233zd(E)	2015	2020	100%	None				
	Non-ODP/GWP	2001	2004	40%	None								
	HFC-134a	2002	2004	20%	Non-ODP/GWP	2015	2020	100%	None				
HCFC-22	HFC-245fa/CO_2 Blend	2009	2010	40%	HCFO-1233zd(E)	2015	2020	100%	None				
	Non-ODP/GWP	2009	2010	20%	None								
	CO_2	2009	2010	20%	None								
	HFC-134a	2009	2010	20%	Non-ODP/GWP	2015	2020	100%	None				
PU Rigid: High Pressure Two-Component Spray Foam													
CFC-11	HCFC-141b	1989	1996	100%	HFC-245fa	2002	2003	C	HFO-1336mzz(Z)	2016	2020	100%	0.8%
					HFC-245fa/CO_2 Blend	2002	2003	C	HFO-1336mzz(Z)/CO_2 Blend	2016	2020	100%	

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate[3]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
					HFC-227ea/HFC-365mfc Blend	2002	2003	C	HCFO-1233zd(E)	2016	2020	100%	
PU Rigid: Low Pressure Two-Component Spray Foam													
CFC-12	HCFC-22	1989	1996	100%	HFC-245fa	2002	2003	15%	HCFO-1233zd(E)	2017	2021	100%	0.8%
					HFC-134a	2002	2003	85%	HFO-1234ze	2017	2021	100%	
XPS: Boardstock Foam													
CFC-12	HCFC-142b/22 Blend	1989	1994	10%	HFC-134a	2009	2010	70%	Non-ODP/GWP	2021	2021	100%	2.5%
					HFC-152a	2009	2010	10%	None				
					CO_2	2009	2010	10%	None				
					Non-ODP/GWP	2009	2010	10%	None				
	HCFC-142b	1989	1994	90%	HFC-134a	2009	2010	70%	Non-ODP/GWP	2021	2021	100%	
					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				

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[1] Transitions between the start year and date of full penetration in new equipment are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.

[2] The CFC-11 PU Rigid: Sandwich Panels: Continuous and Discontinuous market for new systems transitioned to 82 percent HCFC-141b and 18 percent HCFC-22 from 1989 to 1996. These transitions are not shown in the table in order to provide the HFC transitions in greater detail.

[3] Growth Rate is the average annual growth rate for individual market sectors from the base year to 2030.

[4] CFC-11 was the initial blowing agent used for through 1989. This transition is not shown in the table in order to provide the HFC transitions in greater detail.

1

Table A-136: 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
Vending Machine Foam	4	0.25	10	93.5	100
Stand-alone Equipment Foam	4	0.25	10	93.5	100
Ice Machine Foam	4	0.25	8	94.0	100
Refrigerated Food Processing and Dispensing Equipment Foam	4	0.25	10	93.5	100
Small Walk-in Cooler Foam	4	0.25	20	91.0	100
Large Walk-in Cooler Foam	4	0.25	20	91.0	100
CFC-11 Display Case Foam	4	0.25	18	91.5	100
CFC-12 Display Case Foam	4	0.25	18	91.5	100
Road Transport Foam	4	0.25	12	93.0	100
Intermodal Container Foam	4	0.25	15	92.3	100
Rigid PU: High Pressure Two-Component Spray Foam	15	1.5	50	10.0	100
Rigid PU: Low Pressure Two-Component 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	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 (HFC-134a)[a]	6.5	0.5	14	37.2	50.7
Rigid PU: Domestic Refrigerator and Freezer Insulation (all others)[a]	3.75	0.25	14	39.9	47.15
PU and PIR Rigid: Boardstock	10	1	25	22.5	57.5
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 and PU and PIR Boardstock end-uses, 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 and 1.5 percent/year, respectively, 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-137.

Table A-137: Sterilization Market Transition Assumptions

	Primary Substitute				Secondary Substitute				Tertiary Substitute				
Initial Market Segment	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	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	Growth Rate
12/88	EtO	1994	1995	95%	None								2.0%
	Non-ODP/GWP	1994	1995	0.8%	None								
	HCFC-124/EtO Blend	1993	1994	1.4%	Non-ODP/GWP	2015	2015	100%	None				
	HCFC-22/HCFC-124/EtO Blend	1993	1994	3.1%	Non-ODP/GWP	2010	2010	100%	None				

[1] Transitions between the start year and date of full penetration in new equipment are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.

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-138 provides the bank for ODS and ODS substitutes by chemical grouping in metric tons (MT) for 1990 to 2019.

Table A-138: Banks of ODS and ODS Substitutes, 1990-2019 (MT)

Year	CFC	HCFC	HFC
1990	706,317	183,974	872
1995	752,774	428,014	50,353
2000	609,993	878,120	189,534
2001	579,845	954,126	218,902
2002	553,906	1,013,434	251,613
2003	528,383	1,057,175	293,825
2004	502,424	1,101,483	337,838
2005	471,487	1,147,856	384,560
2006	439,576	1,190,007	436,931
2007	410,229	1,219,977	490,965
2008	386,025	1,235,871	541,647
2009	371,224	1,227,368	597,134
2010	341,955	1,194,954	668,796
2011	313,158	1,154,641	742,885
2012	284,514	1,111,521	819,235
2013	256,700	1,062,669	898,644
2014	228,748	1,013,579	980,182
2015	200,560	965,727	1,057,421
2016	171,901	916,604	1,132,200
2017	141,755	868,095	1,196,946
2018	119,362	810,765	1,257,269
2019	104,468	745,836	1,309,707

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.

U.S. EPA (2018) EPA's Vintaging Model of ODS Substitutes: A Summary of the 2017 Peer Review. Office of Air and Radiation. Document Number EPA-400-F-18-001. Available online at: <https://www.epa.gov/sites/production/files/2018-09/documents/epas-vintaging-model-of-ods-substitutes-peer-review-factsheet.pdf>.

U.S. EPA (2004) The U.S. Solvent Cleaning Industry and the Transition to Non Ozone Depleting Substances. September 2004. Available online at: <https://www.epa.gov/sites/production/files/2014-11/documents/epasolventmarketreport.pdf>.

Data are also taken from various government sources, including rulemaking analyses from the U.S. Department of Energy and from the Motor Vehicle Emission Simulator (MOVES) model from EPA's Office of Transportation and Air Quality.

3.10. Methodology for Estimating CH_4 Emissions from Enteric Fermentation

The steps outlined in this annex were used to estimate methane emissions from enteric fermentation for the years 1990 through 2017. As explained in the Enteric Fermentation chapter, a simplified approach was used to estimate emissions for 2018 and 2019. The methodology used for 2019 relied on 2019 population estimates and 2017 implied emission factors and is explained in further detail within Chapter 5.1 Enteric Fermentation (CRF Source Category 3A). The same methods explained in this annex for 2019 estimates were also used for 2018 estimates. 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.[77] 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 2020). State-level cattle population estimates are shown by animal type for 2019 in Table A-139. A national-level summary of the annual average populations upon which all livestock-related emissions are based is provided in Table A-140. Cattle populations used in the Enteric Fermentation source category for the 1990 to 2017 Inventory 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). For 2018, state populations were estimated by calculating ratios of 2017 state populations to the 2017 total national population, then applying those state-specific ratios to the 2018 national total population estimate, see the Enteric Fermentation chapter for more details about this approach.

Table A-139: 2019 Cattle Population Estimates, by Animal Type and State (1,000 head)[78]

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	7	1	3	50	356	699	27	65	25	20	6
Alaska	0	0	0	0	3	2	5	0	1	0	0	0
Arizona	101	198	35	83	20	94	185	8	21	130	19	300
Arkansas	3	6	1	2	60	469	921	39	94	54	35	13
California	901	1,771	227	536	70	336	660	29	71	294	82	513
Colorado	80	156	30	71	55	413	812	42	103	417	285	1,105
Conn.	10	19	3	7	1	3	5	0	1	1	1	0

[77] Additional information on the Cattle Enteric Fermentation Model can be found in ICF (2006).
[78] State-level cattle populations were not estimated for 2019 for this current draft Inventory.

Delaware	3	5	1	2	0	1	3	0	0	1	0	0
Florida	63	123	10	25	60	466	915	28	68	15	16	4
Georgia	43	84	9	21	33	255	501	25	60	18	27	6
Hawaii	1	2	0	1	4	38	74	3	7	5	2	1
Idaho	308	606	93	219	40	257	504	27	65	152	104	315
Illinois	48	94	16	37	25	199	390	17	41	118	59	303
Indiana	95	187	24	56	17	108	212	11	27	53	27	131
Iowa	110	217	40	95	70	495	973	41	100	642	296	1,388
Kansas	77	151	30	71	95	806	1,583	69	168	1,005	784	2,704
Kentucky	29	58	12	28	70	525	1,031	34	81	105	63	21
Louisiana	6	12	1	3	31	230	452	19	46	12	11	3
Maine	15	30	4	11	2	6	11	1	2	2	2	1
Maryland	24	47	9	20	4	22	43	2	6	7	3	11
Mass.	6	12	2	5	1	3	7	0	1	1	1	0
Michigan	218	429	51	120	16	62	121	6	14	83	22	177
Minn.	236	464	88	208	35	190	373	21	52	245	90	450
Miss.	5	9	2	4	38	244	480	21	50	21	17	6
Missouri	44	86	13	32	120	1,055	2,072	83	201	226	129	128
Montana	7	14	3	6	100	763	1,498	95	231	113	140	54
Nebraska	31	61	7	18	110	985	1,936	84	203	1,123	756	2,933
Nevada	15	30	3	8	14	113	222	9	22	22	16	3
N.Hamp.	7	14	2	4	1	3	5	0	1	1	1	0
N.Jersey	3	7	1	3	1	4	8	0	1	1	1	0
N.Mexico	167	328	33	78	35	239	469	22	54	59	49	15
NewYork	318	626	106	250	20	56	111	10	24	22	27	23
N.Car.	23	45	7	16	31	190	373	15	37	21	14	5
N.Dakota	8	16	3	6	65	490	962	46	112	125	118	60
Ohio	135	264	36	85	30	148	290	17	41	108	33	180
Oklahoma	18	35	6	14	161	1,075	2,112	97	236	441	255	360
Oregon	64	125	19	46	40	280	550	23	57	76	63	98
Penn	270	530	94	222	25	95	186	15	35	78	33	110
R.Island	0	1	0	0	0	1	1	0	0	0	0	0
S.Car.	8	15	2	5	15	87	171	7	18	4	5	1
S.Dakota	60	117	13	32	100	854	1,677	88	214	363	290	462
Tenn.	21	41	10	25	65	467	916	32	79	66	49	17
Texas	252	495	78	183	341	2,289	4,496	181	439	1,270	740	2,876
Utah	47	93	16	39	27	173	341	19	46	39	33	25
Vermont	66	130	17	39	3	7	14	1	3	2	4	1
Virginia	45	88	11	27	40	330	648	25	61	81	38	24
Wash.	141	278	36	85	18	115	227	13	31	93	64	226
W.Virg.	4	8	1	3	15	106	209	8	21	19	9	5
Wisconsin	657	1,292	213	501	30	149	292	18	43	196	27	320
Wyoming	3	6	1	2	40	366	720	41	100	78	75	88

Table A-140: Cattle Population Estimates from the CEFM Transition Matrix for 1990–2019 (1,000 head)

Livestock Type	1990	1995	2000	2005	2013	2014	2015	2016	2017	2018	2019
Dairy											
Dairy Calves (0–6 months)	5,369	5,091	4,951	4,628	4,758	4,740	4,771	4,758	4,785	4,800	4,846
Dairy Cows	10,015	9,482	9,183	9,004	9,221	9,208	9,307	9,310	9,346	9,432	9,353
Dairy Replacements 7–11 months	1,214	1,216	1,196	1,257	1,341	1,377	1,415	1,414	1,419	1,423	1,403
Dairy Replacements 12–23 months	2,915	2,892	2,812	2,905	3,185	3,202	3,310	3,371	3,343	3,353	3,306
Beef											
Beef Calves (0–6 months)	16,909	18,177	17,431	16,918	14,859	14,741	15,000	15,563	15,971	16,021	16,175
Bulls	2,160	2,385	2,293	2,214	2,074	2,038	2,109	2,142	2,244	2,252	2,253
Beef Cows	32,455	35,190	33,575	32,674	29,631	29,085	29,302	30,166	31,213	31,466	31,691

Beef Replacements 7–11 months	1,269	1,493	1,313	1,363	1,291	1,385	1,479	1,515	1,484	1,424	1,372
Beef Replacements 12–23 months	2,967	3,637	3,097	3,171	3,041	3,121	3,424	3,578	3,598	3,454	3,328
Steer Stockers	10,321	11,716	8,724	8,185	7,457	7,374	7,496	8,150	7,957	8,032	8,144
Heifer Stockers	5,946	6,699	5,371	5,015	4,455	4,280	4,385	4,810	4,754	4,937	5,086
Feedlot Cattle	9,549	11,064	13,006	12,652	13,267	13,219	12,883	13,450	14,340	15,475	15,718

Note: 2018 and 2019 values are based on a simplified approach as described in Chapter 5.1 Enteric Fermentation and is not a CEFM output.

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.[79] 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 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-141.

Table A-141: 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

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

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-142, 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-143. 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-142: 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-143: 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	1,163	1,154	1,378	1,618	1,552	1,541	2,515	4,711	8,199	6,637	3,089	1,542
5	1,155	1,379	1,619	1,553	1,541	2,516	4,712	8,202	6,640	3,091	1,544	1,151
4	1,426	1,660	1,598	1,580	2,556	4,754	8,243	6,688	3,135	1,588	1,194	1,184
3	1,662	1,599	1,581	2,557	4,755	8,246	6,690	3,136	1,588	1,194	1,185	1,459
2	1,600	1,582	2,558	4,757	8,249	6,693	3,138	1,589	1,195	1,186	1,460	1,698
1	1,584	2,560	4,760	8,253	6,695	3,139	1,590	1,195	1,186	1,461	1,699	1,635
0	2,562	4,763	8,257	6,698	3,140	1,590	1,196	1,187	1,462	1,700	1,636	1,618

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-144) 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-144.

Table A-144: 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.[80] 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).[81] 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 2019) 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-145.

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-146, and weight gain was held constant starting in 2000. Table A-146 provides weight gains that vary by year in the CEFM.

[80] 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.

[81] 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-145: Typical Animal Mass (lbs)[82]

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	1,499	899	1,220	1,830	819	691	651	923	845
1991	270	1,499	897	1,224	1,836	821	694	656	933	855
1992	269	1,499	897	1,262	1,893	840	714	673	936	864
1993	270	1,499	898	1,279	1,918	852	721	683	929	863
1994	270	1,499	897	1,279	1,918	853	720	688	943	875
1995	270	1,499	897	1,281	1,921	857	735	700	947	879
1996	269	1,499	898	1,284	1,926	858	739	707	939	878
1997	270	1,499	899	1,285	1,927	860	736	707	938	876
1998	270	1,499	896	1,295	1,942	865	736	709	956	892
1999	270	1,499	899	1,291	1,936	861	730	708	959	894
2000	270	1,499	896	1,271	1,906	849	719	702	960	898
2001	270	1,499	897	1,271	1,906	850	725	707	963	900
2002	270	1,499	896	1,275	1,912	851	725	707	981	915
2003	270	1,499	899	1,307	1,960	871	718	701	972	904
2004	270	1,499	896	1,322	1,983	877	719	702	966	904
2005	270	1,499	894	1,326	1,989	879	717	706	974	917
2006	270	1,499	897	1,340	2,010	889	724	712	983	925
2007	270	1,499	896	1,347	2,020	894	720	706	991	928
2008	270	1,499	897	1,347	2,020	894	720	704	999	938
2009	270	1,499	895	1,347	2,020	894	730	715	1007	947
2010	270	1,499	897	1,347	2,020	896	726	713	996	937
2011	270	1,499	897	1,347	2,020	891	721	712	989	932
2012	270	1,499	899	1,347	2,020	892	714	706	1003	945
2013	270	1,499	898	1,347	2,020	892	718	709	1016	958
2014	270	1,499	895	1,347	2,020	888	722	714	1022	962
2015	270	1,499	896	1,347	2,020	890	717	714	1037	982
2016	269	1,499	899	1,220	1,830	819	691	651	923	845
2017	269	1,499	899	1,220	1,830	819	691	651	923	845

[a] Input into the model.

[b] Annual average calculated in model based on age distribution.

Table A-146: 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

[82] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

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-147) 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-147 provides a summary of the reported feedlot placement statistics for 2017.

Table A-147: Feedlot Placements in the United States for 2017 (Number of animals placed/1,000 Head)[83]

Weight Placed When:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
< 600 lbs	380	315	350	348	400	375	360	360	405	675	610	470
600 – 700 lbs	445	330	295	255	315	315	235	285	340	590	545	410
700 – 800 lbs	585	490	630	490	529	430	385	418	490	510	455	445
> 800 lbs	571	559	842	755	875	650	635	865	915	618	489	474
Total	**1,981**	**1,694**	**2,117**	**1,848**	**2,119**	**1,770**	**1,615**	**1,928**	**2,150**	**2,393**	**2,099**	**1,799**

Note: Totals may not sum due to independent rounding.
Source: USDA (2018).

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-148. Annual estimates for dairy cows were taken from USDA milk production statistics. Dairy lactation estimates for 1990 through 2017 are shown in Table A-149. 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-148: 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-149: Dairy Lactation Rates by State (lbs/ year/cow)[84]

State/Year	1990	1995	2000	2005	2011	2012	2013	2014	2015	2016	2017
Alabama	12,214	14,176	13,920	14,000	14,300	13,000	13,000	13,625	12,625	13,143	14,833
Alaska	13,300	17,000	14,500	12,273	13,800	14,250	10,667	11,667	11,667	11,667	9,667
Arizona	17,500	19,735	21,820	22,679	23,473	23,979	23,626	24,368	24,402	24,679	24,680
Arkansas	11,841	12,150	12,436	13,545	11,917	13,300	11,667	13,714	13,000	13,333	13,167
California	18,456	19,573	21,130	21,404	23,438	23,457	23,178	23,786	23,028	22,968	22,755

[83] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.
[84] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

Colorado	17,182	18,687	21,618	22,577	23,430	24,158	24,292	24,951	25,733	25,993	26,181
Connecticut	15,606	16,438	17,778	19,200	19,000	19,889	20,556	20,158	20,842	21,526	22,105
Delaware	13,667	14,500	14,747	16,622	18,300	19,542	19,521	20,104	19,700	19,100	18,560
Florida	14,033	14,698	15,688	16,591	19,067	19,024	19,374	20,390	20,656	20,285	20,129
Georgia	12,973	15,550	16,284	17,259	18,354	19,138	19,600	20,877	21,651	21,786	21,905
Hawaii	13,604	13,654	14,358	12,889	14,421	14,200	13,409	13,591	15,909	14,542	16,913
Idaho	16,475	18,147	20,816	22,332	22,926	23,376	23,440	24,127	24,126	24,647	24,378
Illinois	14,707	15,887	17,450	18,827	18,510	19,061	19,063	19,681	20,149	20,340	20,742
Indiana	14,590	15,375	16,568	20,295	20,657	21,440	21,761	21,865	22,115	22,571	22,802
Iowa	15,118	16,124	18,298	20,641	21,191	22,015	22,149	22,449	22,929	23,634	23,725
Kansas	12,576	14,390	16,923	20,505	21,016	21,683	21,881	22,085	22,210	22,801	23,000
Kentucky	10,947	12,469	12,841	12,896	14,342	15,135	15,070	15,905	17,656	18,052	18,589
Louisiana	11,605	11,908	12,034	12,400	12,889	13,059	12,875	13,600	13,429	14,083	13,333
Maine	14,619	16,025	17,128	18,030	18,688	18,576	19,548	19,967	19,800	21,000	21,000
Maryland	13,461	14,725	16,083	16,099	18,654	19,196	19,440	19,740	20,061	19,938	19,854
Massachusetts	14,871	16,000	17,091	17,059	16,923	18,250	17,692	17,923	18,083	18,417	17,583
Michigan	15,394	17,071	19,017	21,635	23,164	23,976	24,116	24,638	25,150	25,957	26,302
Minnesota	14,127	15,894	17,777	18,091	18,996	19,512	19,694	19,841	20,570	20,967	21,537
Mississippi	12,081	12,909	15,028	15,280	14,571	14,214	13,286	14,462	15,000	14,400	15,222
Missouri	13,632	14,158	14,662	16,026	14,611	14,979	14,663	15,539	15,511	14,824	14,588
Montana	13,542	15,000	17,789	19,579	20,571	21,357	21,286	21,500	21,357	21,071	22,154
Nebraska	13,866	14,797	16,513	17,950	20,579	21,179	21,574	22,130	22,930	23,317	24,067
Nevada	16,400	18,128	19,000	21,680	22,966	22,931	22,034	23,793	23,069	22,000	22,156
New Hampshire	15,100	16,300	17,333	18,875	20,429	19,643	20,923	20,143	20,143	20,500	21,000
New Jersey	13,538	13,913	15,250	16,000	16,875	18,571	18,143	18,143	18,143	17,429	19,833
New Mexico	18,815	18,969	20,944	21,192	24,854	24,694	24,944	25,093	24,245	24,479	24,960
New York	14,658	16,501	17,378	18,639	21,046	21,623	22,070	22,325	22,806	23,834	23,936
North Carolina	15,220	16,314	16,746	18,741	20,089	20,435	20,326	20,891	20,957	20,978	21,156
North Dakota	12,624	13,094	14,292	14,182	18,158	19,278	18,944	20,250	20,750	21,500	21,563
Ohio	13,767	15,917	17,027	17,567	19,194	19,833	20,178	20,318	20,573	20,936	21,259
Oklahoma	12,327	13,611	14,440	16,480	17,415	17,896	17,311	18,150	18,641	18,703	18,667
Oregon	16,273	17,289	18,222	18,876	20,488	20,431	20,439	20,565	20,408	20,744	20,395
Pennsylvania	14,726	16,492	18,081	18,722	19,495	19,549	19,797	20,121	20,377	20,454	20,834
Rhode Island	14,250	14,773	15,667	17,000	17,909	16,636	19,000	19,000	17,667	17,625	16,250
South Carolina	12,771	14,481	16,087	16,000	17,438	17,250	16,500	16,438	17,400	16,667	16,467
South Dakota	12,257	13,398	15,516	17,741	20,582	21,391	21,521	21,753	22,255	22,139	22,376
Tennessee	11,825	13,740	14,789	15,743	16,200	16,100	15,938	16,196	16,489	16,571	17,325
Texas	14,350	15,244	16,503	19,646	22,232	22,009	21,991	22,268	22,248	22,680	23,589
Utah	15,838	16,739	17,573	18,875	22,161	22,863	22,432	22,989	23,125	22,772	23,316
Vermont	14,528	16,210	17,199	18,469	18,940	19,316	19,448	20,197	20,197	20,977	21,147
Virginia	14,213	15,116	15,833	16,990	17,906	17,990	18,337	19,129	19,462	19,144	19,954
Washington	18,532	20,091	22,644	23,270	23,727	23,794	23,820	24,088	23,848	24,094	23,818
West Virginia	11,250	12,667	15,588	14,923	15,700	15,400	15,200	15,556	15,667	14,889	15,875
Wisconsin	13,973	15,397	17,306	18,500	20,599	21,436	21,693	21,869	22,697	23,542	23,725
Wyoming	12,337	13,197	13,571	14,878	20,517	20,650	21,367	21,583	22,567	23,300	23,033

Source: USDA (2018).

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-150. For foraging beef cattle from 2007 onwards, the regional designations were revised based on data available from the NAHMS 2007 through 2008 survey on cow-calf system management practices (USDA:APHIS:VS 2010) and are shown in

Table A-151. 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-150: 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-151: Regions used for Characterizing the Diets of Foraging Cattle from 2007–2017

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

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

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 through 1993, 1994 through 1998, 1999 through 2003, 2004 through 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-150 (California, Northern Great Plains, Midwestern, Northeast, Southcentral, Southeast) and

Table A-151 (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-152. 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-153 and Table A-154 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.[85] 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-155.

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

[85] 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-155.

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 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-156 shows the regional DE and Y_m for U.S. cattle in each region for 2017.

Table A-152: 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						

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
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					
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		

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
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%**	**-**	**-**	**-**	**-**	**-**	**-**	**-**

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).
Sources: Preston (2010) and Archibeque (2011).

Table A-153: 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[a]	West	Northern 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).
[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.

Table A-154: DE Values and Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 2007–2017[86]

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%**

[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.
Sources of representative regional diets: Donovan (1999), Preston (2010), Archibeque (2011), and USDA:APHIS:VS (2010).

Table A-155: Foraging Animal DE (% of GE) and Y_m Values for Each Region and Animal Type for 2007–2017[87]

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-151.
[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.

[86] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.
[87] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

Table A-156: Regional DE (% of GE) and Y_m Rates for Dairy and Feedlot Cattle by Animal Type for 2017[88]

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
	Y_m[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
	Y_m	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
	Y_m	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
	Y_m	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
	Y_m	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-150 by the regions shown in the table above. To see the regional designation for foraging cattle per state, please see Table A-150.
[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).[89]
- Standard Reference Weight (kg).[90]
- 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-157.

[88] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.
[89] 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).
[90] Standard Reference Weight is the mature weight of a female animal of the animal type being estimated, used in the model to account for breed potential.

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

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)

1 **Table A-157: Calculated Annual GE by Animal Type and State, for 2017 (MJ)[91]**

State	Dairy Calves	Dairy Cows	Dairy Replace-ment Heifers 7-11 Months	Dairy Replace-ment Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replace-ment Heifers 7-11 Months	Beef Replace-ment Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
Alabama	31	851	55	195	4,166	3,179	55,838	1,432	4,017	1,204	978	285
Alaska	1	29	1	5	240	23	404	13	36	13	15	3
Arizona	857	31,012	1,603	5,698	1,779	911	15,827	489	1,365	6,869	1,025	13,100
Arkansas	26	673	41	146	4,999	4,192	73,645	2,064	5,791	2,649	1,739	577
California	7,670	262,323	10,412	37,010	6,226	3,243	56,341	1,673	4,670	15,553	4,391	22,265
Colorado	677	25,460	1,370	4,870	4,892	3,986	69,243	2,446	6,825	22,033	15,223	48,673
Conn.	83	2,810	130	463	42	23	404	24	67	48	27	10
Delaware	22	668	30	107	25	12	202	8	24	46	11	8
Florida	533	17,431	479	1,704	4,999	4,165	73,162	1,491	4,184	722	815	199
Georgia	363	12,451	411	1,461	2,749	2,280	40,045	1,312	3,682	891	1,359	288
Hawaii	10	305	14	49	356	364	6,331	167	467	259	117	46
Idaho	2,622	94,209	4,247	15,096	3,558	2,476	43,008	1,545	4,311	8,036	5,562	13,980
Illinois	406	13,244	712	2,532	2,036	1,729	30,484	872	2,451	5,636	2,861	13,463
Indiana	809	27,876	1,096	3,896	1,385	938	16,542	581	1,634	2,536	1,324	5,696
Iowa	940	33,194	1,849	6,574	5,701	4,312	76,014	2,151	6,045	30,762	14,303	60,064
Kansas	656	22,722	1,370	4,870	7,738	7,016	123,670	3,604	10,129	48,139	37,878	119,093
Kentucky	249	7,791	548	1,948	5,832	4,692	82,428	1,790	5,021	5,178	3,125	932
Louisiana	52	1,355	55	195	2,583	2,055	36,097	1,014	2,845	602	543	149
Maine	131	4,303	205	730	125	51	889	48	134	97	82	23
Maryland	205	6,525	397	1,412	334	198	3,474	132	369	338	164	466
Mass.	50	1,492	96	341	84	30	525	24	67	48	27	10
Michigan	1,857	70,016	2,329	8,278	1,303	536	9,452	291	817	3,969	1,060	7,508
Minn.	2,010	66,977	4,041	14,366	2,851	1,653	29,145	1,105	3,104	11,741	4,370	19,417
Miss.	39	1,108	82	292	3,166	2,183	38,353	1,110	3,113	1,011	842	242
Missouri	371	10,003	616	2,191	9,774	9,183	161,874	4,302	12,090	10,802	6,225	5,696
Montana	61	2,073	123	438	8,894	7,358	127,821	5,470	15,266	5,962	7,494	2,330
Nebraska	262	9,346	342	1,217	8,959	8,580	151,240	4,360	12,253	53,774	36,553	127,896
Nevada	131	4,443	151	536	1,245	1,089	18,924	528	1,473	1,166	849	155
N. Hamp.	59	1,936	82	292	42	23	404	12	34	36	27	8
N. Jersey	28	902	51	180	84	35	606	19	54	51	33	11

[91] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

State	Dairy Calves	Dairy Cows	Dairy Replace-ment Heifers 7-11 Months	Dairy Replace-ment Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replace-ment Heifers 7-11 Months	Beef Replace-ment Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
N. Mexico	1,420	51,790	1,507	5,357	3,113	2,302	39,998	1,287	3,592	3,111	2,635	696
New York	2,710	96,247	4,863	17,287	1,671	506	8,888	539	1,511	1,087	1,363	1,036
N. Car.	197	6,615	301	1,071	2,583	1,697	29,813	823	2,310	1,036	679	225
N. Dakota	70	2,331	123	438	5,294	4,263	75,147	2,395	6,731	5,988	5,695	2,589
Ohio	1,145	37,854	1,644	5,844	2,443	1,287	22,686	872	2,451	5,166	1,589	7,767
Oklahoma	153	4,701	274	974	13,330	9,610	168,803	5,190	14,562	21,674	12,635	16,052
Oregon	542	17,486	890	3,165	3,558	2,703	46,965	1,351	3,772	4,018	3,367	4,401
Penn.	2,294	74,958	4,315	15,339	2,089	851	14,948	778	2,182	3,865	1,635	4,919
R. Island	3	99	7	24	8	6	113	5	13	12	5	2
S. Car.	66	1,922	96	341	1,250	780	13,698	394	1,105	193	272	60
S. Dakota	507	17,281	616	2,191	8,145	7,436	131,075	4,593	12,906	17,377	14,039	19,676
Tenn.	179	5,396	479	1,704	5,415	4,169	73,242	1,730	4,854	3,251	2,445	746
Texas	2,142	75,504	3,562	12,661	28,327	20,457	359,362	9,665	27,115	62,372	36,682	125,824
Utah	402	14,053	753	2,678	2,401	1,674	29,074	1,094	3,053	2,074	1,756	1,036
Vermont	564	18,581	767	2,727	251	64	1,131	66	185	97	177	35
Virginia	380	12,369	521	1,850	3,333	2,949	51,809	1,336	3,749	3,973	1,902	1,036
Wash.	1,202	42,560	1,644	5,844	1,601	1,114	19,354	747	2,083	4,925	3,425	9,838
W. Virg.	35	983	55	195	1,253	953	16,725	455	1,276	942	463	207
Wisconsin	5,594	197,617	9,727	34,575	2,443	1,296	22,844	930	2,614	9,393	1,324	13,980
Wyoming	26	910	41	146	3,558	3,535	61,416	2,381	6,645	4,147	4,011	3,883

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-158. State-level emission factors are shown by animal type for 2017 in Table A-159.

Table A-158: Calculated Annual National Emission Factors for Cattle by Animal Type, for 2017 (kg CH_4/head/year)[92]

Cattle Type	1990	1995	2000	2005	2010	2011	2012	2013	2014	2015	2016	2017
Dairy												
Calves	12	12	12	12	12	12	12	12	12	12	12	12
Cows	124	125	132	133	142	142	144	144	145	146	147	147
Replacements 7–11 months	48	46	46	45	46	46	46	46	46	46	46	46
Replacements 12–23 months	73	69	70	67	69	69	69	69	69	69	69	69
Beef												
Calves	11	11	11	11	11	11	11	11	11	11	11	11
Bulls	91	94	94	97	98	98	98	98	98	98	98	98
Cows	89	92	91	94	95	95	95	95	95	95	95	95
Replacements 7–11 months	54	57	56	59	60	60	60	60	60	60	60	60
Replacements 12–23 months	63	66	66	68	70	70	70	70	70	70	70	70
Steer Stockers	55	57	58	58	58	58	58	58	58	58	58	58
Heifer Stockers	52	56	60	60	60	60	60	60	60	60	60	60
Feedlot Cattle	38	36	38	38	42	41	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).

[92] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

Table A-159: Emission Factors for Cattle by Animal Type and State, for 2017 (kg CH4/head/year)[93]

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	138	53	80	97	10	94	60	69	58	60	35
Alaska	12	95	46	69	104	11	100	65	74	62	65	35
Arizona	12	154	46	69	104	11	100	65	74	62	65	34
Arkansas	12	118	49	74	97	10	94	60	69	58	60	34
California	12	146	46	69	104	11	100	65	74	62	65	34
Colorado	12	151	43	65	104	11	100	65	74	62	65	35
Conn.	12	153	48	73	98	11	94	60	69	58	60	35
Delaware	12	138	48	73	98	11	94	60	69	58	60	35
Florida	12	162	53	80	97	10	94	60	69	58	60	36
Georgia	12	170	53	80	97	10	94	60	69	58	60	37
Hawaii	12	124	46	69	104	11	100	65	74	62	65	35
Idaho	12	153	46	69	104	11	100	65	74	62	65	35
Illinois	12	131	43	65	95	10	92	58	68	56	59	35
Indiana	12	139	43	65	95	10	92	58	68	56	59	34
Iowa	12	142	43	65	95	10	92	58	68	56	59	34
Kansas	12	140	43	65	95	10	92	58	68	56	59	35
Kentucky	12	155	53	80	97	10	94	60	69	58	60	35
Louisiana	12	118	49	74	97	10	94	60	69	58	60	35
Maine	12	148	48	73	98	11	94	60	69	58	60	36
Maryland	12	143	48	73	98	11	94	60	69	58	60	35
Mass.	12	134	48	73	98	11	94	60	69	58	60	35
Michigan	12	152	43	65	95	10	92	58	68	56	59	33
Minn.	12	134	43	65	95	10	92	58	68	56	59	34
Miss.	12	140	53	80	97	10	94	60	69	58	60	35
Missouri	12	109	43	65	95	10	92	58	68	56	59	35
Montana	12	137	43	65	104	11	100	65	74	62	65	34
Nebraska	12	144	43	65	95	10	92	58	68	56	59	34
Nevada	12	144	46	69	104	11	100	65	74	62	65	37
N. Hamp.	12	148	48	73	98	11	94	60	69	58	60	35
N. Jersey	12	143	48	73	98	11	94	60	69	58	60	36
N. Mexico	12	155	46	69	104	11	100	65	74	62	65	36
New York	12	160	48	73	98	11	94	60	69	58	60	36

[93] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

N. Car.	12	167	53	80	97	10	94	60	69	58	60	36
N. Dakota	12	134	43	65	95	10	92	58	68	56	59	34
Ohio	12	133	43	65	95	10	92	58	68	56	59	34
Oklahoma	12	141	49	74	97	10	94	60	69	58	60	35
Oregon	12	137	46	69	104	11	100	65	74	62	65	35
Penn.	12	147	48	73	98	11	94	60	69	58	60	35
R. Island	12	128	48	73	98	11	94	60	69	58	60	35
S. Car.	12	145	53	80	97	10	94	60	69	58	60	33
S. Dakota	12	137	43	65	95	10	92	58	68	56	59	34
Tenn.	12	149	53	80	97	10	94	60	69	58	60	35
Texas	12	161	49	74	97	10	94	60	69	58	60	35
Utah	12	149	46	69	104	11	100	65	74	62	65	32
Vermont	12	149	48	73	98	11	94	60	69	58	60	36
Virginia	12	161	53	80	97	10	94	60	69	58	60	34
Wash.	12	151	46	69	104	11	100	65	74	62	65	34
W. Virg.	12	127	48	73	98	11	94	60	69	58	60	35
Wisconsin	12	142	43	65	95	10	92	58	68	56	59	34
Wyoming	12	140	43	65	104	11	100	65	74	62	65	35

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-160, indicate that U.S. emission factors are comparable to those of other Annex I countries. Results in Table A-160 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-160: Annex I Countries' Implied Emission Factors for Cattle by Year (kg CH_4/head/year)[94, 95]

	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
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
2016	118	NA	75	NA
2017	119	NA	74	NA
Tier I EFs For North America, from IPCC (2006)		**121**		**53**

NA (Not Applicable)

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:

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

[94] Excluding calves.

[95] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

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-161. The emissions for each subcategory were then aggregated to estimate total emissions from beef cattle and dairy cattle for the entire year.

Table A-161: CH_4 Emissions from Cattle (kt)

Cattle Type	1990	1995	2000	2005	2013	2014	2015	2016	2017	2018	2019
Dairy	**1,574**	**1,498**	**1,519**	**1,503**	**1,664**	**1,679**	**1,706**	**1,722**	**1,730**	**1,744**	**1,729**
Calves (4–6 months)	62	59	59	54	58	58	58	58	58	58	59
Cows	1,242	1,183	1,209	1,197	1,325	1,337	1,355	1,367	1,377	1,390	1,379
Replacements 7–11 months	58	56	55	56	61	63	65	65	65	65	64
Replacements 12–23 months	212	201	196	196	220	221	228	232	230	231	227
Beef	**4,763**	**5,419**	**5,070**	**5,007**	**4,722**	**4,660**	**4,722**	**4,919**	**5,052**	**5,125**	**5,162**
Calves (4–6 months)	182	193	186	179	157	156	158	164	168	169	171
Bulls	196	225	215	214	203	200	207	210	220	221	221
Cows	2,884	3,222	3,058	3,056	2,806	2,754	2,774	2,856	2,954	2,978	3,000
Replacements 7–11 months	69	85	74	80	78	83	89	91	90	86	83
Replacements 12–23 months	188	241	204	217	213	218	239	250	251	241	232
Steer Stockers	563	662	509	473	431	426	433	472	461	465	472
Heifer Stockers	306	375	323	299	267	256	263	289	286	297	306
Feedlot Cattle	375	416	502	488	568	567	558	587	621	667	678
Total	**6,338**	**6,917**	**6,589**	**6,510**	**6,386**	**6,339**	**6,427**	**6,641**	**6,783**	**6,869**	**6,891**

Note: 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 2019) or the Census of Agriculture (USDA 1992, 1997, 2002, 2007, 2012). 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-163). 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 swine, horses, mules and asses were estimated by multiplying national population estimates by the default IPCC emission factor (IPCC 2006). For sheep and goats, default national emission factors were updated to reflect revisions made in the 2019 IPCC Refinement to the *2006 IPCC Guidelines.* 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-162 shows the emission factors used for these other livestock. National enteric fermentation emissions from all livestock types are shown in Table A-163 and Table A-164. Enteric fermentation emissions from most livestock types, broken down by state, for 2017 are shown in Table A-165 and Table A-166. Because a simplified calculation

approach was used for 2019 emissions, state-level emission estimates were not calculated for 2019. Livestock populations are shown in Table A-162.

Table A-162: Emission Factors for Other Livestock (kg CH_4/head/year)

Livestock Type	Emission Factor
Swine	1.5
Horses	18
Sheep	9
Goats	9
American Bison	82.2
Mules and Asses	10.0

Source: IPCC (2006), IPCC (2019), except American Bison, as described in text.

Table A-163: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	1995	2000	2005	2013	2014	2015	2016	2017	2018	2019
Beef Cattle	119.1	135.5	126.7	125.2	118.0	116.5	118.0	123.0	126.3	128.1	129.1
Dairy Cattle	39.4	37.5	38.0	37.6	41.6	42.0	42.6	43.0	43.3	43.6	43.2
Swine	2.0	2.2	2.2	2.3	2.5	2.4	2.6	2.6	2.7	2.8	2.9
Horses	1.0	1.2	1.5	1.7	1.6	1.5	1.4	1.4	1.3	1.2	1.1
Sheep	2.6	2.0	1.6	1.4	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Goats	0.6	0.5	0.5	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6
American Bison	0.1	0.2	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Mules and Asses	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**164.7**	**179.1**	**171.0**	**169.3**	**165.9**	**164.6**	**166.9**	**172.2**	**175.8**	**178.0**	**178.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table A-164: CH_4 Emissions from Enteric Fermentation (kt)

Livestock Type	1990	1995	2000	2005	2013	2014	2015	2016	2017	2018	2019
Beef Cattle	4,763	5,419	5,070	5,007	4,722	4,660	4,722	4,919	5,052	5,125	5,162
Dairy Cattle	1,574	1,498	1,519	1,503	1,664	1,679	1,706	1,722	1,730	1,744	1,729
Swine	81	88	88	92	98	96	102	105	108	111	115
Horses	40	47	61	70	62	60	57	54	51	48	46
Sheep	102	81	63	55	48	47	47	48	47	47	47
Goats	23	21	22	26	24	24	24	24	24	24	24
American Bison	4	9	16	17	14	14	14	15	15	15	16
Mules and Asses	1	1	1	2	3	3	3	3	3	3	3
Total	**6,588**	**7,165**	**6,840**	**6,772**	**6,635**	**6,583**	**6,675**	**6,890**	**7,032**	**7,119**	**7,142**

Note: Totals may not sum due to independent rounding.

Table A-165: CH_4 Emissions from Enteric Fermentation from Cattle (metric tons), by State, for 2017[96]

State	Dairy Calves	Dairy Cows	Dairy Replace-ment Heifers 7-11 Months	Dairy Replace-ment Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replace-ment Heifers 7-11 Months	Beef Replace-ment Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot	Total
Alabama	44	966	63	224	4,866	3,713	65,220	1,672	4,692	1,406	1,143	257	84,265
Alaska	2	29	1	5	280	27	472	15	42	15	17	3	909
Arizona	1,223	30,231	1,591	5,656	2,078	1,064	18,486	571	1,594	8,023	1,197	12,054	83,770
Arkansas	37	705	44	156	5,839	4,897	86,018	2,411	6,764	3,094	2,031	531	112,527
California	10,947	255,718	10,337	36,743	7,272	3,788	65,807	1,954	5,454	18,166	5,129	20,614	441,929
Colorado	967	23,480	1,288	4,578	5,714	4,655	80,877	2,856	7,972	25,735	17,780	44,357	220,260
Conn.	119	2,901	137	486	49	27	472	28	78	56	32	9	4,393
Delaware	31	690	32	113	29	13	236	10	27	54	13	7	1,254
Florida	761	19,772	552	1,964	5,839	4,865	85,454	1,742	4,887	844	952	174	127,806
Georgia	518	14,123	474	1,683	3,211	2,663	46,774	1,533	4,301	1,041	1,587	247	78,154
Hawaii	15	297	14	48	416	426	7,394	195	545	303	137	42	9,832
Idaho	3,742	91,837	4,216	14,987	4,155	2,892	50,234	1,804	5,035	9,386	6,497	12,632	207,418
Illinois	580	12,214	670	2,381	2,378	2,020	35,606	1,019	2,862	6,583	3,341	12,157	81,810
Indiana	1,154	25,708	1,030	3,663	1,617	1,096	19,321	679	1,908	2,962	1,547	5,272	65,958
Iowa	1,341	30,612	1,739	6,181	6,659	5,037	88,785	2,512	7,060	35,930	16,707	55,763	258,326
Kansas	936	20,954	1,288	4,578	9,038	8,195	144,448	4,210	11,831	56,227	44,241	108,565	414,511
Kentucky	356	8,838	631	2,244	6,812	5,481	96,277	2,090	5,865	6,047	3,650	845	139,136
Louisiana	75	1,419	58	207	3,017	2,400	42,162	1,185	3,323	703	635	133	55,317
Maine	187	4,443	216	767	146	59	1,038	56	157	113	96	21	7,298
Maryland	293	6,737	417	1,483	390	231	4,058	154	431	395	191	427	15,208
Mass.	72	1,540	101	358	98	35	613	28	78	56	32	9	3,020
Michigan	2,651	64,570	2,190	7,783	1,522	626	11,041	340	954	4,635	1,238	7,126	104,675
Minn.	2,869	61,767	3,800	13,506	3,330	1,931	34,042	1,290	3,626	13,714	5,105	18,097	163,076
Miss.	56	1,257	95	337	3,698	2,550	44,797	1,296	3,636	1,181	984	221	60,109
Missouri	530	9,225	580	2,060	11,416	10,726	189,071	5,025	14,121	12,617	7,270	5,129	267,770
Montana	87	1,912	116	412	10,389	8,594	149,296	6,389	17,831	6,964	8,753	2,185	212,929
Nebraska	374	8,619	322	1,145	10,465	10,021	176,650	5,093	14,312	62,809	42,695	117,788	450,292
Nevada	187	4,331	150	532	1,454	1,272	22,103	616	1,720	1,362	992	133	34,853
N. Hamp.	84	1,999	86	307	49	27	472	14	39	42	32	7	3,158

[96] This table has not been updated for the current (1990 through 2019) draft Inventory.

N. Jersey	41	931	53	189	98	40	708	22	63	59	38	10	2,252
N. Mexico	2,027	50,486	1,496	5,318	3,636	2,689	46,718	1,503	4,196	3,633	3,077	619	125,399
New York	3,867	99,361	5,108	18,157	1,952	591	10,381	629	1,765	1,270	1,592	912	145,586
N. Car.	281	7,503	347	1,234	3,017	1,982	34,821	962	2,698	1,209	793	197	55,046
N. Dakota	100	2,150	116	412	6,184	4,979	87,773	2,797	7,862	6,994	6,652	2,423	128,442
Ohio	1,634	34,910	1,546	5,494	2,854	1,503	26,498	1,019	2,862	6,034	1,856	7,220	93,430
Oklahoma	218	4,923	292	1,037	15,570	11,224	197,165	6,062	17,008	25,315	14,758	14,436	308,008
Oregon	773	17,045	884	3,142	4,155	3,158	54,856	1,579	4,405	4,693	3,932	3,941	102,564
Penn.	3,275	77,384	4,533	16,111	2,440	994	17,459	909	2,549	4,514	1,910	4,416	136,494
R. Island	5	103	7	26	10	8	132	6	16	14	6	2	334
S. Car.	94	2,181	110	393	1,460	911	15,999	460	1,290	225	317	58	23,498
S. Dakota	724	15,937	580	2,060	9,513	8,685	153,097	5,364	15,075	20,296	16,397	18,574	266,302
Tenn.	256	6,121	552	1,964	6,325	4,870	85,548	2,021	5,669	3,797	2,856	679	120,659
Texas	3,056	79,064	3,794	13,486	33,086	23,895	419,740	11,288	31,671	72,851	42,845	115,505	850,281
Utah	574	13,699	748	2,659	2,805	1,955	33,958	1,278	3,566	2,422	2,052	1,017	66,733
Vermont	805	19,182	806	2,864	293	75	1,321	77	216	113	207	31	25,989
Virginia	543	14,030	600	2,132	3,892	3,445	60,514	1,561	4,379	4,641	2,222	969	98,928
Wash.	1,715	41,488	1,632	5,801	1,870	1,301	22,605	872	2,433	5,753	4,001	9,072	98,544
W. Virg.	50	1,015	58	205	1,464	1,113	19,535	531	1,490	1,100	541	190	27,292
Wisconsin	7,984	182,246	9,145	32,507	2,854	1,514	26,682	1,086	3,053	10,971	1,547	12,871	292,460
Wyoming	37	839	39	137	4,155	4,129	71,735	2,781	7,762	4,844	4,684	3,514	104,657

Table A-166: CH_4 Emissions from Enteric Fermentation from Other Livestock (metric tons), by State, for 2017[97]

State	Swine	Horses	Sheep	Goats	American Bison	Mules and Asses	Total
Alabama	86	725	99	125	21	120	1,175
Alaska	2	16	99	4	131	1	252
Arizona	240	2,089	1,040	506	6	41	3,921
Arkansas	197	778	99	163	27	87	1,350
California	143	1,879	4,800	746	120	62	7,751
Colorado	1,099	1,830	3,360	103	882	68	7,342
Connecticut	4	420	57	21	10	12	524
Delaware	9	150	99	2	8	1	269
Florida	23	2,186	99	232	32	110	2,681
Georgia	120	1,134	99	297	23	88	1,761
Hawaii	8	66	99	84	8	5	269
Idaho	38	879	2,000	92	292	40	3,341
Illinois	7,969	827	440	147	57	32	9,471
Indiana	6,056	2,045	416	151	108	58	8,835
Iowa	33,375	944	1,400	283	151	44	36,196
Kansas	3,011	1,077	544	176	546	34	5,387
Kentucky	615	1,947	384	150	116	135	3,347
Louisiana	9	1,063	99	80	7	84	1,341
Maine	7	213	57	35	22	4	337
Maryland	39	478	99	23	36	12	688
Massachusetts	11	362	57	45	8	3	486
Michigan	1,725	1,347	680	131	156	40	4,080
Minnesota	12,675	767	1,040	153	254	26	14,916
Mississippi	855	937	99	92	4	96	2,083
Missouri	4,969	1,538	720	554	168	86	8,035
Montana	269	1,631	1,840	42	1,206	49	5,036
Nebraska	5,156	1,135	664	85	1,903	43	8,986
Nevada	1	478	504	154	7	7	1,150
New Hampshire	5	149	57	29	25	1	266
New Jersey	19	453	99	29	16	8	624
New Mexico	2	861	776	131	424	18	2,213
New York	72	1,716	640	165	82	41	2,715
North Carolina	13,650	997	240	172	26	96	15,180
North Dakota	221	824	528	26	786	14	2,399
Ohio	4,181	1,963	936	168	70	72	7,391
Oklahoma	3,218	2,741	384	264	796	137	7,540
Oregon	14	926	1,360	142	115	27	2,583
Pennsylvania	1,800	2,222	744	206	108	94	5,173
Rhode Island	3	24	57	5	-	1	91
South Carolina	278	1,107	99	169	11	63	1,726
South Dakota	2,265	1,217	2,000	112	2,765	14	8,373
Tennessee	353	919	368	262	28	126	2,057
Texas	1,459	6,350	5,680	3,089	360	642	17,581
Utah	979	1,047	2,200	61	93	37	4,417
Vermont	6	181	57	73	9	14	340
Virginia	360	1,500	640	193	85	71	2,849
Washington	38	711	384	106	79	34	1,352
West Virginia	8	274	272	49	4	30	635
Wisconsin	458	1,565	608	331	349	58	3,368
Wyoming	135	1,160	2,880	50	787	29	5,041

"-" Indicates there are no emissions, as there is no significant population of this animal type

[97] This table has not been updated for the current (1990 through 2019) draft Inventory.

References

Archibeque, S. (2011) Personal Communication. Shawn Archibeque, Colorado State University, Fort Collins, Colorado and staff at ICF International.

Crutzen, P.J., I. Aselmann, and W. Seiler (1986) Methane Production by Domestic Animals, Wild Ruminants, Other Herbivores, Fauna, and Humans. *Tellus*, 38B:271-284.

Donovan, K. (1999) Personal Communication. Kacey Donovan, University of California at Davis and staff at ICF International.

Doren, P.E., J. F. Baker, C. R. Long and T. C. Cartwright (1989) Estimating Parameters of Growth Curves of Bulls, *J Animal Science* 67:1432-1445.

Enns, M. (2008) Personal Communication. Dr. Mark Enns, Colorado State University and staff at ICF International.

ERG (2016) Development of Methane Conversion Rate Scaling Factor and Diet-Related Inputs to the Cattle Enteric Fermentation Model for Dairy Cows, Dairy Heifers, and Feedlot Animals. ERG, Lexington, MA. December 2016.

Galyean and Gleghorn (2001) Summary of the 2000 Texas Tech University Consulting Nutritionist Survey. Texas Tech University. Available online at <http://www.depts.ttu.edu/afs/burnett_center/progress_reports/bc12.pdf>. June 2009.

Holstein Association (2010) *History of the Holstein Breed* (website). Available online at <http://www.holsteinusa.com/holstein_breed/breedhistory.html>. Accessed September 2010.

ICF (2006) *Cattle Enteric Fermentation Model: Model Documentation*. Prepared by ICF International for the Environmental Protection Agency. June 2006.

ICF (2003) *Uncertainty Analysis of 2001 Inventory Estimates of Methane Emissions from Livestock Enteric Fermentation in the U.S*. Memorandum from ICF International to the Environmental Protection Agency. May 2003.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom 996 pp.

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.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The Intergovernmental Panel on Climate Change. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Hayama, Kanagawa, Japan.

Johnson, D. (2002) Personal Communication. Don Johnson, Colorado State University, Fort Collins, and ICF International.

Johnson, D. (1999) Personal Communication. Don Johnson, Colorado State University, Fort Collins, and David Conneely, ICF International.

Johnson, K. (2010) Personal Communication. Kris Johnson, Washington State University, Pullman, and ICF International.

Kebreab E., K. A. Johnson, S. L. Archibeque, D. Pape, and T. Wirth (2008) Model for estimating enteric methane emissions from United States dairy and feedlot cattle. *J. Anim. Sci.* 86: 2738-2748.

Lippke, H., T. D. Forbes, and W. C. Ellis. (2000) Effect of supplements on growth and forage intake by stocker steers grazing wheat pasture. *J. Anim. Sci.* 78:1625-1635.

National Bison Association (2011) Handling & Carcass Info (on website). Available online at: <http://www.bisoncentral.com/about-bison/handling-and-carcass-info>. Accessed August 16, 2011.

National Bison Association (1999) Total Bison Population—1999. Report provided during personal email communication with Dave Carter, Executive Director, National Bison Association July 19, 2011.

NRC (1999) *1996 Beef NRC: Appendix Table 22*. National Research Council.

NRC (1984) *Nutrient requirements for beef cattle (6th Ed.)*. National Academy Press, Washington, D.C.

Pinchak, W.E., D. R. Tolleson, M. McCloy, L. J. Hunt, R. J. Gill, R. J. Ansley, and S. J. Bevers (2004) Morbidity effects on productivity and profitability of stocker cattle grazing in the southern plains. J. Anim. Sci. 82:2773-2779.

Platter, W. J., J. D. Tatum, K. E. Belk, J. A. Scanga, and G. C. Smith (2003) Effects of repetitive use of hormonal implants on beef carcass quality, tenderness, and consumer ratings of beef palatability. J. Anim. Sci. 81:984-996.

Preston, R.L. (2010) What's The Feed Composition Value of That Cattle Feed? Beef Magazine, March 1, 2010. Available at: <http://beefmagazine.com/nutrition/feed-composition-tables/feed-composition-value-cattle--0301>.

Skogerboe, T. L., L. Thompson, J. M. Cunningham, A. C. Brake, V. K. Karle (2000) The effectiveness of a single dose of doramectin pour-on in the control of gastrointestinal nematodes in yearling stocker cattle. Vet. Parasitology 87:173-181.

Soliva, C.R. (2006) Report to the attention of IPCC about the data set and calculation method used to estimate methane formation from enteric fermentation of agricultural livestock population and manure management in Swiss agriculture. On behalf of the Federal Office for the Environment (FOEN), Berne, Switzerland.

USDA (2019) *Quick Stats: Agricultural Statistics Database*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at <http://quickstats.nass.usda.gov/>.

USDA (2012) *Census of Agriculture: 2012 Census Report*. United States Department of Agriculture. Available online at: <http://www.agcensus.usda.gov/Publications/2012>.

USDA (2007) *Census of Agriculture: 2007 Census Report*. United States Department of Agriculture. Available online at: <http://www.agcensus.usda.gov/Publications/2007/index.asp>.

USDA (2002) *Census of Agriculture: 2002 Census Report*. United States Department of Agriculture. Available online at: <http://www.agcensus.usda.gov/Publications/2002/index.asp>.

USDA (1997) *Census of Agriculture: 1997 Census Report*. United States Department of Agriculture. Available online at: <http://www.agcensus.usda.gov/Publications/1997/index.asp>. Accessed July 18, 2011.

USDA (1996) *Beef Cow/Calf Health and Productivity Audit (CHAPA): Forage Analyses from Cow/Calf Herds in 18 States*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at <http://www.aphis.usda.gov/vs/ceah/cahm>. March 1996.

USDA (1992) Census *of Agriculture: 1992 Census Report*. United States Department of Agriculture. Available online at: <http://www.agcensus.usda.gov/Publications/1992/index.asp>. Accessed July 18, 2011.

USDA:APHIS:VS (2010) Beef 2007–08, Part *V: Reference of Beef Cow-calf Management Practices in the United States, 2007–08*. USDA–APHIS–VS, CEAH. Fort Collins, CO.

USDA:APHIS:VS (2002) *Reference of 2002 Dairy Management Practices*. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at <http://www.aphis.usda.gov/vs/ceah/cahm>.

USDA:APHIS:VS (1998) *Beef '97, Parts I-IV*. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at <http://www.aphis.usda.gov/animal_health/nahms/beefcowcalf/index.shtml#beef97>.

USDA:APHIS:VS (1996) *Reference of 1996 Dairy Management Practices*. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at <http://www.aphis.usda.gov/vs/ceah/cahm>.

USDA:APHIS:VS (1994) *Beef Cow/Calf Health and Productivity Audit*. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at <http://www.aphis.usda.gov/vs/ceah/cahm>.

USDA:APHIS:VS (1993) *Beef Cow/Calf Health and Productivity Audit*. USDA–APHIS–VS, CEAH. Fort Collins, CO. August 1993. Available online at <http://www.aphis.usda.gov/vs/ceah/cahm>.

Vasconcelos and Galyean (2007) Nutritional recommendations of feedlot consulting nutritionists: The 2007 Texas Tech University Study. J. Anim. Sci. 85:2772-2781.

3.11. Methodology for Estimating CH_4 and N_2O Emissions from Manure Management[98]

The following steps were used to estimate methane (CH_4) and nitrous oxide (N_2O) emissions from the management of livestock manure for the years 1990 through 2018. As explained in the Manure Management section (Section 5.2 Manure Management (IPCC Source Category 3B)), a simplified approach was used to estimate emissions for 2019.

Step 1: Livestock Population Characterization Data

Annual animal population data for 1990 through 2018 for all livestock types, except American bison, goats, horses, mules and asses were obtained from the USDA NASS. The population data used in the emissions calculations for cattle, swine, and sheep were downloaded from the USDA NASS Quick Stats Database (USDA 2019a). 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, 2014a, 2014b, 2015a 2015b, 2016a, 2016b, 2017a, 2017b, 2018a, 2018b, 2019b, and 2019c). Goat population data for 1992, 1997, 2002, 2007, 2012, and 2017 were obtained from the Census of Agriculture (USDA 2019d), as were horse, mule and ass population data for 1987, 1992, 1997, 2002, 2007, 2012, and 2017 and American bison population for 2002, 2007, 2012, and 2017. 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 lambs and sheep on feed are not available after 1993 (USDA 1994). The number of lambs and sheep on feed for 1994 through 2018 were calculated using the average of the percent of lambs and sheep on feed from 1990 through 1993. In addition, all of the sheep and lambs "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 lambs in feedlots for all years, it was assumed that the percentage of sheep and lambs 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, 2012, and 2017 (USDA 2019d). The data for 1992 were used for 1990 through 1992. Data for 1993 through 1996, 1998 through 2001, 2003

[98] 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.

through 2006, 2008 through 2011, and 2013 through 2016 were interpolated based on the 1992, 1997, 2002, 2007, 2012, and 2017 Census data. Data for 2018 were extrapolated based on 2017 Census data.

Horses: Annual horse population data by state were available for 1987, 1992, 1997, 2002, 2007, 2012, and 2017 (USDA 2019d). Data for 1990 through 1991, 1993 through 1996, 1998 through 2001, 2003 through 2006, 2008 through 2011, and 2013 through 2016 were interpolated based on the 1987, 1992, 1997, 2002, 2007, 2012, and 2017 Census data. Data for 2018 were extrapolated based on 2017 Census data.

Mules and Asses: Annual mule and ass (burro and donkey) population data by state were available for 1987, 1992, 1997, 2002, 2007, 2012, and 2017 (USDA 2019d). Data for 1990 through 1991, 1993 through 1996, 1998 through 2001, 2003 through 2006, 2008 through 2011, and 2013 through 2016 were interpolated based on the 1987, 1992, 1997, 2002, 2007, 2012, and 2017 Census data. Data for 2018 were extrapolated based on 2017 Census data.

American Bison: Annual American bison population data by state were available for 2002, 2007, 2012, and 2017 (USDA 2019d). 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 2016 were interpolated based on the Bison Association and 2002, 2007, 2012, and 2017 Census data. Data for 2018 were extrapolated based on 2017 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, 2014a, 2014b, 2015a, 2015b, 2016a, 2016b, 2017a, 2017b, 2018a, 2018b, 2019b, and 2019c). 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 broilers 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-167.

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_0) for U.S. animal waste;
- Nitrogen excretion rate (Nex); and
- Typical animal mass (TAM).

Table A-168 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-169 (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:

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

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, based on the 10th Corrigenda for the *2006 IPCC Guidelines* (IPCC 2018).

$$Nex_{(T)} = N_{intake} \times \left(1 - N_{retention_fract(T)}\right)$$

where,

$Nex_{(T)}$	=	Annual N excretion rates (kg N animal^{-1} yr^{-1})
$N_{intake(T)}$	=	The annual N intake per head of animal of species/category *T* (kg N animal^{-1} yr^{-1})
$N_{retention(T)}$	=	Fraction of annual N intake that is retained by animal

N intake is estimated as:

$$N_{intake(T)} = \frac{GE}{18.45} \bullet \left(\frac{\frac{CP\%}{100}}{6.25} \right)$$

where,

$N_{intake(T)}$	=	Daily N consumed per animal of category T (kg N animal^{-1} day^{-1})
GE	=	Gross energy intake of the animal based on digestible energy, milk production, pregnancy, current weight, mature weight, rate of weight gain, and IPCC constants (MJ animal^{-1} day^{-1})
18.45	=	Conversion factor for dietary GE per kg of dry matter (MJ kg^{-1})
CP%	=	Percent crude protein in diet, input
6.25	=	Conversion from kg of dietary protein to kg of dietary N (kg feed protein per kg N)

The portion of consumed N that is retained as product equals the nitrogen in milk plus the nitrogen required for weight gain. The N content of milk produced is calculated using milk production and percent protein, along with conversion factors. The nitrogen retained in body weight gain by stockers, replacements, or feedlot animals is calculated using the net energy for growth (NE_g), weight gain (WG), and other conversion factors and constants. The equation matches the 10th Corrigenda to the *2006 IPCC Guidelines* (IPCC 2018), and is as follows:

$$N_{retention(T)} = \left[\frac{Milk \times \left(\frac{Milk\ PR\%}{100} \right)}{6.38} \right] + \left[\frac{WG \times \left[268 - \left(\frac{7.03 \times NE_g}{WG} \right) \right]}{1000 \times 6.25} \right]$$

where,

$N_{retention(T)}$	=	Daily N retained per animal of category T (kg N animal^{-1} day^{-1})
Milk	=	Milk production (kg animal^{-1} day^{-1})
268	=	Constant from *2006 IPCC Guidelines*
7.03	=	Constant from *2006 IPCC Guidelines*
NE_g	=	Net energy for growth, calculated in livestock characterization, based on current weight, mature weight, rate of weight gain, and IPCC constants, (MJ day^{-1})
1,000	=	Conversion from grams to kilograms (g kg^{-1})
6.25	=	Conversion from kg dietary protein to kg dietary N (kg protein per kg N)
Milk PR%	=	Percent of protein in milk (%)
6.38	=	Conversion from milk protein to milk N (kg protein per kg N)
WG	=	Weight gain, as input into the CEFM transition matrix (kg day^{-1})

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-170 presents the state-specific VS and Nex production rates used for cattle in 2018. As shown in Table A-170, the differences in the VS daily excretion and Nex rate trends between dairy cattle animal types is due to milk production. Milk production by cow varies from state to state and is used in calculating net energy for lactating, which is used to calculate VS and Nex for dairy cows. Milk production is zero for dairy heifers (dairy heifers do not produce milk because they have not yet had a calf). Over time, the differences in milk production are also a big driver for the higher variability of VS and Nex rates in dairy cows.

Step 3: Waste Management System Usage Data

Table A-171 and Table A-172 summarize 2018 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-173.

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, 2007, 2012, and 2017 Census of Agriculture (USDA 2019d). It was assumed that the Census data provided for 1992 were the same as that for 1990 and 1991, and data provided for 2017 were the same as that for 2018. Data for 1993 through 1996, 1998 through 2001, and 2003 through 2006, 2008 through 2011, and 2013 through 2016 were interpolated using the 1992, 1997, 2002, 2007, 2012, and 2017 Census data. The percent of waste by system was estimated using the USDA data broken out by geographic region and farm size.

For 1990 through 1996 the following methodology and sources were used to estimate dairy WMS:

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, 2012, and 2017 (USDA 2019d) 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 2018, which were obtained from the USDA NASS (USDA 2018a).

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).

Starting in 2016, EPA estimate dairy WMS based on 2016 USDA Economic Research Service (ERS) Agricultural Resource Management Survey (ARMS) data. These data were obtained from surveys of nationally representative dairy producers. WMS data for 2016 were assumed the same for 2017 and 2018. WMS for 1997 through 2015 were interpolated between the data sources used for the 1990-1997 dairy WMS (noted above) and the 2016 ARMs data (ERG 2019).

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 2019). 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 1995 USDA APHIS survey, EPA's Office of Water site visits, and 2009 USDA ERS ARMS data (Bush 1998, ERG 2000a, ERG 2018). The USDA APHIS data are based on a statistical sample of farms in the 16 U.S. states with the most hogs. The ERS ARMS data are based on surveys of nationally representative swine producers. Prior to 2009, operations with less than 200 head were assumed to use pasture, range, or paddock systems and swine operations with greater than 200 head were assigned WMS as obtained from USDA APHIS (Bush 1998). WMS data for 2009 were obtained from USDA ERS ARMS; WMS data for 2010 through 2018 were assumed to be the same as 2009 (ERG 2018). 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, 2012, and 2017 Census of Agriculture (USDA 2019d) 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. Data for 1993 through 1996, 1998 through 2001, 2003 through 2006, and 2008 through 2011, and 2013 through 2016 were interpolated using the 1992, 1997, 2002, 2007, 2012, and 2017 Census data.

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 2019).

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 2018 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 2018 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 2019), 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 2019).

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-174. 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 2019) 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 (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, 2007, 2012, and 2017 Census data (USDA 2019d). 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 distribution data for 1998 through 2001 were interpolated based on 1997 and 2002 data; county population distribution data for 2003 through 2006 were interpolated based on 2002 and 2007 data; county population distribution data for 2008 through 2011 were interpolated based on 2007 and 2012 data; county population distribution data for 2013 through 2016 were interpolated based on 2012 and 2017 data; county population distributions for 2018 were assumed to be the same as 2017.

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 B_0.

The annual MCF is then calculated as:

$$MCF_{annual} = \frac{CH_4\ generated_{annual}}{VS\ produced_{annual} \times B_o}$$

where,

MCF_{annual}	= Methane conversion factor
$VS\ produced_{annual}$	= Volatile solids excreted annually
B_0	= 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-175 by state, WMS, and animal group for 2018.

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-176.

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-177.

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,

VS excreted $_{\text{State, Animal, WMS}}$	= Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
Population $_{\text{State, Animal}}$	= Annual average state animal population by animal type (head)
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:

$$\text{VS excreted}_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \text{VS} \times \text{WMS}$$

where,

VS excreted $_{\text{State, Animal, WMS}}$	= Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
Population $_{\text{State, Animal}}$	= Annual average state animal population by animal type (head)
VS	= Volatile solids production rate (kg VS/animal/year)
WMS	= Distribution of manure by WMS for each animal type in a state (percent)

For all animals, the estimated amount of VS excreted into a WMS was used to calculate CH_4 emissions using the following equation:

$$CH_4 = \sum_{State, Animal, WMS} \left(VS\ excreted_{State, Animal, WMS} \times B_o \times MCF \times 0.662 \right)$$

where,

CH_4	= CH_4 emissions (kg CH_4/yr)
VS excreted $_{WMS, State}$	= Amount of VS excreted in manure managed in each WMS (kg/yr)
B_0	= Maximum CH_4 producing capacity (m^3 CH_4/kg VS)
MCF $_{animal, state, WMS}$	= 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 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:

$$CH_4\ ProductionAD_{ADSystem} = ProductionAD_{ADSystem} \times \frac{TAM}{1000} \times VS \times B_0 \times 0.662 \times 365.25 \times 0.90$$

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_0	= 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:

$$CH_4\ Emissions\ AD = \sum_{State, Animal, ADSystems} \left(\begin{array}{l} \left[CH_4\ ProductionAD_{ADsystem} \times CE_{ADsystem} \times (1 - DE) \right] \\ + \left[CH_4\ ProductionAD_{ADsystem} \times (1 - CE_{ADsystem}) \right] \end{array} \right)$$

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 $_{\text{State, Animal, WMS}}$	= Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
Population $_{\text{state}}$	= Annual average state animal population by animal type (head)
WMS	= Distribution of manure by waste management system for each animal type in a state (percent)
TAM	= Typical animal mass (kg)
Nex	= 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	= Nitrogen excretion rate (kg N/animal/year)

For all animals, direct N_2O emissions were calculated as follows:

$$\text{Direct N}_2\text{O} = \sum_{\text{State,Animal,WMS}} \left(\text{N excreted}_{\text{State,Animal,WMS}} \times \text{EF}_{\text{WMS}} \times \frac{44}{28} \right)$$

where,

Direct N_2O	= Direct N_2O emissions (kg N_2O/yr)
N excreted $_{\text{State, Animal, WMS}}$	= Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
EF_{WMS}	= Direct N_2O emission factor from IPCC guidelines (kg N_2O-N /kg N)
44/28	= Conversion factor of N_2O-N to N_2O

Indirect N_2O emissions were calculated for all animals with the following equation:

$$\text{Indirect N}_2\text{O} = \sum_{\text{State, Animal, WMS}} \left(\left[\text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{gas, WMS}}}{100} \times \text{EF}_{\text{volatilization}} \times \frac{44}{28} \right] + \left[\text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{runoff/leach, WMS}}}{100} \times \text{EF}_{\text{runoff/leach}} \times \frac{44}{28} \right] \right)$$

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)

$Frac_{gas,WMS}$ = Nitrogen lost through volatilization in each WMS

$Frac_{runoff/leach,WMS}$ = Nitrogen lost through runoff and leaching in each WMS (data were not available for leaching so the value reflects only runoff)

$EF_{volatilization}$ = Emission factor for volatilization (0.010 kg N_2O-N/kg N)

$EF_{runoff/leach}$ = 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-178 and Table A-179 respectively. Emission estimates for 2018 are presented by animal type and state in Table A-180 and Table A-181 respectively.

Table A-167: Livestock Population (1,000 Head)

Animal Type	1990	1995	2005	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Dairy Cattle	19,512	18,681	17,793	18,297	18,442	18,587	18,505	18,527	18,803	18,853	18,893	19,008	18,909
Dairy Cows	*10,015*	*9,482*	*9,004*	*9,087*	*9,156*	*9,236*	*9,221*	*9,208*	*9,307*	*9,310*	*9,346*	*9,432*	*9,353*
Dairy Heifer	*4,129*	*4,108*	*4,162*	*4,545*	*4,577*	*4,581*	*4,525*	*4,579*	*4,725*	*4,785*	*4,762*	*4,776*	*4,709*
Dairy Calves	*5,369*	*5,091*	*4,628*	*4,666*	*4,709*	*4,770*	*4,758*	*4,740*	*4,771*	*4,758*	*4,785*	*4,800*	*4,846*
Swine[a]	53,941	58,899	61,073	64,723	65,572	66,363	65,437	64,195	68,178	70,065	72,125	73,793	76,907
Market <50 lb.	*18,359*	*19,656*	*20,228*	*19,067*	*19,285*	*19,472*	*19,002*	*18,939*	*19,843*	*20,572*	*20,973*	*21,494*	*22,402*
Market 50-119 lb.	*11,734*	*12,836*	*13,519*	*16,645*	*16,904*	*17,140*	*16,834*	*16,559*	*17,577*	*18,175*	*18,767*	*19,133*	*20,097*
Market 120-179 lb.	*9,440*	*10,545*	*11,336*	*12,377*	*12,514*	*12,714*	*12,674*	*12,281*	*13,225*	*13,575*	*13,982*	*14,365*	*14,843*
Market >180 lb.	*7,510*	*8,937*	*9,997*	*10,856*	*11,078*	*11,199*	*11,116*	*10,525*	*11,555*	*11,714*	*12,282*	*12,497*	*13,151*
Breeding	*6,899*	*6,926*	*5,993*	*5,778*	*5,791*	*5,839*	*5,812*	*5,892*	*5,978*	*6,030*	*6,122*	*6,303*	*6,415*
Beef Cattle[b]	81,576	90,361	82,193	80,484	78,937	76,858	76,075	75,245	76,080	79,374	81,560	83,061	83,766
Feedlot Steers	*6,357*	*7,233*	*8,116*	*8,584*	*8,771*	*8,586*	*8,614*	*8,695*	*8,570*	*9,019*	*9,572*	*10,329*	*10,491*
Feedlot Heifers	*3,192*	*3,831*	*4,536*	*4,620*	*4,830*	*4,742*	*4,653*	*4,525*	*4,313*	*4,431*	*4,768*	*5,146*	*5,226*
NOF Bulls	*2,160*	*2,385*	*2,214*	*2,190*	*2,165*	*2,100*	*2,074*	*2,038*	*2,109*	*2,142*	*2,244*	*2,252*	*2,253*
Beef Calves	*16,909*	*18,177*	*16,918*	*16,067*	*15,817*	*15,288*	*14,859*	*14,741*	*15,000*	*15,563*	*15,971*	*16,021*	*16,175*
NOF Heifers	*10,182*	*11,829*	*9,550*	*9,349*	*8,874*	*8,687*	*8,787*	*8,787*	*9,288*	*9,903*	*9,835*	*9,815*	*9,786*
NOF Steers	*10,321*	*11,716*	*8,185*	*8,234*	*7,568*	*7,173*	*7,457*	*7,374*	*7,496*	*8,150*	*7,957*	*8,032*	*8,144*
NOF Cows	*32,455*	*35,190*	*32,674*	*31,440*	*30,913*	*30,282*	*29,631*	*29,085*	*29,302*	*30,166*	*31,213*	*31,466*	*31,691*
Sheep	11,358	8,989	6,135	5,620	5,470	5,375	5,360	5,235	5,270	5,295	5,270	5,265	5,230
Sheep On Feed	*1,180*	*1,771*	*2,971*	*2,778*	*2,687*	*2,666*	*2,655*	*2,585*	*2,584*	*2,621*	*2,615*	*2,619*	*2,602*
Sheep NOF	*10,178*	*7,218*	*3,164*	*2,842*	*2,783*	*2,709*	*2,705*	*2,650*	*2,686*	*2,674*	*2,655*	*2,646*	*2,628*
Goats	2,516	2,357	2,897	2,829	2,725	2,622	2,637	2,652	2,668	2,683	2,699	2,714	2,696
Poultry[c]	1,537,074	1,826,977	2,150,410	2,104,335	2,095,951	2,168,697	2,106,502	2,116,333	2,134,445	2,173,216	2,214,462	2,252,265	2,277,413
Hens >1 yr.	*273,467*	*299,071*	*348,203*	*341,884*	*338,944*	*346,965*	*361,403*	*370,637*	*351,656*	*377,299*	*388,006*	*396,870*	*403,273*
Pullets	*73,167*	*81,369*	*96,809*	*105,738*	*102,233*	*104,460*	*106,646*	*106,490*	*118,114*	*112,061*	*117,173*	*124,135*	*122,095*
Chickens	*6,545*	*7,637*	*8,289*	*7,390*	*6,922*	*6,827*	*6,853*	*6,403*	*7,211*	*6,759*	*6,859*	*6,568*	*7,130*
Broilers	*1,066,209*	*1,331,940*	*1,613,091*	*1,567,927*	*1,565,018*	*1,625,945*	*1,551,600*	*1,553,636*	*1,579,764*	*1,595,764*	*1,620,691*	*1,643,109*	*1,668,582*
Turkeys	*117,685*	*106,960*	*84,018*	*81,396*	*82,833*	*84,500*	*80,000*	*79,167*	*77,700*	*81,333*	*81,733*	*81,583*	*76,333*
Horses	2,212	2,632	3,875	3,784	3,703	3,621	3,467	3,312	3,157	3,002	2,847	2,692	2,538
Mules and Asses	63	101	212	289	291	293	298	303	308	313	318	323	328
American Bison	47	104	212	177	169	162	166	171	175	179	184	188	189

Note: Totals may not sum due to independent rounding.

[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.

Source(s): See *Step 1: Livestock Population Characterization Data.*

Table A-168: Waste Characteristics Data

	Typical Animal Mass, TAM		Total 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-170	CEFM	0.24	Morris 1976	Table A-170	CEFM
Dairy Heifers	406-408	CEFM	Table A-170	CEFM	0.17	Bryant et al. 1976	Table A-170	CEFM
Feedlot Steers	419-457	CEFM	Table A-170	CEFM	0.33	Hashimoto 1981	Table A-170	CEFM
Feedlot Heifers	384-430	CEFM	Table A-170	CEFM	0.33	Hashimoto 1981	Table A-170	CEFM
NOF Bulls	831-917	CEFM	Table A-170	CEFM	0.17	Hashimoto 1981	Table A-170	CEFM
NOF Calves	118	ERG 2003b	Table A-169	USDA 1996, 2008	0.17	Hashimoto 1981	Table A-169	USDA 1996, 2008
NOF Heifers	296-407	CEFM	Table A-170	CEFM	0.17	Hashimoto 1981	Table A-170	CEFM
NOF Steers	314-335	CEFM	Table A-170	CEFM	0.17	Hashimoto 1981	Table A-170	CEFM
NOF Cows	554-611	CEFM	Table A-170	CEFM	0.17	Hashimoto 1981	Table A-170	CEFM
American Bison	578.5	Meagher 1986	Table A-170	CEFM	0.17	Hashimoto 1981	Table A-170	CEFM
Market Swine <50 lbs.	13	ERG 2010a	Table A-169	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-169	USDA 1996, 2008
Market Swine <60 lbs.	16	Safley 2000	Table A-169	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-169	USDA 1996, 2008
Market Swine 50-119 lbs.	39	ERG 2010a	Table A-169	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-169	USDA 1996, 2008
Market Swine 60-119 lbs.	41	Safley 2000	Table A-169	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-169	USDA 1996, 2008
Market Swine 120-179 lbs.	68	Safley 2000	Table A-169	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-169	USDA 1996, 2008
Market Swine >180 lbs.	91	Safley 2000	Table A-169	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-169	USDA 1996, 2008
Breeding Swine	198	Safley 2000	Table A-169	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-169	USDA 1996, 2008
Feedlot Sheep	25	EPA 1992	Table A-169	ASAE 1998, USDA 2008	0.36	EPA 1992	Table A-169	ASAE 1998, USDA 2008
NOF Sheep	80	EPA 1992	Table A-169	ASAE 1998, USDA 2008	0.19	EPA 1992	Table A-169	ASAE 1998, USDA 2008
Goats	64	ASAE 1998	Table A-169	ASAE 1998	0.17	EPA 1992	Table A-169	ASAE 1998
Horses	450	ASAE 1998	Table A-169	ASAE 1998, USDA 2008	0.33	EPA 1992	Table A-169	ASAE 1998, USDA 2008
Mules and Asses	130	IPCC 2006	Table A-169	IPCC 2006	0.33	EPA 1992	Table A-169	IPCC 2006
Hens >/= 1 yr	1.8	ASAE 1998	Table A-169	USDA 1996, 2008	0.39	Hill 1982	Table A-169	USDA 1996, 2008
Pullets	1.8	ASAE 1998	Table A-169	USDA 1996, 2008	0.39	Hill 1982	Table A-169	USDA 1996, 2008
Other Chickens	1.8	ASAE 1998	Table A-169	USDA 1996, 2008	0.39	Hill 1982	Table A-169	USDA 1996, 2008
Broilers	0.9	ASAE 1998	Table A-169	USDA 1996, 2008	0.36	Hill 1984	Table A-169	USDA 1996, 2008
Turkeys	6.8	ASAE 1998	Table A-169	USDA 1996, 2008	0.36	Hill 1984	Table A-169	USDA 1996, 2008

[a] Nex and VS values vary by year; Table A-170 shows state-level values for 2018 only.

Table A-169: Estimated Volatile Solids (VS) and Total 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)[99]

Animal Type	1990	1995	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
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
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
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
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
Swine, Breeding	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
NOF Cattle Calves	6.4	6.4	7.4	7.5	7.6	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
Sheep	9.2	9.2	8.6	8.5	8.4	8.3	8.3	8.3	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
Hens >1yr.	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	10.2	10.2	10.2
Pullets	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	10.2	10.2	10.2
Chickens	10.8	10.8	11.0	11.0	11.0	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	16.5	16.7	16.8	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
Turkeys	9.7	9.7	8.8	8.7	8.6	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Horses	10.0	10.0	7.3	6.9	6.5	6.1	6.1	6.1	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
Nex																
Swine, Market <50 lbs.	0.60	0.60	0.84	0.87	0.89	0.92	0.92	0.92	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	0.51	0.52	0.53	0.54	0.54	0.54	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	0.51	0.52	0.53	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Market >180 lbs.	0.42	0.42	0.51	0.52	0.53	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Breeding	0.24	0.24	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
NOF Cattle Calves	0.30	0.30	0.41	0.43	0.44	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sheep	0.42	0.42	0.44	0.44	0.45	0.45	0.45	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
Hens >1yr.	0.70	0.70	0.77	0.77	0.78	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79

[99] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

Animal Type	1990	1995	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Pullets	0.70	0.70	0.77	0.77	0.78	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
Chickens	0.83	0.83	1.03	1.06	1.08	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Broilers	1.10	1.10	1.00	0.98	0.97	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Turkeys	0.74	0.74	0.65	0.64	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Horses	0.30	0.30	0.26	0.26	0.25	0.25	0.25	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

Table A-170: Estimated Volatile Solids (VS) and Total Nitrogen Excreted (Nex) Production Rates by State for Cattle (other than Calves) and American Bison[a] for 2018 (kg/animal/year)[100]

	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	2,262	1,252	1,664	1,100	975	691	669	1,721	1,721	136	69	73	50	42	56	57	83	83
Alaska	1,821	1,252	1,891	1,252	1,120	691	669	1,956	1,956	115	69	59	41	33	56	57	69	69
Arizona	2,943	1,252	1,891	1,236	1,120	691	670	1,956	1,956	163	69	59	40	33	56	57	69	69
Arkansas	2,087	1,252	1,664	1,096	975	691	670	1,721	1,721	126	69	73	50	42	56	57	83	83
California	2,780	1,252	1,891	1,230	1,120	691	670	1,956	1,956	155	69	59	39	33	56	57	69	69
Colorado	3,055	1,252	1,891	1,205	1,120	691	669	1,956	1,956	168	69	59	38	33	56	57	69	69
Connecticut	2,751	1,252	1,674	1,097	981	691	669	1,731	1,731	155	69	74	51	42	56	57	84	84
Delaware	2,486	1,252	1,674	1,094	981	691	669	1,731	1,731	143	69	74	51	42	56	57	84	84
Florida	2,657	1,252	1,664	1,103	975	691	668	1,721	1,721	153	69	73	51	42	56	57	83	83
Georgia	2,790	1,252	1,664	1,093	975	691	668	1,721	1,721	158	69	73	50	42	55	57	83	83
Hawaii	2,363	1,252	1,891	1,262	1,120	691	669	1,956	1,956	138	69	59	41	33	56	57	69	69
Idaho	2,920	1,252	1,891	1,220	1,120	691	669	1,956	1,956	162	69	59	39	33	56	57	69	69
Illinois	2,649	1,252	1,589	1,013	927	691	669	1,643	1,643	150	69	75	50	43	56	57	85	85
Indiana	2,803	1,252	1,589	1,022	927	691	670	1,643	1,643	157	69	75	50	43	56	57	85	85
Iowa	2,872	1,252	1,589	995	927	691	670	1,643	1,643	160	69	75	48	43	56	57	85	85
Kansas	2,817	1,252	1,589	986	927	691	669	1,643	1,643	158	69	75	48	43	56	57	85	85
Kentucky	2,542	1,252	1,664	1,081	975	691	669	1,721	1,721	148	69	73	49	42	56	57	83	83
Louisiana	2,100	1,252	1,664	1,103	975	691	669	1,721	1,721	127	69	73	51	42	56	57	83	83
Maine	2,668	1,252	1,674	1,088	981	691	669	1,731	1,731	151	69	74	50	42	56	57	84	84
Maryland	2,582	1,252	1,674	1,095	981	691	670	1,731	1,731	147	69	74	51	42	56	57	84	84
Massachusetts	2,413	1,252	1,674	1,097	981	691	669	1,731	1,731	140	69	74	51	42	56	57	84	84
Michigan	3,064	1,252	1,589	1,010	927	691	670	1,643	1,643	168	69	75	49	43	56	57	85	85
Minnesota	2,708	1,252	1,589	1,008	927	691	670	1,643	1,643	153	69	75	49	43	56	57	85	85
Mississippi	2,291	1,252	1,664	1,098	975	691	669	1,721	1,721	137	69	73	50	42	56	57	83	83
Missouri	2,189	1,252	1,589	1,033	927	691	669	1,643	1,643	131	69	75	51	43	56	57	85	85
Montana	2,754	1,252	1,891	1,248	1,120	691	670	1,956	1,956	155	69	59	40	33	56	57	69	69
Nebraska	2,897	1,252	1,589	991	927	691	670	1,643	1,643	161	69	75	48	43	56	57	85	85
Nevada	2,754	1,252	1,891	1,244	1,120	691	668	1,956	1,956	155	69	59	40	33	55	56	69	69
New Hampshire	2,668	1,252	1,674	1,081	981	691	669	1,731	1,731	151	69	74	50	42	56	57	84	84
New Jersey	2,581	1,252	1,674	1,088	981	691	668	1,731	1,731	147	69	74	50	42	56	57	84	84
New Mexico	2,964	1,252	1,891	1,237	1,120	691	669	1,956	1,956	164	69	59	40	33	56	57	69	69
New York	2,887	1,252	1,674	1,078	981	691	668	1,731	1,731	161	69	74	49	42	56	57	84	84
North Carolina	2,734	1,252	1,664	1,097	975	691	668	1,721	1,721	156	69	73	50	42	56	57	83	83

[100] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

	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
North Dakota	2,710	1,252	1,589	1,021	927	691	670	1,643	1,643	153	69	75	50	43	56	57	85	85
Ohio	2,687	1,252	1,589	1,027	927	691	670	1,643	1,643	152	69	75	51	43	56	57	85	85
Oklahoma	2,498	1,252	1,664	1,073	975	691	669	1,721	1,721	144	69	73	49	42	56	57	83	83
Oregon	2,623	1,252	1,891	1,231	1,120	691	669	1,956	1,956	149	69	59	40	33	56	57	69	69
Pennsylvania	2,656	1,252	1,674	1,083	981	691	669	1,731	1,731	151	69	74	50	42	56	57	84	84
Rhode Island	2,313	1,252	1,674	1,097	981	691	669	1,731	1,731	136	69	74	51	42	56	57	84	84
South Carolina	2,384	1,252	1,664	1,100	975	691	671	1,721	1,721	141	69	73	50	42	56	58	83	83
South Dakota	2,771	1,252	1,589	1,014	927	691	670	1,643	1,643	156	69	75	50	43	56	57	85	85
Tennessee	2,448	1,252	1,664	1,086	975	691	669	1,721	1,721	144	69	73	50	42	56	57	83	83
Texas	2,866	1,252	1,664	1,061	975	691	670	1,721	1,721	160	69	73	48	42	56	57	83	83
Utah	2,841	1,252	1,891	1,244	1,120	692	671	1,956	1,956	159	69	59	40	33	56	58	69	69
Vermont	2,679	1,252	1,674	1,077	981	691	668	1,731	1,731	152	69	74	49	42	56	57	84	84
Virginia	2,644	1,252	1,664	1,086	975	691	670	1,721	1,721	152	69	73	50	42	56	57	83	83
Washington	2,878	1,252	1,891	1,213	1,120	691	670	1,956	1,956	160	69	59	39	33	56	57	69	69
West Virginia	2,285	1,252	1,674	1,100	981	691	670	1,731	1,731	135	69	74	51	42	56	57	84	84
Wisconsin	2,872	1,252	1,589	1,033	927	691	670	1,643	1,643	160	69	75	51	43	56	57	85	85
Wyoming	2,820	1,252	1,891	1,242	1,120	691	669	1,956	1,956	158	69	59	40	33	56	57	69	69

[a] Beef NOF Bull values were used for American bison Nex and VS.

Source: CEFM.

Table A-171: 2018 Manure Distribution Among Waste Management Systems by Operation (Percent)[101]

	Beef Feedlots		Beef Not on Feed Operations	Dairy Cow Farms[a]							Dairy Heifer Facilities			
State	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock	Pasture, Range, Paddock	Daily Spread	Dry Lot	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[b]	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock[b]
Alabama	100	1	100	48	0	0	14	2	22	14	17	38	0	45
Alaska	100	1	100	25	12	0	26	5	9	22	6	90	1	4
Arizona	100	0	100	10	0	11	42	6	30	2	10	90	0	0
Arkansas	100	1	100	47	0	0	13	3	23	14	15	28	0	57
California	100	1	100	5	0	3	26	3	54	9	11	88	1	1
Colorado	100	0	100	11	0	11	41	5	30	2	1	98	0	1
Connecticut	100	1	100	15	3	0	16	6	33	28	43	51	0	6
Delaware	100	1	100	14	2	0	18	7	29	31	44	50	0	6
Florida	100	1	100	48	0	0	7	0	40	4	22	61	1	17

[101] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

	Beef Feedlots		Beef Not on Feed Operations	Dairy Cow Farms[a]							Dairy Heifer Facilities			
State	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock	Pasture, Range, Paddock	Daily Spread	Dry Lot	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[b]	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock[b]
Georgia	100	1	100	48	0	0	9	1	36	6	18	42	0	40
Hawaii	100	1	100	4	0	4	27	2	54	9	0	99	1	1
Idaho	100	0	100	5	0	3	26	2	53	10	1	99	0	0
Illinois	100	1	100	24	0	0	23	3	33	18	8	87	0	5
Indiana	100	1	100	21	0	0	21	2	41	16	13	79	0	8
Iowa	100	1	100	20	0	0	21	3	41	16	10	83	0	6
Kansas	100	1	100	14	0	0	16	1	55	13	5	92	0	3
Kentucky	100	1	100	51	0	0	14	2	23	11	14	24	0	61
Louisiana	100	1	100	48	0	0	13	3	23	12	14	26	0	60
Maine	100	1	100	18	4	0	16	5	30	28	45	48	0	7
Maryland	100	1	100	21	4	0	16	6	23	29	44	49	0	7
Massachusetts	100	1	100	25	5	0	17	6	17	30	45	47	0	7
Michigan	100	1	100	11	3	0	22	6	36	22	6	91	0	3
Minnesota	100	1	100	16	6	0	24	6	26	23	10	84	0	6
Mississippi	100	1	100	50	0	0	14	2	23	11	15	28	0	57
Missouri	100	1	100	29	0	0	25	2	26	17	14	77	0	8
Montana	100	0	100	19	0	0	21	4	38	18	4	93	0	3
Nebraska	100	1	100	15	0	0	18	2	50	15	6	90	0	4
Nevada	100	0	100	11	0	0	14	2	61	13	0	99	0	0
New Hampshire	100	1	100	21	4	0	17	5	22	31	44	49	0	7
New Jersey	100	1	100	27	5	0	16	6	16	29	45	47	0	8
New Mexico	100	0	100	10	0	11	42	6	30	2	10	90	0	0
New York	100	1	100	14	3	0	15	5	38	25	45	48	0	7
North Carolina	100	1	100	48	0	0	10	2	31	9	15	31	0	54
North Dakota	100	1	100	18	0	0	19	3	44	16	11	83	0	6
Ohio	100	1	100	24	0	0	23	2	35	17	14	78	0	8
Oklahoma	100	0	100	11	0	8	41	5	23	12	6	94	0	0
Oregon	100	1	100	9	0	3	24	4	50	11	0	80	1	20
Pennsylvania	100	1	100	27	6	0	16	5	18	29	47	44	0	9
Rhode Island	100	1	100	29	6	0	17	5	14	30	47	44	0	9
South Carolina	100	1	100	45	0	0	10	2	33	11	15	31	0	54
South Dakota	100	1	100	14	0	0	16	2	54	14	8	87	0	5
Tennessee	100	1	100	48	0	0	12	2	26	11	15	26	0	59
Texas	100	0	100	11	0	10	41	5	30	3	8	92	0	0
Utah	100	0	100	12	0	9	40	5	28	7	1	98	0	1
Vermont	100	1	100	14	3	0	16	5	36	26	44	49	0	7

	Beef Feedlots		Beef Not on Feed Operations	Dairy Cow Farms[a]							Dairy Heifer Facilities			
State	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock	Pasture, Range, Paddock	Daily Spread	Dry Lot	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[b]	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock[b]
Virginia	100	1	100	49	0	0	12	2	26	11	15	28	0	57
Washington	100	1	100	8	0	3	25	3	51	10	0	83	1	17
West Virginia	100	1	100	29	6	0	17	5	13	30	45	48	0	7
Wisconsin	100	1	100	15	5	0	24	6	27	23	12	82	0	7
Wyoming	100	0	100	16	0	0	18	2	49	15	12	81	0	7

[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. Deep pit systems are their own manure management systems in the U.S. but are included under Liquid Systems in the UNFCCC CRF tables due to lack of a separate allocation for those systems within the tables. For Dairy Cows, solid storage and dry lot systems calculated separately in Table A-171, but are reported as "NE" in the UNFCCC CRF tables due to lack of a separate allocation for those systems within the tables.

[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.

Source(s): *See Step 3: Waste Management System Usage Data*.

Table A-172: 2018 Manure Distribution Among Waste Management Systems by Operation (Percent) Continued[102]

	Swine Operations[a]						Layer Operations		Broiler and Turkey Operations	
State	Pasture, Range, Paddock	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Deep Pit (<1 month)	Anaerobic Lagoon	Poultry without Litter	Pasture, Range, Paddock	Poultry with Litter
Alabama	15	0	29	30	12	14	42	58	1	99
Alaska	57	0	3	2	34	4	25	75	1	99
Arizona	19	0	28	29	11	13	60	40	1	99
Arkansas	6	0	60	26	5	2	0	100	1	99
California	15	0	28	29	13	14	12	88	1	99
Colorado	2	0	53	0	23	22	60	40	1	99
Connecticut	66	0	2	2	26	4	5	95	1	99
Delaware	29	0	4	5	56	5	5	95	1	99
Florida	53	0	20	14	9	5	42	58	1	99
Georgia	13	0	56	28	3	1	42	58	1	99
Hawaii	42	0	22	18	11	7	25	75	1	99
Idaho	16	0	16	3	57	8	60	40	1	99
Illinois	2	0	15	7	71	5	2	98	1	99
Indiana	1	0	3	12	78	7	0	100	1	99
Iowa	1	0	10	4	80	5	0	100	1	99
Kansas	1	0	13	35	21	30	2	98	1	99
Kentucky	8	0	19	21	31	21	5	95	1	99
Louisiana	67	0	17	9	6	2	60	40	1	99
Maine	74	0	2	1	20	4	5	95	1	99
Maryland	37	0	10	2	44	6	5	95	1	99
Massachusetts	60	0	2	2	31	4	5	95	1	99
Michigan	3	0	12	6	69	9	2	98	1	99
Minnesota	1	0	3	2	88	5	0	100	1	99
Mississippi	2	0	31	36	13	18	60	40	1	99
Missouri	2	0	16	33	34	15	0	100	1	99
Montana	3	0	21	2	64	9	60	40	1	99
Nebraska	2	0	9	22	49	19	2	98	1	99
Nevada	12	0	29	32	12	15	0	100	1	99
New Hampshire	65	0	2	2	27	4	5	95	1	99
New Jersey	54	0	3	3	36	4	5	95	1	99
New Mexico	67	0	17	9	6	2	60	40	1	99

[102] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

	Swine Operations[a]						Layer Operations		Broiler and Turkey Operations	
State	Pasture, Range, Paddock	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Deep Pit (<1 month)	Anaerobic Lagoon	Poultry without Litter	Pasture, Range, Paddock	Poultry with Litter
New York	41	0	6	3	44	5	5	95	1	99
North Carolina	1	0	33	49	1	16	42	58	1	99
North Dakota	2	0	21	2	65	9	2	98	1	99
Ohio	1	0	10	9	67	13	0	100	1	99
Oklahoma	1	0	11	53	3	32	60	40	1	99
Oregon	51	0	20	15	9	5	25	75	1	99
Pennsylvania	1	0	8	5	77	9	0	100	1	99
Rhode Island	64	0	2	2	28	4	5	95	1	99
South Carolina	6	0	30	34	13	16	60	40	1	99
South Dakota	1	0	17	11	57	14	2	98	1	99
Tennessee	7	0	30	33	13	16	5	95	1	99
Texas	6	0	31	34	13	17	12	88	1	99
Utah	1	0	22	2	65	9	60	40	1	99
Vermont	69	0	2	1	24	4	5	95	1	99
Virginia	6	0	14	29	15	35	5	95	1	99
Washington	35	0	12	2	45	7	12	88	1	99
West Virginia	82	0	1	0	13	3	5	95	1	99
Wisconsin	15	0	23	1	57	4	2	98	1	99
Wyoming	3	0	21	2	64	9	60	40	1	99

[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. Deep pit systems are their own manure management systems in the U.S. but are included under Liquid Systems in the UNFCCC CRF tables due to lack of a separate allocation for those systems within the tables.

[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.

Source(s): *See Step 3: Waste Management System Usage Data.*

Table A-173: 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 and the classification of manure as managed or unmanaged 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-174: 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
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-175: Methane Conversion Factors by State for Liquid Systems for 2018 (Percent)[103]

	Dairy		Swine		Beef	Poultry
State	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry and Pit Storage	Liquid/Slurry	Anaerobic Lagoon
Alabama	77	42	77	42	44	77
Alaska	49	15	49	15	15	49
Arizona	78	60	76	48	46	75
Arkansas	75	38	76	40	39	75
California	74	33	74	33	45	74
Colorado	66	22	69	25	25	65
Connecticut	71	27	71	27	27	71
Delaware	75	34	75	34	33	75
Florida	79	58	79	56	53	79
Georgia	78	44	77	42	49	77
Hawaii	77	59	77	59	59	77
Idaho	68	24	64	21	22	64
Illinois	73	31	73	31	30	74
Indiana	72	29	72	29	30	72
Iowa	70	27	71	27	27	71
Kansas	74	34	74	33	33	74
Kentucky	75	34	75	35	34	75
Louisiana	78	50	78	49	52	78
Maine	65	22	65	22	21	65
Maryland	74	32	75	33	32	74
Massachusetts	69	25	70	26	26	70
Michigan	69	25	70	26	26	69
Minnesota	68	25	69	25	25	67
Mississippi	77	45	77	44	46	78
Missouri	74	34	74	34	34	74
Montana	59	19	61	20	20	61
Nebraska	71	28	71	28	27	71
Nevada	71	27	71	27	24	73

[103] This table has not been updated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

State	Dairy		Swine		Beef	Poultry
	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry and Pit Storage	Liquid/Slurry	Anaerobic Lagoon
New Hampshire	66	23	67	23	22	67
New Jersey	73	30	73	31	29	73
New Mexico	73	33	70	28	31	71
New York	68	24	69	25	25	69
North Carolina	76	36	78	41	36	76
North Dakota	65	23	65	23	23	65
Ohio	72	29	72	29	29	72
Oklahoma	76	40	75	37	37	76
Oregon	65	22	64	21	22	64
Pennsylvania	72	28	72	28	28	73
Rhode Island	71	27	71	27	27	71
South Carolina	77	43	78	44	41	77
South Dakota	69	25	69	26	26	69
Tennessee	75	35	76	38	36	75
Texas	75	42	76	44	41	77
Utah	68	23	67	23	24	68
Vermont	65	22	65	22	22	65
Virginia	73	30	76	35	31	74
Washington	64	21	64	21	23	65
West Virginia	72	29	72	29	29	72
Wisconsin	68	24	69	25	25	69
Wyoming	61	20	62	20	21	62

Note: MCFs developed using Tier 2 methods described in *2006 IPCC Guidelines*, Section 10.4.2.

Table A-176: Direct Nitrous Oxide Emission Factors (kg N_2O-N/kg N excreted)

Waste Management System	Direct N_2O Emission
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
Pit Storage	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-177: 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
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-178: Total Methane Emissions from Livestock Manure Management (kt)[a,b]

Animal Type	1990	1995	2005	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Dairy Cattle	**589**	**684**	**970**	**1,124**	**1,144**	**1,188**	**1,167**	**1,190**	**1,233**	**1,259**	**1,270**	**1,292**	**1,281**
Dairy Cows	*581*	*676*	*962*	*1,115*	*1,134*	*1,177*	*1,157*	*1,180*	*1,222*	*1,248*	*1,259*	*1,281*	*1,270*
Dairy Heifer	*7*	*7*	*7*	*8*	*8*	*9*	*8*	*8*	*9*	*9*	*9*	*9*	*9*
Dairy Calves	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*
Swine	**622**	**763**	**812**	**797**	**791**	**821**	**756**	**719**	**808**	**846**	**840**	**888**	**924**
Market Swine	483	607	665	657	653	678	623	585	665	699	697	736	770
Market <50 lbs.	*102*	*121*	*128*	*95*	*94*	*98*	*88*	*86*	*95*	*101*	*100*	*106*	*110*
Market 50-119 lbs.	*101*	*123*	*131*	*144*	*142*	*149*	*136*	*130*	*145*	*155*	*153*	*161*	*170*
Market 120-179 lbs.	*136*	*170*	*184*	*188*	*185*	*193*	*179*	*169*	*192*	*203*	*200*	*213*	*220*
Market >180 lbs.	*144*	*193*	*222*	*229*	*231*	*238*	*220*	*201*	*232*	*241*	*244*	*256*	*270*
Breeding Swine	139	155	147	140	138	143	133	133	143	146	143	152	155
Beef Cattle	**126**	**139**	**133**	**132**	**131**	**128**	**122**	**120**	**126**	**132**	**136**	**135**	**136**
Feedlot Steers	*14*	*14*	*15*	*16*	*17*	*16*	*16*	*16*	*16*	*17*	*18*	*20*	*20*
Feedlot Heifers	*7*	*8*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*10*	*10*
NOF Bulls	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*
Beef Calves	*6*	*7*	*7*	*7*	*7*	*7*	*6*	*6*	*7*	*7*	*7*	*7*	*7*
NOF Heifers	*12*	*15*	*13*	*13*	*12*	*12*	*12*	*12*	*13*	*14*	*14*	*13*	*13*
NOF Steers	*12*	*14*	*10*	*10*	*10*	*9*	*9*	*9*	*9*	*10*	*10*	*10*	*10*
NOF Cows	*69*	*76*	*73*	*71*	*71*	*69*	*65*	*63*	*67*	*69*	*71*	*70*	*70*
Sheep	**7**	**5**	**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**
Poultry	**131**	**128**	**129**	**129**	**127**	**128**	**129**	**132**	**136**	**136**	**137**	**141**	**142**
Hens >1 yr.	*73*	*69*	*66*	*64*	*64*	*63*	*65*	*67*	*69*	*69*	*70*	*71*	[b]
Total Pullets	*25*	*22*	*22*	*24*	*23*	*23*	*24*	*24*	*27*	*26*	*26*	*28*	[b]
Chickens	*4*	*4*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	[b]
Broilers	*19*	*23*	*31*	*31*	*31*	*32*	*31*	*31*	*32*	*32*	*32*	*33*	[b]
Turkeys	*10*	*9*	*7*	*6*	*6*	*6*	*6*	*6*	*6*	*6*	*6*	*6*	[b]
Horses	**9**	**11**	**12**	**10**	**10**	**10**	**9**	**8**	**8**	**8**	**7**	**7**	**7**
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.

[b] Disaggregated poultry values (e.g., Broilers, Turkeys, etc.) have not been estimated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

Table A-179: Total (Direct and Indirect) Nitrous Oxide Emissions from Livestock Manure Management (kt)[a]

Animal Type	1990	1995	2005	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Dairy Cattle	**17.7**	**18.2**	**18.4**	**19.0**	**19.3**	**19.5**	**19.4**	**19.6**	**20.1**	**20.3**	**20.4**	**20.6**	**20.3**
Dairy Cows	*10.6*	*10.7*	*10.5*	*10.7*	*10.9*	*11.1*	*11.1*	*11.2*	*11.4*	*11.5*	*11.6*	*11.8*	*11.7*
Dairy Heifer	*7.1*	*7.5*	*7.8*	*8.3*	*8.4*	*8.5*	*8.3*	*8.4*	*8.7*	*8.8*	*8.8*	*8.8*	*8.7*
Dairy Calves	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Swine	**4.0**	**4.5**	**5.5**	**5.8**	**5.9**	**6.0**	**6.0**	**5.8**	**6.2**	**6.3**	**6.6**	**6.7**	**7.0**
Market Swine	*3.0*	*3.5*	4.6	5.1	5.2	5.2	5.2	5.0	5.4	5.6	5.7	5.9	*6.1*
Market <50 lbs.	*0.6*	*0.6*	*0.9*	*0.7*	*0.8*	*0.8*	*0.7*	*0.7*	*0.8*	*0.8*	*0.8*	*0.8*	*0.9*
Market 50-119 lbs.	*0.6*	*0.7*	*0.9*	*1.1*	*1.2*	*1.2*	*1.2*	*1.1*	*1.2*	*1.2*	*1.3*	*1.3*	*1.4*
Market 120-179 lbs.	*0.9*	*1.0*	*1.3*	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*	*1.6*	*1.6*	*1.7*	*1.7*	*1.8*
Market >180 lbs.	*0.9*	*1.1*	*1.5*	*1.7*	*1.8*	*1.8*	*1.8*	*1.7*	*1.8*	*1.9*	*2.0*	*2.0*	*2.1*
Breeding Swine	*1.0*	*1.1*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*
Beef Cattle	**19.8**	**21.8**	**24.0**	**25.3**	**25.9**	**25.8**	**26.0**	**26.0**	**25.8**	**27.2**	**28.7**	**31.0**	**31.5**
Feedlot Steers	*13.4*	*14.4*	*15.5*	*16.6*	*16.9*	*16.7*	*17.0*	*17.3*	*17.3*	*18.4*	*19.3*	*20.8*	*21.2*
Feedlot Heifers	*6.4*	*7.4*	*8.5*	*8.7*	*9.1*	*9.0*	*9.0*	*8.8*	*8.5*	*8.8*	*9.4*	*10.1*	*10.3*
Sheep	**0.4**	**0.7**	**1.2**	**1.1**	**1.1**	**1.1**	**1.1**	**1.0**	**1.0**	**1.0**	**1.0**	**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**
Poultry	**4.7**	**5.1**	**5.4**	**5.2**	**5.2**	**5.3**	**5.2**	**5.2**	**5.2**	**5.4**	**5.5**	**5.6**	**5.6**
Hens >1 yr.	*1.0*	*1.0*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.4*	*1.3*	*1.4*	*1.4*	*1.5*	*[b]*
Total Pullets	*0.3*	*0.3*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.5*	*[b]*
Chickens	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*[b]*
Broilers	*2.2*	*2.7*	*3.0*	*2.8*	*2.8*	*2.9*	*2.7*	*2.7*	*2.8*	*2.8*	*2.9*	*2.9*	*[b]*
Turkeys	*1.2*	*1.1*	*0.8*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*[b]*
Horses	**0.3**	**0.4**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**
Mules and Asses	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
American Bison	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**

Note: American bison are maintained entirely on pasture, range, and paddock. Emissions from manure deposited on pasture are included in the Agricultural Soils Management sector.

+ Does not exceed 0.05 kt.

NA (Not Applicable)

[a] Disaggregated poultry values (e.g., Broilers, Turkeys, etc.) have not been estimated for the current (1990 through 2019) Inventory. It will be updated for the next (1990 through 2020) Inventory submission.

Table A-180: Methane Emissions by State from Livestock Manure Management for 2019 (kt)[a,b]

State	Beef Cattle[b]	Dairy Cattle[b]	Swine[b]	Poultry[b]	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Alabama	2.5970	0.6539	0.9431	14.2777	0.0090	0.0190	0.1453	0.0126	0.0004	18.6580
Alaska	0.0190	0.0083	0.0058	0.3928	0.0060	0.0002	0.0030	+	0.0033	0.4385
Arizona	1.8199	22.8236	2.9344	1.2735	0.0875	0.0219	0.2331	0.0031	0.0003	29.1973
Arkansas	3.4941	0.5077	2.1049	5.4465	0.0090	0.0133	0.1306	0.0087	0.0005	11.7153
California	5.0833	329.5456	1.5365	3.8795	0.3991	0.0492	0.2819	0.0065	0.0046	340.7861
Colorado	4.9474	17.0556	6.7462	4.4197	0.2077	0.0128	0.1961	0.0045	0.0248	33.6149
Connecticut	0.0156	2.6040	0.0128	0.1598	0.0038	0.0014	0.0210	0.0007	0.0008	2.8199
Delaware	0.0082	0.7016	0.0623	1.1306	0.0060	0.0004	0.0078	0.0001	0.0003	1.9173
Florida	3.2825	16.7442	0.1560	5.6139	0.0090	0.0235	0.2618	0.0124	0.0002	26.1036
Georgia	1.9183	11.5361	1.1291	22.8182	0.0090	0.0260	0.1484	0.0120	0.0004	37.5974
Hawaii	0.3126	0.4541	0.1380	0.5880	0.0090	0.0063	0.0137	0.0004	0.0003	1.5224
Idaho	2.2426	95.8068	0.2125	1.0905	0.1097	0.0075	0.0947	0.0023	0.0479	99.6146
Illinois	1.6164	11.8024	63.0469	0.5847	0.0257	0.0092	0.0817	0.0033	0.0013	77.1717
Indiana	0.8167	18.5810	50.6376	1.8749	0.0266	0.0104	0.1529	0.0034	0.0013	72.1048
Iowa	5.6496	33.8749	228.1373	2.4088	0.0770	0.0215	0.1002	0.0027	0.0046	270.2766
Kansas	10.3704	31.1596	37.0565	0.1043	0.0313	0.0125	0.1014	0.0032	0.0103	78.8494
Kentucky	2.6600	5.2184	4.4147	1.8824	0.0271	0.0146	0.2377	0.0093	0.0040	14.4682
Louisiana	1.6747	1.1009	0.0546	2.5533	0.0090	0.0070	0.1253	0.0073	0.0002	5.5324
Maine	0.0351	3.3247	0.0120	0.1520	0.0038	0.0014	0.0162	0.0003	0.0005	3.5459
Maryland	0.1417	5.6168	0.1724	1.4430	0.0060	0.0036	0.0566	0.0014	0.0001	7.4416
Massachusetts	0.0198	0.5108	0.0348	0.0388	0.0038	0.0018	0.0277	0.0008	+	0.6384
Michigan	0.7107	64.6416	12.4077	1.3205	0.0373	0.0074	0.1227	0.0030	0.0054	79.2562
Minnesota	2.0272	49.4142	74.2930	1.6461	0.0607	0.0091	0.0887	0.0025	0.0053	127.5468
Mississippi	1.8258	0.7213	10.4619	10.7866	0.0090	0.0119	0.1141	0.0095	0.0006	23.9406
Missouri	5.3067	8.0597	53.0807	2.0319	0.0467	0.0177	0.1635	0.0084	0.0019	68.7172
Montana	4.6164	1.5076	1.4068	0.8241	0.1050	0.0038	0.1547	0.0027	0.0444	8.6655
Nebraska	11.5142	11.3358	46.0411	0.7482	0.0373	0.0074	0.0938	0.0017	0.0540	69.8336
Nevada	0.6500	6.2466	0.0941	0.0643	0.0285	0.0029	0.0257	0.0004	+	7.1125
New Hampshire	0.0143	1.3386	0.0139	0.1540	0.0038	0.0010	0.0136	0.0003	0.0006	1.5402
New Jersey	0.0217	0.6247	0.0508	0.1629	0.0060	0.0028	0.0465	0.0010	0.0002	0.9168
New Mexico	1.4516	38.8152	0.0086	1.2190	0.0448	0.0089	0.0865	0.0018	0.0108	41.6472
New York	0.4138	88.9549	0.3207	0.7945	0.0397	0.0073	0.1327	0.0023	0.0022	90.6682
North Carolina	1.4282	5.7061	175.1429	16.4504	0.0189	0.0209	0.1491	0.0125	0.0007	198.9297
North Dakota	2.5934	2.3633	1.2216	0.0996	0.0327	0.0017	0.0542	0.0007	0.0235	6.3907
Ohio	1.1691	33.2220	31.2699	1.7210	0.0555	0.0152	0.1936	0.0059	0.0019	67.6542

State	Beef Cattle[b]	Dairy Cattle[b]	Swine[b]	Poultry[b]	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Oklahoma	6.5282	3.6825	45.9594	4.3495	0.0378	0.0366	0.3681	0.0187	0.0060	60.9866
Oregon	1.8615	10.1657	0.0623	1.1271	0.0770	0.0119	0.1295	0.0030	0.0044	13.4425
Pennsylvania	0.8386	48.6026	13.5409	1.8015	0.0448	0.0132	0.1693	0.0073	0.0024	65.0207
Rhode Island	0.0040	0.0592	0.0072	0.1602	0.0038	0.0002	0.0039	0.0001	+	0.2387
South Carolina	0.6475	1.8395	4.0787	5.5800	0.0090	0.0153	0.1243	0.0069	0.0002	12.3014
South Dakota	5.3934	20.7760	18.6498	0.2778	0.1167	0.0045	0.1021	0.0015	0.0545	45.3763
Tennessee	3.5044	4.0683	3.8974	0.9312	0.0322	0.0369	0.2632	0.0210	0.0010	12.7556
Texas	26.7301	62.5412	20.1568	7.8725	0.5251	0.3090	0.9836	0.0973	0.0238	119.2393
Utah	1.0865	9.0730	5.0870	4.2658	0.1284	0.0051	0.1068	0.0013	0.0023	19.7560
Vermont	0.0485	12.9769	0.0127	0.0390	0.0038	0.0024	0.0163	0.0002	0.0003	13.1002
Virginia	1.7166	8.6173	5.6098	1.8196	0.0350	0.0121	0.1266	0.0059	0.0013	17.9442
Washington	1.2747	41.8214	0.0988	1.5168	0.0210	0.0074	0.1039	0.0024	0.0022	44.8485
West Virginia	0.5443	0.6030	0.0104	0.5523	0.0163	0.0060	0.0472	0.0028	0.0002	1.7825
Wisconsin	1.4987	136.4337	2.7568	0.6653	0.0350	0.0269	0.1428	0.0032	0.0116	141.5740
Wyoming	2.3194	0.9227	0.5007	1.0652	0.1610	0.0038	0.1081	0.0024	0.0217	5.1050

+ 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] Disaggregated animal type (E.g., Beef on Feedlots or Dairy Heifer animal types) methane emissions were not estimated by state for the current (1990 through 2019) Inventory. Disaggregated animal types will be estimated for the next (1990 through 2020) Inventory submission.

Table A-181: Total (Direct and Indirect) Nitrous Oxide Emissions by State from Livestock Manure Management for 2019 (kt)[a]

	Beef Cattle[a]	Dairy Cow	Dairy Heifer	Swine[a]	Poultry[a]	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Alabama	0.0131	0.0042	0.0036	0.0050	0.4390	0.0049	0.0015	0.0050	0.0004	NA	0.4767
Alaska	0.0002	0.0002	0.0002	0.0001	0.0088	0.0016	+	0.0002	+	NA	0.0112
Arizona	0.6041	0.3673	0.2451	0.0150	0.0092	0.0137	0.0017	0.0080	0.0001	NA	1.2642
Arkansas	0.0270	0.0034	0.0020	0.0125	0.5371	0.0042	0.0011	0.0045	0.0003	NA	0.5921
California	1.0464	2.4317	1.5716	0.0098	0.1223	0.0705	0.0039	0.0097	0.0002	NA	5.2661
Colorado	2.2211	0.2955	0.2273	0.0803	0.0289	0.0487	0.0015	0.0101	0.0002	NA	2.9136
Connecticut	0.0005	0.0201	0.0118	0.0001	0.0085	0.0031	0.0002	0.0011	+	NA	0.0453
Delaware	0.0004	0.0051	0.0027	0.0004	0.0941	0.0049	+	0.0004	+	NA	0.1080
Florida	0.0088	0.0738	0.0507	0.0007	0.0599	0.0049	0.0019	0.0090	0.0004	NA	0.2101
Georgia	0.0125	0.0537	0.0300	0.0065	0.5695	0.0049	0.0021	0.0051	0.0004	NA	0.6847
Hawaii	0.0021	0.0030	0.0023	0.0006	0.0088	0.0016	0.0005	0.0005	+	NA	0.0194
Idaho	0.6321	0.8598	0.7097	0.0025	0.0092	0.0257	0.0009	0.0049	0.0001	NA	2.2449

Illinois	0.6103	0.0919	0.1053	0.5020	0.0464	0.0179	0.0011	0.0042	0.0002	NA	1.3793
Indiana	0.2652	0.1924	0.1469	0.3908	0.2384	0.0186	0.0012	0.0079	0.0002	NA	1.2617
Iowa	2.8060	0.2304	0.2621	2.1552	0.3172	0.0538	0.0025	0.0052	0.0001	NA	5.8325
Kansas	5.4547	0.1609	0.2134	0.2194	0.0084	0.0218	0.0015	0.0052	0.0002	NA	6.0856
Kentucky	0.0428	0.0355	0.0233	0.0277	0.1330	0.0220	0.0017	0.0122	0.0005	NA	0.2988
Louisiana	0.0068	0.0067	0.0025	0.0003	0.0332	0.0042	0.0006	0.0043	0.0003	NA	0.0587
Maine	0.0010	0.0297	0.0175	0.0001	0.0085	0.0031	0.0002	0.0008	+	NA	0.0610
Maryland	0.0216	0.0445	0.0344	0.0013	0.1118	0.0049	0.0004	0.0029	0.0001	NA	0.2220
Massachusetts	0.0005	0.0098	0.0081	0.0003	0.0033	0.0031	0.0002	0.0014	+	NA	0.0267
Michigan	0.3592	0.5314	0.3579	0.1164	0.1058	0.0261	0.0009	0.0063	0.0002	NA	1.5041
Minnesota	0.9110	0.4930	0.5771	0.7380	0.1938	0.0424	0.0011	0.0046	0.0001	NA	2.9611
Mississippi	0.0112	0.0052	0.0040	0.0566	0.2868	0.0049	0.0009	0.0039	0.0003	NA	0.3741
Missouri	0.2574	0.0697	0.0811	0.3173	0.2178	0.0326	0.0021	0.0084	0.0004	NA	0.9868
Montana	0.1097	0.0148	0.0194	0.0180	0.0078	0.0246	0.0004	0.0080	0.0001	NA	0.2029
Nebraska	5.9232	0.0659	0.0524	0.3281	0.0585	0.0261	0.0009	0.0048	0.0001	NA	6.4601
Nevada	0.0066	0.0320	0.0253	0.0007	0.0084	0.0067	0.0003	0.0013	+	NA	0.0814
New Hampshire	0.0004	0.0131	0.0071	0.0001	0.0085	0.0031	0.0001	0.0007	+	NA	0.0332
New Jersey	0.0005	0.0056	0.0042	0.0004	0.0085	0.0049	0.0003	0.0024	0.0001	NA	0.0269
New Mexico	0.0309	0.6138	0.2303	0.0001	0.0092	0.0105	0.0011	0.0045	0.0001	NA	0.9004
New York	0.0460	0.6766	0.4145	0.0030	0.0457	0.0322	0.0009	0.0068	0.0001	NA	1.2258
North Carolina	0.0100	0.0296	0.0160	0.9120	0.4671	0.0102	0.0017	0.0051	0.0004	NA	1.4521
North Dakota	0.1220	0.0166	0.0173	0.0134	0.0084	0.0228	0.0002	0.0028	+	NA	0.2036
Ohio	0.3633	0.2603	0.2196	0.2584	0.2130	0.0448	0.0018	0.0100	0.0003	NA	1.3715
Oklahoma	0.7220	0.0539	0.0434	0.2135	0.0854	0.0176	0.0029	0.0126	0.0007	NA	1.1520
Oregon	0.1995	0.1547	0.1209	0.0005	0.0329	0.0204	0.0014	0.0067	0.0002	NA	0.5371
Pennsylvania	0.2231	0.4610	0.3403	0.1241	0.2096	0.0363	0.0016	0.0087	0.0004	NA	1.4052
Rhode Island	0.0001	0.0006	0.0005	0.0001	0.0085	0.0031	+	0.0002	+	NA	0.0131
South Carolina	0.0030	0.0092	0.0051	0.0232	0.1039	0.0049	0.0012	0.0043	0.0002	NA	0.1551
South Dakota	0.9360	0.1236	0.0914	0.1651	0.0250	0.0815	0.0005	0.0053	0.0001	NA	1.4284
Tennessee	0.0344	0.0254	0.0220	0.0224	0.0709	0.0174	0.0029	0.0090	0.0007	NA	0.2051
Texas	5.7874	0.8862	0.5554	0.1188	0.3261	0.0821	0.0244	0.0338	0.0035	NA	7.8178
Utah	0.0512	0.1580	0.1244	0.0580	0.0269	0.0301	0.0006	0.0055	0.0001	NA	0.4548
Vermont	0.0015	0.1335	0.0664	0.0001	0.0034	0.0031	0.0003	0.0008	+	NA	0.2092
Virginia	0.0491	0.0567	0.0252	0.0338	0.1555	0.0284	0.0014	0.0065	0.0003	NA	0.3569
Washington	0.4604	0.3785	0.2331	0.0011	0.0516	0.0056	0.0009	0.0054	0.0001	NA	1.1366
West Virginia	0.0096	0.0062	0.0047	0.0001	0.0434	0.0133	0.0007	0.0024	0.0001	NA	0.0805
Wisconsin	0.6472	1.4557	1.3512	0.0299	0.0530	0.0244	0.0032	0.0074	0.0002	NA	3.5722
Wyoming	0.1759	0.0064	0.0056	0.0073	0.0092	0.0378	0.0004	0.0056	0.0001	NA	0.2483

+ Does not exceed 0.00005 kt.

References

Anderson, S. (2000) Personal Communication. Steve Anderson, Agricultural Statistician, National Agriculture Statistics Service, U.S. Department of Agriculture and Lee-Ann Tracy, ERG. Washington, D.C. May 31, 2000.

ASAE (1998) *ASAE Standards 1998, 45th Edition*. American Society of Agricultural Engineers. St. Joseph, MI.Bryant, M.P., V.H. Varel, R.A. Frobish, and H.R. Isaacson (1976) In H.G. Schlegel (ed.); *Seminar on Microbial Energy Conversion*. E. Goltz KG. Göttingen, Germany.

Bush, E. (1998) Personal communication with Eric Bush, Centers for Epidemiology and Animal Health , U.S. Department of Agriculture regarding *National Animal Health Monitoring System's (NAHMS) Swine '95 Study.*

Deal, P. (2000) Personal Communication. Peter B. Deal, Rangeland Management Specialist, Florida Natural Resource Conservation Service and Lee-Ann Tracy, ERG. June 21, 2000.

EPA (2019) AgSTAR Anaerobic Digester Database. Available online at: < https://www.epa.gov/agstar/livestock-anaerobic-digester-database>, accessed July 2019.

EPA (2008) *Climate Leaders Greenhouse Gas Inventory Protocol Offset Project Methodology for Project Type Managing Manure with Biogas Recovery Systems*. U.S. Environmental Protection Agency. Available online at: <http://www.epa.gov/climateleaders/documents/resources/ClimateLeaders_DraftManureOffsetProtocol.pdf>.

EPA (2005) *National Emission Inventory—Ammonia Emissions from Animal Agricultural Operations, Revised Draft Report*. U.S. Environmental Protection Agency. Washington, D.C. April 22, 2005. Available online at: <ftp://ftp.epa.gov/EmisInventory/2002finalnei/documentation/nonpoint/nh3inventory_draft_042205.pdf>. Retrieved August 2007.

EPA (2002a) *Development Document for the Final Revisions to the National Pollutant Discharge Elimination System (NPDES) Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations (CAFOS).* U.S. Environmental Protection Agency. EPA-821-R-03-001. December 2002.

EPA (2002b) *Cost Methodology for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations*. U.S. Environmental Protection Agency. EPA-821-R-03-004. December 2002.

EPA (1992) *Global Methane Emissions from Livestock and Poultry Manure*, Office of Air and Radiation, U.S. Environmental Protection Agency. February 1992.

ERG (2019) "Incorporation of USDA 2016 ARMS Dairy Data into the Manure Management Greenhouse Gas Inventory." Memorandum to USDA OCE and EPA from ERG. December 2019.

ERG (2018) "Incorporation of USDA 2009 ARMS Swine Data into the Manure Management Greenhouse Gas Inventory." Memorandum to USDA OCE and EPA from ERG. November 2018.

ERG (2010a) "Typical Animal Mass Values for Inventory Swine Categories." Memorandum to EPA from ERG. July 19, 2010.

ERG (2010b) Telecon with William Boyd of USDA NRCS and Cortney Itle of ERG Concerning Updated VS and Nex Rates. August 8, 2010.

ERG (2010c) "Updating Current Inventory Manure Characteristics new USDA Agricultural Waste Management Field Handbook Values." Memorandum to EPA from ERG. August 13, 2010.

ERG (2008) "Methodology for Improving Methane Emissions Estimates and Emission Reductions from Anaerobic Digestion System for the 1990-2007 Greenhouse Gas Inventory for Manure Management." Memorandum to EPA from ERG. August 18, 2008.

ERG (2003a) "Methodology for Estimating Uncertainty for Manure Management Greenhouse Gas Inventory." Contract No. GS-10F-0036, Task Order 005. Memorandum to EPA from ERG, Lexington, MA. September 26, 2003.

ERG (2003b) "Changes to Beef Calves and Beef Cows Typical Animal Mass in the Manure Management Greenhouse Gas Inventory." Memorandum to EPA from ERG, October 7, 2003.

ERG (2001) Summary of development of MDP Factor for methane conversion factor calculations. ERG, Lexington, MA. September 2001.

ERG (2000a) *Calculations: Percent Distribution of Manure for Waste Management Systems.* ERG, Lexington, MA. August 2000.

ERG (2000b) *Discussion of Methodology for Estimating Animal Waste Characteristics* (Summary of B_0 Literature Review). ERG, Lexington, MA. June 2000.

Garrett, W.N. and D.E. Johnson (1983) "Nutritional energetics of ruminants." *Journal of Animal Science*, 57(suppl.2):478-497.

Groffman, P.M., R. Brumme, K. Butterbach-Bahl, K.E. Dobbie, A.R. Mosier, D. Ojima, H. Papen, W.J. Parton, K.A. Smith, and C. Wagner-Riddle (2000) "Evaluating annual nitrous oxide fluxes at the ecosystem scale." *Global Biogeochemcial Cycles,* 14(4):1061-1070.

Hashimoto, A.G. (1984) "Methane from Swine Manure: Effect of Temperature and Influent Substrate Composition on Kinetic Parameter (k)." *Agricultural Wastes*, 9:299-308.

Hashimoto, A.G., V.H. Varel, and Y.R. Chen (1981) "Ultimate Methane Yield from Beef Cattle Manure; Effect of Temperature, Ration Constituents, Antibiotics and Manure Age." *Agricultural Wastes*, 3:241-256.

Hill, D.T. (1984) "Methane Productivity of the Major Animal Types." *Transactions of the ASAE*, 27(2):530-540.

Hill, D.T. (1982) "Design of Digestion Systems for Maximum Methane Production." *Transactions of the ASAE*, 25(1):226-230.

IPCC (2018) *10th Corrigenda for the 2006 IPCC Guidelines*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. Available online at: <https://www.ipcc-nggip.iges.or.jp/public/2006gl/corrigenda10.html>.

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.

Johnson, D. (2000) Personal Communication. Dan Johnson, State Water Management Engineer, California Natural Resource Conservation Service and Lee-Ann Tracy, ERG. June 23, 2000.

Lange, J. (2000) Personal Communication. John Lange, Agricultural Statistician, U.S. Department of Agriculture, National Agriculture Statistics Service and Lee-Ann Tracy, ERG. Washington, D.C. May 8, 2000.

Meagher, M. (1986). Bison. Mammalian Species. 266: 1-8.

Miller, P. (2000) Personal Communication. Paul Miller, Iowa Natural Resource Conservation Service and Lee-Ann Tracy, ERG. June 12, 2000.

Milton, B. (2000) Personal Communication. Bob Milton, Chief of Livestock Branch, U.S. Department of Agriculture, National Agriculture Statistics Service and Lee-Ann Tracy, ERG. May 1, 2000.

Moffroid, K. and D. Pape. (2014) *1990-2013 Volatile Solids and Nitrogen Excretion Rates*. Dataset to EPA from ICF International. August 2014.

Morris, G.R. (1976) *Anaerobic Fermentation of Animal Wastes: A Kinetic and Empirical Design Fermentation.* M.S. Thesis. Cornell University.

National Bison Association (1999) Total Bison Population—1999. Report provided during personal email communication with Dave Carter, Executive Director, National Bison Association July 19, 2011.

NOAA (2019) *National Climate Data Center (NCDC).* Available online at: <ftp://ftp.ncdc.noaa.gov/pub/data/cirs/climdiv/> (for all states except Alaska and Hawaii) and <ftp://ftp.ncdc.noaa.gov/pub/data/gsod/2018/> (for Alaska and Hawaii). July 2019.

Ott, S.L. (2000) *Dairy '96 Study.* Stephen L. Ott, Animal and Plant Health Inspection Service, U.S. Department of Agriculture. June 19, 2000.

Poe, G., N. Bills, B. Bellows, P. Crosscombe, R. Koelsch, M. Kreher, and P. Wright (1999) *Staff Paper Documenting the Status of Dairy Manure Management in New York: Current Practices and Willingness to Participate in Voluntary Programs*. Department of Agricultural, Resource, and Managerial Economics; Cornell University, Ithaca, New York, September.

Safley, L.M., Jr. (2000) Personal Communication. Deb Bartram, ERG and L.M. Safley, President, Agri-Waste Technology. June and October 2000.

Safley, L.M., Jr. and P.W. Westerman (1990) "Psychrophilic anaerobic digestion of animal manure: proposed design methodology." *Biological Wastes*, 34:133-148.

Stettler, D. (2000) Personal Communication. Don Stettler, Environmental Engineer, National Climate Center, Oregon Natural Resource Conservation Service and Lee-Ann Tracy, ERG. June 27, 2000.

Sweeten, J. (2000) Personal Communication. John Sweeten, Texas A&M University and Indra Mitra, ERG. June 2000.

UEP (1999) *Voluntary Survey Results—Estimated Percentage Participation/Activity*. Caged Layer Environmental Management Practices, Industry data submissions for EPA profile development, United Egg Producers and National Chicken Council. Received from John Thorne, Capitolink. June 2000.

USDA (2019a) *Quick Stats: Agricultural Statistics Database*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: <http://quickstats.nass.usda.gov/>.

USDA (2019b) *Chicken and Eggs 2018 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 2019. Available online at: < https://www.nass.usda.gov/Publications/>.

USDA (2019c) *Poultry - Production and Value 2018 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2019. Available online at: < https://www.nass.usda.gov/Publications/>.

USDA (2019d) *1987, 1992, 1997, 2002, 2007, 2012, and 2017 Census of Agriculture*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: < https://www.nass.usda.gov/AgCensus/index.php>. May 2019.

USDA (2018a) *Chicken and Eggs 2017 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2018. Available online at: < https://www.nass.usda.gov/Publications/>.

USDA (2018b) *Poultry - Production and Value 2017 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2018. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2017a) *Chicken and Eggs 2016 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2017. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2017b) *Poultry - Production and Value 2016 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2017. Available online at: < https://www.nass.usda.gov/Publications/ >.

USDA (2016a) *Chicken and Eggs 2015 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. July 2016. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2016b) *Poultry - Production and Value 2015 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. July 2016. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2015a) *Chicken and Eggs 2014 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2015. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2015b) *Poultry - Production and Value 2014 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2015. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2014a) *Chicken and Eggs 2013 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2014. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2014b) *Poultry - Production and Value 2013 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2014. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2013a) *Chicken and Eggs 2012 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2013. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2013b) *Poultry - Production and Value 2012 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2013. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2012a) *Chicken and Eggs 2011 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2012. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2012b) *Poultry - Production and Value 2011 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2012. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2011a) *Chicken and Eggs 2010 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2011. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2011b) *Poultry - Production and Value 2010 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2011. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2010a) *Chicken and Eggs 2009 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2010. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2010b) *Poultry - Production and Value 2009 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2010. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2009a) *Chicken and Eggs 2008 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2009. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2009b) *Poultry - Production and Value 2008 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2009. Available online at: <https://www.nass.usda.gov/Publications/>.

USDA (2009c) *Chicken and Eggs – Final Estimates 2003-2007*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 2009. Available online at: < https://downloads.usda.library.cornell.edu/usda-esmis/files/8623hx75j/x633f384z/5m60qv97x/chikneggest_Chickens-and-Eggs-Final-Estimates-2003-07.pdf

USDA (2009d) *Poultry Production and Value—Final Estimates 2003-2007*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. May 2009. Available online at: <http://usda.mannlib.cornell.edu/usda/nass/SB994/sb1028.pdf>.

USDA (2008) *Agricultural Waste Management Field Handbook*, *National Engineering Handbook (NEH)*, Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture.

USDA (2004a) *Chicken and Eggs—Final Estimates 1998-2003*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2004. Available online at: <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (2004b) *Poultry Production and Value—Final Estimates 1998-2002*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2004. Available online at: <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1999) *Poultry Production and Value—Final Estimates 1994-97*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 1999. Available online at: <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1998) *Chicken and Eggs—Final Estimates 1994-97*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. December 1998. Available online at: <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1996) *Agricultural Waste Management Field Handbook*, *National Engineering Handbook (NEH)*, Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture. July 1996.

USDA (1995a) *Poultry Production and Value—Final Estimates 1988-1993*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 1995. Available online at: <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1995b) *Chicken and Eggs—Final Estimates 1988-1993*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. December 1995. Available online at: <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1994) S*heep and Goats—Final Estimates 1989-1993*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. January 31, 1994. Available online at: <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA, APHIS (2003) *Sheep 2001, Part I: Reference of Sheep Management in the United States, 2001* and *Part IV:Baseline Reference of 2001 Sheep Feedlot Health and Management*. USDA-APHIS-VS. Fort Collins, CO. #N356.0702. < https://www.aphis.usda.gov/animal_health/nahms/sheep/downloads/sheep01/Sheep01_dr_PartI.pdf> and < https://www.aphis.usda.gov/animal_health/nahms/sheep/downloads/sheep01/Sheep01_dr_PartIV.pdf>.

USDA, APHIS (2000) *Layers '99—Part II: References of 1999 Table Egg Layer Management in the U.S.* USDA-APHIS-VS. Fort Collins, CO. <http://www.aphis.usda.gov/animal_health/nahms/poultry/downloads/layers99/Layers99_dr_PartII.pdf>.

USDA, APHIS (1996) *Swine '95: Grower/Finisher Part II: Reference of 1995 U.S. Grower/Finisher Health & Management Practices.* USDA-APHIS-VS. Fort Collins, CO. <http://www.aphis.usda.gov/animal_health/nahms/swine/downloads/swine95/Swine95_dr_PartII.pdf>.

Wright, P. (2000) Personal Communication. Lee-Ann Tracy, ERG and Peter Wright, Cornell University, College of Agriculture and Life Sciences. June 23, 2000.

3.12. Methodologies for Estimating Soil Organic C Stock Changes, Soil N_2O Emissions, and CH_4 Emissions and from Agricultural Lands (Cropland and Grassland)

This annex provides a detailed description of Tier 1, 2, and 3 methods that are used to estimate 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 associated with volatilization, leaching, and runoff of N from croplands and grasslands; and CH_4 emissions from rice cultivation.

Nitrous oxide (N_2O) is produced in soils through the microbial processes of nitrification and denitrification.[104] 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; Paustian et al. 2016). 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 crop and forage production and microbial decomposition (Paustian et al. 1997, Paustian et al. 2016). CH_4 emissions from rice cultivation occur under flooded conditions through the process of methanogenesis, and is influenced by water management practices, organic amendments and cultivar choice (Sanchis et al. 2014). This annex provides the underlying methodologies for these three emission sources because there is considerable overlap in the methods with the majority of emissions are estimated using the DayCent ecosystem simulation model.

A combination of Tier 1, 2, and 3 approaches are used to estimate soil organic C stock changes, direct and indirect soil N_2O emissions and CH_4 emissions from rice cultivation in agricultural croplands and grasslands. The methodologies used to estimate soil organic C stock changes include:

1) A Tier 3 method using the DayCent ecosystem model to estimate soil organic C stock changes in mineral soils on non-federal lands that have less than 35 percent coarse fragments by volume and are used to produce alfalfa hay, barley, corn, cotton, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, 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) Tier 2 methods with country-specific 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 not simulated with DayCent;
3) Tier 2 methods with country-specific factors for estimating mineral soil organic C stock changes on federal lands;
4) Tier 2 methods with country-specific factors for estimating losses of C from organic soils that are drained for agricultural production; and
5) Tier 2 methods for estimating additional changes in mineral soil organic C stocks due to additions of biosolids (i.e., treated sewage sludge) to soils.

The methodologies used to estimate soil N_2O emissions include:

1) A Tier 3 method using the DayCent ecosystem 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, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco 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 1 and 3 methods to estimate indirect N_2O emissions associated with management of cropland and grassland simulated with DayCent;

[104] 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 nitrification and denitrification.

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; crops that are rotated with the crops that are not simulated with DayCent; Pasture/Range/Paddock (PRP) manure N deposited on federal grasslands; and land application of biosolids (i.e., treated sewage sludge) to soils; 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 ecosystem 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 crops that are simulated with DayCent, including alfalfa hay, barley, corn, cotton, grass hay, grass-clover hay, oats, peanuts, potatoes, sorghum, soybeans, sugar beets, sunflowers, tobacco, and wheat; 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.

As described above, the Inventory uses a Tier 3 approach to estimate C stock changes, direct soil N_2O emissions, and CH_4 emissions from rice cultivation for most 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 a broad climate region classification for soil organic 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;
4) The legacy effects of past management can be addressed with the Tier 3 approach such as land use change from decades prior to the inventory time period that can have ongoing effects on soil organic C stocks, and the ongoing effects of N fertilization that may continue to stimulate N_2O emissions in years after the application; and
5) 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.

More information is provided about the model structure and evaluation of the Tier 3 method at the end of this Annex (See section Tier 3 Model Description, Parameterization and Evaluation).

Splicing methods are used to fill gaps in the time series for the emission sources and are not described in this annex. Specifically, the splicing methods are applied when there are gaps in the activity data at the end of the time series and the Tier 1, 2 and 3 methods cannot be applied. The splicing methods are described in the main chapters, particularly Box 6-6 in the *Cropland Remaining Cropland* section and Box 5-5 in the Agricultural Soil Management section.

Inventory Compilation Steps

There are five steps involved in this inventory to estimate the following sources: a) soil organic C stock changes for *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland* and *Land Converted to Grassland;* b) direct N_2O emissions from cropland and grassland soils; indirect N_2O emissions from volatilization, leaching, and runoff from croplands and grasslands; and c) CH_4 emissions from rice cultivation. First, the activity data are compiled 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, and CH_4 emissions are

estimated using Tier 1, 2 and 3 methods. In the fifth step, total emissions are calculated by summing all components for soil organic C stock changes, N_2O emissions and CH_4 emissions. The remainder of this annex describes the methods underlying each step.

Step 1: Derive Activity Data

This step describes how the activity data are derived to estimate soil organic C stock changes, direct and indirect N_2O emissions, and CH_4 emissions from rice cultivation. The activity data requirements include: (1) land base and history data, (2) crop-specific mineral N fertilizer rates and timing,[105] (3) crop-specific manure amendment N rates and timing, (4) other N inputs, (5) tillage practices, (6) cover crop management, (7) planting and harvesting dates for crops, (8) irrigation data, (9) Enhanced Vegetation Index (EVI), (10) daily weather data, and (11) edaphic characteristics.[106]

Step 1a: Activity Data for the Agricultural Land Base and Histories

The U.S. Department of Agriculture's 2015 National Resources Inventory (NRI) (USDA-NRCS 2018a) 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.*[107] The NRI program have data available from 1979 through 2015 (USDA-NRCS 2018a). The time series will be extended as new data are released by the USDA NRI program.

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 locations are selected according to a restricted randomization procedure. Each sample location in the survey is assigned an area weight (expansion factor) (Nusser and Goebel 1997). In principle, the expansion factors represent the amount of area with the land use and land use change history that is the same as the survey location. The NRI uses a sampling approach, and therefore there is some uncertainty associated with scaling the survey location data to a region or the country using the expansion factors. In general, the uncertainty declines at larger scales because of a larger sample size, such as states compared to smaller county units. An extensive amount of soils, land-use, and land management data have been collected through the survey (Nusser et al. 1998).[108] Primary sources for data include aerial photography as well as field visits and county office records.

The NRI survey provides crop data for most years between 1979 and 2015, 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 survey 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 survey locations are included in the land base for the agricultural soil organic C and N_2O emissions inventories if they are identified as cropland or grassland[109] between 1990 and 2015 (See Section 6.1 Representation of the U.S. Land Base for more information about areas in each land use and land use change category).[110] NRI survey locations on federal lands are not sampled by the USDA NRI program. The land use at the survey locations in federal lands is determined from the National Land Cover Dataset (NLCD) (Yang et al. 2018), and included in the agricultural land base if the land uses are cropland and/or grassland. The NRI data are harmonized with the Forest Inventory and Analysis Dataset, and in this process, the land use and land use change data are modified to address differences in *Forest Land Remaining Forest*

[105] 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, such as application of enhanced efficiency fertilizers.

[106] Edaphic characteristics include such factors as soil texture and pH.

[107] 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.

[108] In the current Inventory, NRI data only provide land use and management statistics through 2015. More recent data will be incorporated in the future to extend the time series of activity data.

[109] 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).

[110] Land use for 2016 to 2019 is not compiled, but will be updated with a new release of the NRI data.

Land, *Land Converted to Forest Land* and Forest Land converted to other land uses between the two national surveys (See Section 6.1 for more information on the U.S. land representation). Through this process, 524,991 survey locations in this NRI are designated as agricultural land in the conterminous United States and Hawaii.

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 crop management in a specific year are classified as *Cropland Remaining Cropland* if the parcel has been used as cropland for at least 20 years.[111] 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 IPCC (2006). Lands converted into Cropland and Grassland are further subdivided into the specific land use conversions (e.g., *Forest Land Converted to Cropland)*.

The Tier 3 method using the DayCent model is applied to estimate soil organic C stock changes, CH_4, and N_2O emissions for 349,464 NRI survey locations that occur on mineral soils. 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[112] and to estimate CH_4 emissions from rice cultivation (Table A-182).

The land base for the Tier 1 and 2 methods includes 175,527 survey locations, and is comprised of (1) land parcels occurring on organic soils; (2) land parcels that include non-agricultural uses such as forest or settlements 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 and perennial/horticultural crops, 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., lettuce), 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-182: Total Cropland and Grassland Area Estimated with Tier 1/2 and 3 Inventory Approaches (Million Hectares)

	Land Areas (million ha)				
		Mineral		Organic	
Year	Tier 1/2	Tier 3	Total	Tier 1/2	Total[113]
1990	152.22	307.63	459.85	1.39	**461.24**
1991	151.49	307.89	459.37	1.38	**460.75**
1992	150.83	308.07	458.90	1.38	**460.28**
1993	149.84	308.47	458.31	1.38	**459.69**
1994	149.04	308.87	457.91	1.38	**459.29**
1995	147.92	309.28	457.20	1.37	**458.57**
1996	146.90	309.75	456.65	1.36	**458.01**
1997	145.69	310.19	455.88	1.35	**457.23**
1998	144.67	310.63	455.31	1.35	**456.65**
1999	143.71	311.10	454.81	1.35	**456.16**
2000	142.98	311.38	454.36	1.35	**455.71**

[111] NRI points are classified according to land-use history records starting in 1979 when the NRI survey began, and consequently the classifications are based on less than 20 years from 1990 to 1998.

[112] 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 the Tier 1 method is only dependent on the amount of N input to mineral soils and not the actual land area.

[113] The current Inventory includes estimation of greenhouse gas emissions and removals from all privately-owned and federal grasslands and croplands in the conterminous United States and Hawaii, but does not include the croplands and grasslands in Alaska. This leads to a discrepancy between the total area in this table, which is included in the estimation, compared to the total managed land area in Section 6.1 Representation of the U.S. Land Base. See Planned Improvement sections in *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland* and *Land Converted to Grassland* for more information about filling these gaps in the future so that emissions and removals will be estimated for all managed land.

2001	142.49	311.82	454.31	1.34	**455.66**
2002	141.78	312.09	453.87	1.35	**455.22**
2003	141.15	312.00	453.16	1.32	**454.48**
2004	140.65	311.92	452.57	1.34	**453.90**
2005	140.12	311.81	451.93	1.34	**453.27**
2006	139.57	311.77	451.34	1.33	**452.68**
2007	139.04	311.74	450.78	1.32	**452.10**
2008	138.71	311.60	450.31	1.32	**451.63**
2009	138.36	311.54	449.89	1.32	**451.21**
2010	138.05	311.43	449.48	1.32	**450.80**
2011	137.65	311.41	449.06	1.32	**450.38**
2012	137.28	311.33	448.61	1.32	**449.93**
2013	136.99	311.12	448.10	1.32	449.42
2014	136.75	310.79	447.54	1.31	448.86
2015	136.38	310.66	447.04	1.30	448.34

Note: In the current Inventory, NRI data only provide land use and management statistics through 2015. Additional data will be incorporated in the future to extend the time series of the land use data.

NRI survey locations on mineral soils are classified into specific crop categories, continuous pasture/rangeland, and other non-agricultural uses for the Tier 2 inventory analysis for soil organic C (Table A-183). NRI locations 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 crop 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 based on replicate weights that allow for proper variance estimates that correctly account for the complex sampling design. In particular, the variance estimates and resulting PDFs correctly account for spatial or temporal dependencies. For example, dependencies in land use result from the likelihood that current use is correlated with past use. These dependencies occur because as an area of a land use/management category increases, the area of another land use/management category must decline.

Table A-183: 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**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Cropland Systems	**33.47**	**33.18**	**32.87**	**32.36**	**31.86**	**31.39**	**30.96**	**30.49**	**29.69**	**29.17**	**28.78**	**28.44**	**28.13**
Conservation Reserve Program	2.74	3.15	3.08	2.91	2.67	2.59	2.46	2.45	1.96	2.12	1.86	1.99	1.73
High Input Cropping Systems, Full Tillage	2.41	2.21	2.20	2.11	2.28	2.26	2.10	1.99	1.94	1.93	1.97	1.78	1.58
High Input Cropping Systems, Reduced Tillage	0.57	0.50	0.50	0.50	0.54	0.52	0.50	0.48	0.49	0.49	0.50	0.49	0.45
High Input Cropping Systems, No Tillage	0.41	0.37	0.37	0.37	0.38	0.36	0.45	0.43	0.44	0.45	0.45	0.52	0.51
High Input Cropping Systems with Manure, Full Tillage	0.67	0.64	0.61	0.59	0.55	0.52	0.51	0.49	0.47	0.43	0.40	0.34	0.32
High Input Cropping Systems with Manure, Reduced Tillage	0.18	0.17	0.16	0.16	0.16	0.15	0.14	0.14	0.13	0.13	0.12	0.12	0.11

High Input Cropping Systems with Manure, No Tillage	0.22	0.20	0.19	0.19	0.19	0.18	0.17	0.16	0.15	0.15	0.14	0.17	0.17
Medium Input Cropping Systems, Full Tillage	7.03	7.02	6.78	6.57	6.49	6.26	6.32	5.97	5.65	5.47	5.54	4.29	4.03
Medium Input Cropping Systems, Reduced Tillage	1.71	1.66	1.62	1.58	1.58	1.53	1.53	1.49	1.40	1.37	1.42	1.68	1.69
Medium Input Cropping Systems, No Tillage	1.85	1.71	1.68	1.63	1.62	1.60	1.58	1.52	1.45	1.41	1.44	2.33	2.35
Low Input Cropping Systems, Full Tillage	9.46	9.31	9.31	9.34	9.30	9.40	9.14	9.17	9.30	9.13	9.08	8.21	8.25
Low Input Cropping Systems, Reduced Tillage	1.06	1.04	1.04	1.05	1.05	1.07	1.08	1.07	1.11	1.05	1.04	1.11	1.11
Low Input Cropping Systems, No Tillage	0.68	0.73	0.73	0.74	0.73	0.72	0.90	0.90	0.92	0.86	0.89	1.53	1.52
Hay with Legumes or Irrigation	1.67	1.67	1.69	1.64	1.50	1.44	1.35	1.38	1.31	1.25	1.14	1.04	1.20
Hay with Legumes or Irrigation and Manure	0.50	0.49	0.50	0.51	0.48	0.45	0.43	0.47	0.46	0.44	0.41	0.42	0.54
Hay, Unimproved	0.01	0.01	0.02	0.02	0.02	0.02	0.00	0.01	0.07	0.05	0.01	0.03	0.04
Pasture with Legumes or Irrigation in Rotation	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.04	0.03	0.01	0.02	0.02
Pasture with Legumes or Irrigation and Manure, in Rotation	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
Rice	0.04	0.05	0.04	0.04	0.05	0.06	0.05	0.05	0.05	0.05	0.06	0.07	0.08
Perennials	2.24	2.24	2.31	2.36	2.28	2.25	2.24	2.32	2.38	2.37	2.31	2.28	2.42
Grassland Systems	**118.68**	**118.22**	**117.88**	**117.40**	**117.11**	**116.46**	**115.87**	**115.14**	**114.93**	**114.47**	**114.13**	**113.98**	**113.57**
Pasture with Legumes or Irrigation	3.62	3.47	3.28	3.25	3.27	3.14	2.83	2.41	2.51	2.46	2.26	2.17	2.08
Pasture with Legumes or Irrigation and Manure	0.17	0.16	0.15	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.12	0.11	0.11
Rangelands and Unimproved Pasture	82.27	81.87	81.82	81.68	81.42	80.82	79.85	79.64	78.94	78.42	78.83	78.54	79.53
Rangelands and Unimproved Pasture, Moderately Degraded	23.62	23.78	23.91	23.79	23.84	23.95	24.43	24.30	25.08	25.11	24.46	24.70	23.63
Rangelands and Unimproved Pasture, Severely Degraded	9.01	8.93	8.72	8.53	8.43	8.41	8.60	8.65	8.25	8.34	8.46	8.46	8.22
Total	**152.15**	**151.40**	**150.75**	**149.76**	**148.97**	**147.85**	**146.83**	**145.63**	**144.61**	**143.64**	**142.91**	**142.42**	**141.70**

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Land-Use/Management System	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Cropland Systems	**27.88**	**27.55**	**27.39**	**27.16**	**26.99**	**26.83**	**26.62**	**26.51**	**26.33**	**26.29**	**26.24**	**26.16**	**25.96**
Conservation Reserve Program	1.60	1.50	1.52	1.42	1.38	1.30	1.35	1.26	1.89	0.92	1.43	0.90	0.73
High Input Cropping Systems, Full Tillage	1.59	1.59	1.60	1.37	1.34	1.37	1.42	1.44	1.30	1.24	1.18	1.14	1.06
High Input Cropping Systems, Reduced Tillage	0.47	0.47	0.47	0.49	0.49	0.52	0.53	0.53	0.57	0.55	0.52	0.52	0.50
High Input Cropping Systems, No Tillage	0.48	0.50	0.50	0.59	0.61	0.63	0.65	0.63	0.72	0.73	0.71	0.71	0.67

High Input Cropping Systems with Manure, Full Tillage	0.30	0.29	0.29	0.24	0.26	0.27	0.26	0.27	0.25	0.26	0.28	0.27	0.26
High Input Cropping Systems with Manure, Reduced Tillage	0.11	0.11	0.11	0.13	0.14	0.13	0.14	0.14	0.17	0.18	0.19	0.18	0.18
High Input Cropping Systems with Manure, No Tillage	0.18	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.19	0.19	0.20	0.20	0.20
Medium Input Cropping Systems, Full Tillage	3.98	3.99	3.82	3.50	3.58	3.55	3.49	3.49	3.16	3.39	3.19	3.41	3.26
Medium Input Cropping Systems, Reduced Tillage	1.72	1.75	1.71	1.83	1.85	1.85	1.78	1.78	1.87	2.04	1.93	2.10	2.07
Medium Input Cropping Systems, No Tillage	2.41	2.40	2.39	2.53	2.57	2.58	2.49	2.49	2.39	2.77	2.49	2.83	2.79
Low Input Cropping Systems, Full Tillage	8.26	8.11	8.13	7.93	7.83	7.78	7.75	7.72	7.46	7.54	7.52	7.46	7.60
Low Input Cropping Systems, Reduced Tillage	1.06	1.01	1.01	1.08	1.02	1.00	1.00	1.01	1.00	1.04	1.04	0.97	1.01
Low Input Cropping Systems, No Tillage	1.45	1.36	1.38	1.67	1.59	1.56	1.54	1.55	1.39	1.45	1.45	1.34	1.42
Hay with Legumes or Irrigation	1.18	1.16	1.18	1.16	1.14	1.11	1.06	1.02	0.98	0.99	1.02	1.02	1.02
Hay with Legumes or Irrigation and Manure	0.52	0.54	0.50	0.49	0.48	0.47	0.46	0.45	0.43	0.43	0.47	0.47	0.48
Hay, Unimproved	0.04	0.05	0.04	0.02	0.03	0.01	0.02	0.02	0.03	0.02	0.01	0.00	0.00
Pasture with Legumes or Irrigation in Rotation	0.03	0.03	0.03	0.01	0.02	0.02	0.03	0.02	0.01	0.01	0.01	0.00	0.00
Pasture with Legumes or Irrigation and Manure, in Rotation	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rice	0.06	0.06	0.04	0.04	0.04	0.04	0.03	0.04	0.03	0.03	0.03	0.03	0.03
Perennials	2.43	2.46	2.49	2.46	2.44	2.46	2.44	2.47	2.50	2.53	2.55	2.59	2.65
Grassland Systems	**113.20**	**113.04**	**112.67**	**112.34**	**111.96**	**111.80**	**111.65**	**111.45**	**111.22**	**110.90**	**110.66**	**110.50**	**110.29**
Pasture with Legumes or Irrigation	2.01	2.05	1.97	1.91	1.86	1.84	1.85	1.80	1.79	1.71	1.61	1.64	1.59
Pasture with Legumes or Irrigation and Manure	0.11	0.11	0.11	0.10	0.09	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.07
Rangelands and Unimproved Pasture	79.60	78.73	78.47	78.36	78.00	77.90	77.74	77.75	77.73	77.46	77.40	77.04	77.37
Rangelands and Unimproved Pasture, Moderately Degraded	23.19	23.22	23.25	23.15	23.25	23.24	23.25	23.17	23.06	22.89	22.80	22.61	22.51
Rangelands and Unimproved Pasture, Severely Degraded	8.28	8.93	8.87	8.82	8.76	8.74	8.71	8.65	8.57	8.77	8.79	9.14	8.74
Total	**141.08**	**140.59**	**140.05**	**139.50**	**138.95**	**138.63**	**138.27**	**137.96**	**137.55**	**137.19**	**136.90**	**136.66**	**136.25**

Note: In the current Inventory, NRI data only provide land use and management statistics through 2015. Additional data will be incorporated in the future to extend the time series for the land use and management data.

Organic soils are categorized into land-use systems based on drainage (IPCC 2006) (Table A-184). 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. N_2O emissions are assumed to be similar for both drained croplands and grasslands.

Table A-184: 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	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Cold Temperate														
Cultivated Cropland (high drainage)	0.59	0.58	0.59	0.59	0.59	0.59	0.59	0.60	0.60	0.60	0.59	0.59	0.59	0.59
Managed Pasture (low drainage)	0.34	0.34	0.35	0.35	0.35	0.35	0.34	0.34	0.34	0.34	0.34	0.35	0.35	0.35
Undrained	0.04	0.05	0.04	0.04	0.03	0.03	0.04	0.03	0.03	0.03	0.04	0.03	0.03	0.02
Total	**0.97**	**0.97**	**0.98**	**0.98**	**0.98**	**0.98**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.97**	**0.96**	**0.96**
Warm Temperate														
Cultivated Cropland (high drainage)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.16
Managed Pasture (low drainage)	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.09
Undrained	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.00	0.00
Total	**0.25**	**0.25**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.25**	**0.25**	**0.25**	**0.25**
Sub-Tropical														
Cultivated Cropland (high drainage)	0.24	0.24	0.24	0.25	0.25	0.25	0.26	0.26	0.26	0.17	0.17	0.29	0.28	0.28
Managed Pasture (low drainage)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.11	0.10	0.10	0.09
Undrained	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.00	0.01	0.00
Total	**0.37**	**0.37**	**0.37**	**0.37**	**0.37**	**0.38**	**0.38**	**0.38**	**0.38**	**0.38**	**0.38**	**0.39**	**0.39**	**0.37**

IPCC Land-Use Category for Organic Soils	Land Areas (million ha)											
	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cold Temperate												
Cultivated Cropland (high drainage)	0.59	0.59	0.59	0.59	0.59	0.58	0.58	0.58	0.59	0.60	0.60	0.60
Managed Pasture (low drainage)	0.37	0.37	0.37	0.37	0.37	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Undrained	0.02	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.01	0.01
Total	**0.98**	**0.98**	**0.98**	**0.98**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**1.00**
Warm Temperate												
Cultivated Cropland (high drainage)	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Managed Pasture (low drainage)	0.09	0.10	0.09	0.10	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.10
Undrained	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Total	**0.26**	**0.26**	**0.26**	**0.26**	**0.26**	**0.26**	**0.27**	**0.27**	**0.27**	**0.28**	**0.28**	**0.28**
Sub-Tropical												
Cultivated Cropland (high drainage)	0.27	0.27	0.27	0.26	0.26	0.26	0.26	0.26	0.26	0.24	0.26	0.25
Managed Pasture (low drainage)	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Undrained	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.03	0.01	0.01
Total	**0.37**	**0.37**	**0.37**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.36**	**0.35**	**0.36**	**0.35**

Note: In the current Inventory, NRI data only provide land use and management statistics through 2015. Additional data will be incorporated in the future to extend the time series for the land use and management data.

The harvested area for rice cultivation is estimated from the NRI based on survey locations classified as flooded rice (Table A-185). Ratoon crops occur in the Southeastern United States with a second season of rice during the year, including Louisiana (LSU 2015 for years 2000 through 2015) and Texas (TAMU 2015 for years 1993 through 2015), averaging 32 percent and 48 percent of rice acres planted, respectively. Florida also has a large fraction of area with a ratoon crops (45 percent), but ratoon cropping is uncommon in Arkansas occurring on a relatively small fraction of fields estimated at about 1 percent. No data are available for ratoon crops in Missouri or Mississippi, and so the amount of ratooning is assumed similar to Arkansas. Ratoon rice crops are not grown in California.

Table A-185: Total Rice Harvested Area Estimated with Tier 1 and 3 Inventory Approaches (Million Hectares)

	Land Areas (Million Hectares)		
Year	**Tier 1**	**Tier 3**	**Total**
1990	0.21	1.50	1.71
1991	0.21	1.54	1.74
1992	0.22	1.65	1.87
1993	0.22	1.58	1.80
1994	0.23	1.51	1.74
1995	0.21	1.53	1.74
1996	0.22	1.52	1.74
1997	0.20	1.47	1.67
1998	0.25	1.46	1.70
1999	0.38	1.43	1.81
2000	0.42	1.48	1.90
2001	0.24	1.39	1.63
2002	0.23	1.57	1.80
2003	0.21	1.42	1.63
2004	0.21	1.50	1.71
2005	0.21	1.58	1.79
2006	0.17	1.27	1.44
2007	0.18	1.38	1.56
2008	0.15	1.28	1.44
2009	0.21	1.52	1.73
2010	0.20	1.57	1.77
2011	0.17	1.24	1.41
2012	0.22	1.18	1.40
2013	0.16	1.26	1.42
2014	0.24	1.39	1.63
2015	0.17	1.45	1.62

Note: In the current Inventory, NRI data only provide land use and management statistics through 2015. Additional data will be incorporated in the future to extend the time series of the land use and management data.

Step 1b: Obtain Management Activity Data to estimate Soil Organic C Stock Changes, N_2O and CH_4 Emissions from Mineral Soils

The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover cropping management, as well as planting and harvest dates (USDA-NRCS 2018b; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006. Respondents provide detailed information about management practices at the NRI survey locations, such as time of planting and harvest; amount, type and time of fertilization; implement type and timing of soil cultivation events; and type and timing of cover crop planting and termination practices.

These data are combined with other datasets in an imputation analysis that extends the time series from 1980 to 2015. The imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information from several datasets (discussed below); b) use an artificial neural network to determine the likely management practice at a given NRI survey location (Cheng and Titterington 1994); and c) assign management practices from the CEAP survey to the specific NRI locations using a predictive mean matching method that

is adapted to reflect the trending information (Little 1988, van Buuren 2012). The artificial neural network is a machine learning method that approximates nonlinear functions of inputs and searches through a large class of models to impute an initial value for management practices at specific NRI survey locations. The predictive mean matching method identifies the most similar management activity recorded in the CEAP survey that matches the prediction from the artificial neural network. The matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the artificial neural network. The final imputation product includes six complete imputations of the management activity data in order to adequately capture the uncertainty. The sections below provide additional information for each of the management practices.

Synthetic and Manure N Fertilizer Applications: Data on synthetic mineral N fertilizer rates are imputed based on crop-specific fertilizer rates in the USDA-NRCS CEAP product and fertilizer trends based on USDA–Economic Research Service (ERS) data. The ERS crop management data had been collected as part of Cropping Practices Surveys through 1995 (USDA-ERS 1997), and are now compiled as part of Agricultural Resource Management Surveys (ARMS) starting in 1996 (USDA-ERS 2018). In these surveys, data on inorganic N fertilization rates are collected for crops in the high production states and for a subset of low production states. Additional data on fertilization practices are compiled from other sources, particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). These data are used to build a time series of mineral fertilizer application rates for specific crops and states for 1980 to 2015, to the extent that data are available. These data are then used to inform the imputation product in combination with the USDA CEAP survey, as described previously. The donor survey data from CEAP contain both mineral fertilizer rates and manure amendment rates, so that the selection of a donor via predictive mean matching yields the joint imputation of both mineral and manure amendment rates. This approach captures the relationship between mineral fertilization and manure amendment practices for US croplands based directly on the observed patterns in the CEAP survey data.

Fertilizer sales data are used to check and adjust synthetic mineral fertilizer amounts that are simulated with DayCent. The total amount of synthetic fertilizer used on-farms (cropland and grazing land application) has been estimated by the USGS from 1990 through 2012 on a county scale from fertilizer sales data (Brakebill and Gronberg 2017). For 2013 through 2015, county-level fertilizer used on-farms is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 2013 through 2017).[114] The resulting data are used to check the simulated synthetic fertilizer inputs in the DayCent simulations at the state scale. Specifically, the simulated amounts of mineral fertilizer application for each state and year are compared to the sales data. If the simulated amounts exceed the sales data in a year, then the simulated N_2O emissions are reduced based on the amount of simulated fertilizer that exceeded the sales data relative to the total application of fertilizer in the DayCent simulations for the state. For example, if the simulated amount exceeded the sales data by 3 percent, then the emissions associated with synthetic mineral fertilization[115] is reduced by 3 percent (the same adjustments are also made for leaching and volatilization losses of N that are used to estimate indirect N_2O emissions). This method ensures that the simulated amount of mineral fertilization using bottom-up data from the ARMS and CEAP surveys are adjusted so that they do not exceed the sales data. The bottom-up data from CEAP and ARMS will be further investigated in the future to evaluate the discrepancies with the sales data, and potentially improve these datasets to attain greater consistency.

Similar to synthetic mineral fertilization in DayCent, total amount of manure available for application to soils is used to check and adjust the simulated amounts of manure application to soils in the DayCent simulations. The available manure is estimated using methods described in the Manure Management section (Section 5.2) and annex (Annex 3.10), and it is assumed that all available manure is applied to soils in cropland and grazing lands. If the amount of manure amendments in DayCent simulations exceeded the available manure for application to soils, the amount of N_2O emissions is reduced based on the amount of over-application in the simulations. For example, if the simulated amount exceeded the available amount by 2 percent, then the emissions associated with manure N inputs are reduced by 2 percent (the same adjustments is also made for leaching and volatilization losses of N that are used to estimate indirect N_2O emissions). This method ensures that the simulated amount of manure amendments using bottom-up data from the CEAP survey are adjusted so that they do not exceed the amount of manure available for application to soils. The

[114] The fertilizer consumption data in AAPFCO 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).

[115] See Step 2A for the approach that is used to disaggregate N_2O emissions from DayCent into the sources of N inputs (e.g., mineral fertilizer inputs).

bottom-up data from CEAP will be further investigated in the future to evaluate the discrepancies with the manure availability data, and potentially improve these datasets to attain greater consistency.

The resulting amounts of synthetic and manure fertilizer application data are found in Table A-186.

Simulations are also conducted for the time period prior to 1980 in order to initialize the DayCent model (see Step 2a), and crop-specific regional fertilizer rates prior to 1980 are based largely on extrapolation/interpolation of mineral fertilizer and manure amendment rates from the years with available data. There are little or no data are available for some states so a geographic regional mean is used to simulate fertilization rates (e.g., no data are available for Alabama during the 1970s for corn fertilization rates so mean values from the southeastern United States are used to simulate fertilization to corn fields in this state).

PRP Manure N: Another key source of N for grasslands is PRP manure N (i.e., manure deposited by grazing livestock on pasture, range or paddock). The total amount of PRP manure N is estimated using methods described in the Manure Management section (Section 5.2) and annex (Annex 3.10). 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. During the simulations, the PRP N input is subdivided equally between urine and solid manure (i.e., 50:50 split), and C is also added with the solids using C:N ratios estimated from livestock-specific data on manure chemical content in the Agricultural Waste Management Field Handbook (USDA-NRCS 1996). Total PRP manure N added to soils is found in Table A-186.

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 these sources of N are estimated in the DayCent simulations as a function of vegetation type, weather, and soil properties. That is, the model accounts for the contribution of N from crop residues to the soil profile based on simulating the growth of the crop and senescence. This includes the total N inputs of above- and below-ground N and fixed N in residues that are not harvested or burned (DayCent simulations assumed that 3 percent of non-harvested above ground residues for crops are burned),[116] and the resulting amounts can be found in Table A-186.

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 estimation of all emissions from managed lands, as recommended by the IPCC (2006). The simulated N input from soil organic matter mineralization and asymbiotic N fixation are provided in Table A-186.

Tillage Practices: 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. The remainder of the cultivated area is classified as reduced tillage, 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 are derived from the 1995 Cropping Practices Survey by the Economic Research Service (USDA-ERS 1997).

Tillage practices are estimated for each cropping system based on data from the Conservation Technology Information Center for 1980 through 2004 (CTIC 2004), USDA-NRCS CEAP survey for 2000 through 2005 (USDA-NRCS 2018b), and USDA ARMS surveys for 2002 through 2015 (Claasen et al. 2018). CTIC compiles data on cropland area under tillage management classes by major crop species and year for each county. The CTIC and ARMS surveys involve aggregate area, and therefore 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. These estimates include a relatively high proportion of "intermittent" no-till, where no-till in one year may be followed by tillage in a subsequent year, leading to no-till practices that 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 organic C (Towery 2001).

[116] Another improvement is to reconcile the amount of crop residues burned with the Field Burning of Agricultural Residues source category (Section 5.5).

Tillage data are further processed to impute a tillage management system for each NRI survey location over the time series from 1980 to 2015. First, we impute a tillage management system for every NRI survey location in the "base block" of 2001-2005 by forming imputation classes consisting of all NRI survey locations within the same CEAP region, crop group, and soil texture class. Within one imputation class, NRI locations with missing tillage systems are assigned the tillage system of a randomly-selected CEAP donor. Once the base block is imputed, tillage systems for remaining five-year time blocks are imputed forward and backward in time using trending information obtained from CTIC and ARMS, described above. The trending information from one-time block to the next is reflected in the imputations by first constructing the 3x3 transition probability matrix, **M**, between the two blocks. Let **a** denote the vector of proportions in the current time block (already imputed) and let **b** denote the vector of desired proportions in the target time block (to be imputed) based on the trending information. The rows of **M** correspond to the tillage type (no-till, reduced till, or conventional till) in the target time block and the columns of **M** correspond to the tillage type in the current time block. The elements of **M** are constrained so that (a) each column is a probability distribution (all elements between 0 and 1 and column sums to 1); (b) **Ma**=**b**; and (c) the diagonal elements of **M** are as large as possible. The last constraint implies as much temporal continuity as possible at a location, subject to overall trends. The solution for **M** is obtained by a mathematical optimization technique known as linear programming. Once **M** is obtained, it is used for imputing the tillage system as follows: determine the column that corresponds to the tillage system (imputed or real) of the current block, and use the probabilities in that column to randomly select the tillage system for the target block. Repeat the construction of **M** and the imputation block by block forward in time and backward in time.

Cover Crops: Cover crop data are based on USDA CEAP data (USDA-NRCS 2018b) and information from 2011 to 2016 in the USDA Census of Agriculture (USDA-NASS 2012, 2017). It is assumed that cover cropping was minimal prior to 1990 and the rates increased over the decade to the levels of cover crop management derived from the CEAP survey. Cover crops in the "base block" of 2001-2005 are determined from the imputation for planting date (cover crops are assigned based on recipients with donor that had a cover crop in the USDA CEAP survey). For 1996-2000, we randomly remove cover crop from locations so that remaining cover crop area is about one-half of the 2001-2005 cover crop area. For 1991-1995, we randomly remove a subset of the remaining area each year until no cover crops are remaining in 1990. For the blocks 2006-2010, 2011-2015, and 2016-2020, we add (or possibly delete, if cover crops declined in a region) cover crops at random to match the trending information from USDA Census of Agriculture (USDA-NASS 2012, 2017).

Irrigation: NRI (USDA-NRCS 2018a) 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 water is applied to the level of field capacity on the day after the soil at an NRI survey location drains to 60 percent of field capacity in the DayCent model simulation.

Daily Weather Data: Daily maximum/minimum temperature and precipitation data are based on gridded weather data from the PRISM Climate Group (2018). Computer-generated weather data are used to drive the DayCent model simulations because weather station data do not exist near all NRI points. The PRISM product uses interpolation algorithms to derive weather patterns for areas between the existing network of weather stations (Daly et al. 1998). PRISM weather data are available for the United States from 1981 through 2015 at a 4 km resolution. Each NRI survey location is assigned the PRISM weather data for the grid cell containing the survey location.

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.[117]

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 an NRI survey location. 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

[117] Additional crops and grassland will be used with the NASA-CASA method in the future, as a planned improvement.

individual pixels in the MODIS EVI products is determined by aggregating the crop cover data in CDL to the 250 m resolution of the EVI data. In this step, the percent cover of individual crops is determined for the 250 m EVI pixels. Pixels that do not meet a 90 percent purity level for any crop are eliminated from the dataset. CDL does not provide full coverage for crops across 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 survey location based on a 10 km buffer surrounding the survey location. EVI data are not assigned to a survey location 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 plant growth.

Water Management for Rice Cultivation: Rice crop production in the United States is mostly managed with continuous flooding, but does include a minor amount of land with mid-season drainage or alternate wet-dry periods (Hardke 2015; UCCE 2015; Hollier 1999; Way et al. 2014). However, continuous flooding is applied to all rice cultivation areas in the inventory because water management data are not available. 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 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 United States. The C input from rice straw is simulated directly within the DayCent model for the Tier 3 method. For the Tier 1 method, residues 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 second crop in the season. 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 are not collected by USDA for Florida, and so are derived based on NRI crop areas and 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 drainage capacity (i.e., hydric vs. non-hydric soil characterization) are the main soil variables used as inputs to the DayCent model. Texture is one of the main controls on soil C turnover and stabilization in the model, which uses particle size fractions of sand (50-2,000 µm), silt (2-50 µm), and clay (<2 µm) as inputs. Hydric condition in soils are associated with poor drainage, 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.[118] 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 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).[119] 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 2019). The data are based on field measurements collected as part of soil survey and mapping. Each NRI survey location 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 synthetic fertilizer used on-farms has been estimated using USGS and AAPFCO

[118] Artificial drainage (e.g., ditch- or tile-drainage) is simulated as a management variable.

[119] Hydric soils are primarily subject to anaerobic conditions outside the plant growing season, such as late winter or early spring prior to planting. Soils that are flooded during much of the year are typically classified as organic soils (e.g., peat), which are not simulated with the DayCent model.

datasets, as discussed in Step 1b (Brakebill and Gronberg 2017; AAPFCO 2013 through 2017). 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 that is used on farms after subtracting the amount applied to crops and non-federal grasslands simulated by DayCent. The differences are aggregated to the national 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-186.

Managed Livestock Manure and Other Organic Fertilizers: Managed 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. The total amount of manure available for application to soils has been estimated with methods described in the Manure Management section (Section 5.2) and annex (Annex 3.10). Managed manure N applied to croplands for the Tier 1 method is calculated using a process of elimination approach. Specifically, the amount of managed manure N that is amended to soils in the DayCent model simulations is subtracted from total managed manure N available for application to soils. The difference is assumed to be applied to croplands that are not included in the DayCent model simulations. The fate of manure available for application to soils is summarized in Table A-186.

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 2017).[120] Commercial organic fertilizers include dried blood, tankage, compost, and other organic materials, which are recorded in mass units of fertilizer. These data are converted to mass units of N by multiplying the consumption values by the average organic fertilizer N content of commercial organic fertilizers, which range between 2.3 to 4.2 percent across the time series (TVA 1991 through 1994; AAPFCO 1995 through 2017). There is potential for double-counting N applications to soils for dried manure and biosolids (i.e., treated sewage sludge) that are included as commercial fertilizers because these N inputs are already addressed in the manure dataset (See Manure Management Section 5.2 and Annex 3.10) and biosolids (See Biosolids below) that are estimated for this Inventory. Therefore, the amounts of dried manure and biosolids in other commercial organic fertilizer, which are provided in the reports[121] (TVA 1991 through 1994; AAPFCO 1995 through 2017), are subtracted from the total commercial organic fertilizer before estimating emissions. The 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-186.

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 3.10. PRP N deposited on federal grasslands is calculated using a process of elimination approach. Specifically, the amount of PRP N included in the DayCent model simulations of non-federal grasslands is subtracted from total PRP N. This difference was assumed to be deposited on federal grasslands. The total PRP manure N added to soils is found in Table A-186.

Biosolids (i.e., Treated Sewage Sludge) Amendments: Biosolids are generated from the treatment of raw sewage in public or private wastewater treatment works and are typically used as a soil amendment, or are sent to waste disposal facilities, such as landfills. In this Inventory, all biosolids that are amended to agricultural soils are assumed to be applied to grasslands. Estimates of the amounts of biosolids N applied to agricultural lands are derived from national data on biosolids generation, disposition, and N content. Total biosolids generation data for 1990 through 2004, in dry mass units, are obtained from AAPFCO (1995 through 2004). Values for 2005 through 2019 are not available so a "least squares line" statistical extrapolation using the previous 16 years of data to impute 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 biosolids N applied to agricultural land are used to estimate N_2O emissions from agricultural soil management; the estimates of biosolids N

[120] 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).

[121] The amount of reported dried manure and biosolids in other organic fertilizers must be converted into units of N. While the amounts of dried manure and biosolids are provided in each report (TVA 1991 through 1994; AAPFCO 1995 through 2017), the N contents of dried manure and biosolids are only provided in AAPFCO (2000). The values are 0.5 and 6.0 percent, respectively, for dried manure and biosolids.

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). Biosolids disposal data are provided in Table A-186.

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 2019). Total production for each crop is converted to tons of dry matter product using the residue dry matter fractions. 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 is 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-186.

Table A-186: Sources of Soil Nitrogen (kt N)

N Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
1. Synthetic Fertilizer N: Cropland	9,892	10,285	10,274	10,110	11,126	10,300	10,871	10,852	10,815	10,970
2. Synthetic Fertilizer N: Grassland	13	12	24	56	42	12	10	19	78	19
3. Managed Manure N: Cropland	2,463	2,495	2,505	2,491	2,553	2,587	2,578	2,596	2,616	2,618
4. Managed Manure N: Grassland	+	1	1	2	1	+	+	2	1	1
5. Pasture, Range, & Paddock Manure N	4,097	4,104	4,265	4,354	4,427	4,529	4,495	4,393	4,350	4,287
6. N from Crop Residue Decomposition[a]	6,875	7,091	6,693	7,047	6,789	7,255	6,977	6,842	6,881	7,739
7. N from Grass Residue Decomposition[a]	12,374	12,298	12,623	12,757	12,217	12,937	12,551	12,644	11,960	13,366
8. Min. SOM / Asymbiotic N-Fixation: Cropland[b]	11,344	10,931	10,686	12,089	10,722	11,596	11,000	11,219	12,605	11,296
9. Min. SOM / Asymbiotic N-Fixation: Grassland[b]	16,445	17,261	17,389	17,205	16,020	17,028	16,820	17,824	17,363	16,807
10. Treated Sewage Sludge N: Grassland	52	55	58	62	65	68	72	75	78	81
11. Other Organic Amendments: Cropland[c]	4	8	6	5	8	10	13	14	12	11
Total	**63,559**	**64,541**	**64,524**	**66,178**	**63,970**	**66,321**	**65,385**	**66,479**	**66,759**	**67,195**

N Source	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
1. Synthetic Fertilizer N: Cropland	10,792	10,105	10,542	10,602	11,324	10,723	10,454	11,493	10,932	10,215
2. Synthetic Fertilizer N: Grassland	24	30	27	24	44	18	19	15	22	18
3. Managed Manure N: Cropland	2,650	2,635	2,668	2,676	2,595	2,630	2,704	2,726	2,698	2,675
4. Managed Manure N: Grassland	1	2	+	1	+	1	1	+	1	+
5. Pasture, Range, & Paddock Manure N	4,194	4,191	4,198	4,203	4,156	4,207	4,260	4,150	4,111	4,078
6. N from Crop Residue Decomposition[a]	7,428	7,336	7,262	7,504	7,171	7,337	7,375	7,141	7,255	7,442
7. N from Grass Residue Decomposition[a]	12,532	12,936	12,677	13,040	12,243	13,092	12,689	13,178	13,034	12,571
8. Min. SOM / Asymbiotic N-Fixation: Cropland[b]	11,414	11,821	11,284	11,433	12,839	11,494	11,346	11,961	12,054	12,484
9. Min. SOM / Asymbiotic N-Fixation: Grassland[b]	15,687	16,599	16,475	16,991	19,099	17,701	16,934	18,549	17,474	18,120
10. Treated Sewage Sludge N: Grassland	84	86	89	91	94	98	101	104	107	110
11. Other Organic Amendments: Cropland[c]	9	7	8	8	9	10	12	15	12	10
Total	**64,814**	**65,748**	**65,228**	**66,574**	**69,574**	**67,311**	**65,896**	**69,334**	**67,701**	**67,722**

N Source	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
1. Synthetic Fertilizer N: Cropland	10,784	11,261	11,906	11,905	11,706	11,480	12,758	12,690	12,956	13,011
2. Synthetic Fertilizer N: Grassland	11	12	13	11	12	14	12	12	12	12
3. Managed Manure N: Cropland	2,663	2,686	2,710	2,687	2,680	2,718	2,778	2,844	2,924	2,947
4. Managed Manure N: Grassland	+	1	1	1	+	1	+	+	+	+
5. Pasture, Range, & Paddock Manure N	4,027	3,929	3,843	3,801	3,755	3,817	3,949	4,019	4,037	4,052
6. N from Crop Residue Decomposition[a]	7,887	7,676	7,448	7,359	7,621	7,231	7,436	7,422	7,622	7,692

7. N from Grass Residue Decomposition[a]	12,910	12,499	13,091	12,107	12,211	11,769	12,200	12,089	12,232	12,687
8. Min. SOM / Asymbiotic N-Fixation: Cropland[b]	13,366	11,272	10,216	12,694	13,536	14,311	11,604	11,631	11,995	12,121
9. Min. SOM / Asymbiotic N-Fixation: Grassland[b]	18,527	16,127	15,341	18,472	18,501	19,041	16,731	16,579	16,774	17,398
10. Treated Sewage Sludge N: Grassland	113	116	119	122	124	127	130	133	136	139
11. Other Organic Amendments: Cropland[c]	10	12	13	13	11	12	13	12	11	10
Total	**70,298**	**65,591**	**64,701**	**69,172**	**70,157**	**70,522**	**67,610**	**67,430**	**68,698**	**70,069**

Note: For most activity sources data were not available after 2015 and emissions were estimated with a data splicing method. Additional activity data will be collected and the Tier 1, 2 and 3 methods will be applied in a future inventory to recalculate the part of the time series that is estimated with the data splicing methods.
+ Does not exceed 0.5 kt
[a] Residue N inputs include unharvested fixed N from legumes as well as crop and grass residue N.
[b] Mineralization of soil organic matter and the asymbiotic fixation of nitrogen gas.
[c] Includes dried blood, tankage, compost, other. Excludes dried manure and bio-solids (i.e., treated sewage sludge) used as commercial fertilizer to avoid double counting.

Step 1d: Obtain Additional Management Activity Data for Tier 2 Method to estimate Soil Organic C Stock Changes in Mineral Soils

Biosolids (i.e., Treated Sewage Sludge) Amendments: Biosolids are generated from the treatment of raw sewage in public or private wastewater treatment facilities and are typically used as soil amendments or are sent for waste disposal to landfills. In this Inventory, all biosolids that are amended to agricultural soils are assumed to be applied to grasslands. See section on biosolids in Step 1c for more information about the methods used to derive biosolid N estimates. The total amount of biosolid N is given in Table A-186. Biosolid 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. In this Inventory, all biosolids are applied to grasslands so these rates may not be fully representative of amendments of a biosolids, but there are no data available on N amendments that are specific to grasslands (Future Inventories will incorporate new information when it is available). This capacity varies from year to year, because it is based on specific crop yields during the respective year (Kellogg et al. 2000). Total biosolid N available for application is divided by the assimilative capacity to estimate the total land area over which biosolids had been applied. The resulting estimates are used for the estimation of soil organic C stock changes associated with application of biosolids.

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.

Step 1e: Additional Activity Data for Indirect N_2O Emissions

A portion of the N that is applied as synthetic fertilizer, livestock manure, biosolids (i.e., treated sewage sludge), and other organic amendments volatilizes as NH_3 and NO_x. In turn, the volatilized N is eventually 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 regions in the Western United States, 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, biosolids 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-186.

Using the DayCent model, volatilization and leaching/surface run-off of N from soils is estimated in the simulations 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[122], which are addressed in the Tier 1 methodology. Similarly, the N available for producing indirect emissions resulting from grassland management as well as PRP manure is also estimated by DayCent. However, indirect emissions are not estimated for leaching and runoff of N if precipitation water input does not exceed 80 percent of the potential evapotranspiration (Note: Irrigated systems are always assumed to have leaching of N even in drier climates). 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 the measure of variability in the fertilizer and organic amendment activity data (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, applications of biosolids, and PRP manure on federal grasslands, which are not simulated by DayCent. To estimate volatilized N losses, the amount of synthetic fertilizers, manure, biosolids, 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 0.03-0.3 kg NH_3-N+NO_x-N/kg N for synthetic fertilizer and 0.05-0.5 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, biosolids, and above- and below-ground crop residues, and then multiplied by the default fraction subject to leaching/runoff losses of 0.3 kg N/kg N applied, with an uncertainty from 0.1–0.8 kg NO_3-N/kg N (IPCC 2006). However, N leaching is assumed to be an insignificant source of indirect N_2O emissions if the amount of precipitation did not exceed 80 percent of the potential evapotranspiration, consistent with the Tier 3 method (Note: Irrigated systems are always assumed to have leaching of N even in drier climates). 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 GHG Emissions and Stocks Changes for Mineral Soils: Soil Organic C Stock Changes, Direct N_2O Emissions, 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 types, grasslands (i.e., federal grasslands) and soil types that are 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.

Step 2a: Estimate Soil Organic C Stock Changes, Soil 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, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, and wheat, which combined represent approximately 85 percent of total cropland in the United States. The DayCent simulations also include all non-federal grasslands in the United States.

The methodology description is divided into two sub-steps. First, the DayCent model is used to establish the initial conditions and C stocks for 1979, which is the first year of the NRI survey. In the second sub-step, DayCent is used to simulate changes in soil organic C stocks, direct soil N_2O emissions, leaching and volatilization losses of N contributing to

[122] The amount of volatilization and leaching are reduced if the simulated amount of synthetic mineral fertilization in DayCent exceeds the amount mineral fertilizer sales, or the simulated amount of manure application in DayCent exceeds the manure available for applications to soils. See subsection on Synthetic and Manure N Fertilizer Applications in Step 1b for more information.

indirect N_2O emissions, and CH_4 emissions from rice cultivation based on the land-use and management histories recorded in the NRI (USDA-NRCS 2018a).

Simulate Initial Conditions (Pre-NRI Conditions): The purpose of the DayCent model initialization is to estimate 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 subdivided by the pools 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 (PRISM Climate Group 2018), and the soil characteristics for the NRI survey locations. 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 2015. The simulations address the influence of soil management on direct soil 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, cover crop usage, and EVI data (See Step 1b for description of the inputs). There are six DayCent simulations for each NRI survey location based on the imputation product in order to capture the uncertainty in the management activity data derived by combining data from CEAP, ARMS, Census of Agriculture and CTIC surveys. See Step 1b for more information. The simulation system incorporates a dedicated MySQL database server and a parallel processing computer cluster. Input/output operations are managed by a set of run executive programs.

Evaluating uncertainty is an integral part of the analysis and includes three components: (1) uncertainty in the management activity data inputs (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 the first component, the uncertainty is based on the six imputations underlying the data product combining CEAP, ARMS, Census of Agriculture and CTIC survey data. See Step 1b for discussion about the imputation product. 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 72 long-term experiment sites and 142 NRI soil monitoring network sites (Spencer et al. 2011) with 948 observations across all of the sites that represent a variety of management conditions (e.g., variation in crop rotation, tillage, fertilization rates, and manure amendments). There are 41 experimental sites available with over 200 treatment observations to evaluate structural uncertainty in the N_2O emission predictions from DayCent (Del Grosso et al. 2010). There are 17 long-term experiments with data on CH_4 emissions from rice cultivation, representing 238 combinations of management treatments. 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). However, additional uncertainty is introduced with the measurements from the NRI soil monitoring network because the management data are represented by the six imputations. Therefore, we statistically analyzed the results and quantified uncertainty for each imputation separately for soil organic C.

The empirical relationship between field measurements and modeled soil organic C stocks, soil N_2O emissions and CH_4 emissions are statistically analyzed using linear-mixed effect modeling techniques. The modeled stocks and emissions are treated as a fixed effect in the statistical models. The resulting relationships are used to make an adjustment to modeled values if there are biases due to significant mismatches between the modeled and measured values. Several other variables are tested in these models including soil characteristics, geographic location (i.e., state), and management practices (e.g., tillage practices, fertilizer rates, rice production with and without winter flooding). Random effects are included in all of these models 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. See the Tier 3 Model Description, Parameterization and Evaluation Section for more information about model evaluation, including graphs illustrating the relationships between modeled and measured values.

The third element is the uncertainty associated with scaling the DayCent results for each NRI survey location to the entire land base, using the expansion factors and replicate weights provided with the NRI dataset. The expansion factors represent the number of hectares associated with the land-use and management history for a particular survey location. The scaling uncertainty is due to the complex sampling design that selects the locations for NRI, and this uncertainty is properly reflected in the replicate weights for the expansion factor. Briefly, each set of replicate weights is used to compute one weighted estimate. The empirical variation across the weighted estimates from all replicates is an estimate of the theoretical scaling uncertainty due to the complex sampling design.

A Monte Carlo approach is used to propagate uncertainty from the three components through the analysis with 1000 iterations for each NRI survey location. In each iteration, there is a random selection of management activity data from the imputation product; a random draw of parameter values for the uncertainty estimator (Ogle et al. 2010); and a random draw of a set of replicate weights to scale the emissions and stock changes from the individual NRI survey locations to the entire domain of the inventory analysis. Note that parameter values for the statistical equations (i.e., fixed effects) are selected from their joint probability distribution, as well as random error associated with the time series and data collected from the same site, and the residual/unexplained error. The randomly selected parameter values for soil organic C, N_2O and CH_4 emissions and associated management information are then used as input into the linear mixed-effect model, and adjusted values are computed for each C stock change, N_2O and CH_4 emissions estimate. After completing the Monte Carlo stochastic simulation, the median of the final distribution from the 1000 replicates is used as the estimate of total emissions or soil organic C stock changes, and a 95 percent confidence interval is based on 2.5 and 97.5 percentile values.

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 survey location, 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. For example, if 70 percent of the mineral N made available in the soil is due to synthetic mineral fertilization, then 70 percent of the N_2O emissions are assigned to this practice.

A portion 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. Mineralization of soil organic matter is significant source of N, but is typically less than half of the amount of N made available in 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. Asymbiotic N fixation by soil bacteria is a minor source of N, typically not exceeding 10 percent of total N inputs to agroecosystems. Accounting for the influence of “other N inputs” is necessary because the processes leading to these inputs of N are influenced by management.

This attribution of N_2O emissions to the individual N inputs to the soils is required for reporting emissions based on UNFCCC reporting guidelines. However, 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. 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.

For the land base that is simulated with the DayCent model, direct soil N_2O emissions are provided in Table A-190 and Table A-191, soil organic C stock changes are provided in Table A-192, and rice cultivation CH_4 emissions in Table A-194.

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). The uncertainty is determined based on simple error propagation methods (IPCC 2006). The uncertainty in the default emission factor ranges from 0.3–3.0 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 0.000–0.006 kg N_2O-N/kg N (IPCC 2006).[123] 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 biosolids (i.e., treated 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. The uncertainty is determined based on the simple 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).

The results for direct soil N_2O emissions using the Tier 1 method are provided in Table A-190 and Table A-191.

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 analysis (IPCC 2006), combining uncertainties associated with the adjusted daily emission factor and the harvested areas derived from the USDA NRI survey data.

The results for rice CH_4 emissions using the Tier 1 method are provided in Table A-194.

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 through 2015, 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 quantity in the inventory calculations has uncertainty that is quantified in PDFs, including the land use and management activity data based on the six imputations in the data product combining CEAP,

[123] Due to lack of data, uncertainties are not addressed for managed manure N production, PRP manure N production, other commercial organic fertilizer amendments, indirect losses of N in the DayCent simulations, and biosolids (i.e., treated sewage sludge), but these sources of uncertainty will be included in future Inventories.

ARMS, Census of Agriculture, and CTIC data (See Step 1b for more information); reference C stocks and stock change factors; and the replicated weights form the NRI survey. A Monte Carlo Analysis is used to quantify uncertainty in soil organic C stock changes for the inventory period based on random selection of values from each of these sources of uncertainty. Input values are randomly selected from PDFs in an iterative process to estimate soil organic C change for 1,000 iterations in the analysis.

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 soil organic C 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.

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). Seven of these climate zones occur in the conterminous United States and Hawaii (Eve et al. 2001). Climate zones are classified using mean annual precipitation and temperature (1950-2000) data 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).

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-187). These stocks are used in conjunction with management factors to estimate the change in soil organic C 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.

Table A-187: U.S. Soil Groupings Based on the IPCC Categories and Dominant Taxonomic Soil, and Reference Carbon Stocks (Metric Tons C/ha)

		Reference Carbon Stock in Climate Regions					
IPCC Inventory Soil Categories	**USDA Taxonomic Soil Orders**	**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 stock change factors for land use, management and input, studies had to report soil organic C 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 models, 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 observation 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-188). Variance is calculated for each of the country-specific factor values, and used to construct PDFs with a normal density. In the IPCC method, 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.[124] Organic amendments in annual cropping systems also increase soil organic C stocks due to greater C inputs, while high soil organic C 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, the factor values from IPCC (2006) are used under the assumption that they would best approximate the impacts, given the lack of data to derive country-specific factors. A measure of uncertainty is provided for these factors in IPCC (2006), which is used to construct PDFs.

[124] Improved grasslands are identified in the NRI as grasslands that are irrigated or seeded with legumes, in addition to those reclassified as improved with manure amendments.

Table A-188: Soil Organic Carbon Stock Change Factors for the United States and the IPCC Default Values Associated with Management Impacts on Mineral Soils

		U.S. Factor			
	IPCC default	Warm Moist Climate	Warm Dry Climate	Cool Moist Climate	Cool Dry Climate
Land-Use Change Factors					
Cultivated[a]	1	1	1	1	1
General Uncult[a,b] (n=251)	1.4	1.42±0.06	1.37±0.05	1.24±0.06	1.20±0.06
Set-Aside[a] (n=142)	1.25	1.31±0.06	1.26±0.04	1.14±0.06	1.10±0.05
Improved Grassland Factors					
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 soil organic C 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 soil organic C 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 soil organic C 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-189). 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-189).

Table A-189: 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 organic C are calculated by subtracting the beginning stock from the ending stock and then dividing by 20.[125] For this analysis, stocks are estimated for each year and difference between years is the stock change. From the final distribution of 1,000 values, the median is used as the estimate of soil organic C stock change and a 95 percent confidence interval is generated based on the simulated values at the 2.5 and 97.5 percentiles in the distribution.

Soil organic C stock changes using the Tier 2 method are provided in Table A-192 and Table A-194.

[125] 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 Biosolids (i.e., Treated Sewage Sludge) Amendments

There are two additional land use and management activities occurring on mineral soils of U.S. agricultural lands that are not estimated in Steps 2a and 2b. The first activity involves the application of biosolids to agricultural lands. Minimal data exist on where and how much biosolids are applied to U.S. agricultural soils. However, national estimates of mineral soil land area receiving biosolids can be approximated based on biosolids N production data, and the assumption that amendments are applied at a rate equivalent to the assimilative capacity from Kellogg et al. (2000). In this Inventory, it is assumed that biosolids for agricultural land application to soils is only used as an amendment in grassland. The impact of organic amendments on soil organic C is calculated as 0.38 metric tonnes C/ha-yr. This rate is based on the IPCC default method and country-specific factors, by calculating the effect of converting nominal, medium-input grassland to high input improved grassland. The assumptions for this estimation are as follows: a) the reference C stock is 50 metric tonnes C/ha, which represents a mid-range value of reference C stocks for the cropland soils in the United States,[126] b) the land use factor for grassland of 1.4 and 1.11 for high input improved grassland are representative of typical conditions, and c) the change in stocks are occurring over a 20 year (default value) time period (i.e., [50 × 1.4 × 1.11 – 50 × 1.4] / 20 = 0.38). A ±50 percent uncertainty is attached to these estimates due to limited information on application and the rate of change in soil organic C stock change with amendments of biosolids.

The influence of biosolids (i.e., treated sewage sludge) on soil organic C stocks is provided in Table A-194.

Table A-190: Direct Soil N_2O Emissions from Mineral Soils in Cropland (MMT CO_2 Eq.)

Land Use Change Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Cropland Mineral Soil Emission	**182.1**	**173.6**	**169.8**	**187.5**	**182.2**	**180.0**	**187.7**	**178.9**	**176.6**	**178.6**
Tier 3 Cropland	165.0	157.5	152.8	170.7	163.9	161.5	169.0	160.2	158.6	160.7
Inorganic N Fertilizer Application	58.5	57.4	57.1	59.2	63.2	56.7	63.3	59.7	56.8	58.7
Managed Manure Additions	5.3	5.2	5.1	5.3	5.2	4.8	5.3	4.9	4.6	4.6
Crop Residue N	34.2	33.9	31.2	35.4	33.1	35.0	35.3	32.7	30.8	36.4
Min. SOM / Asymbiotic N-Fixation[a]	67.1	61.0	59.4	70.8	62.4	65.1	65.1	62.9	66.4	61.0
Tier 1 Cropland	17.1	16.2	17.0	16.8	18.4	18.5	18.7	18.7	18.0	17.9
Inorganic N Fertilizer Application	4.6	3.9	4.3	4.6	5.3	5.4	5.9	5.7	4.8	4.8
Managed Manure Additions	7.4	7.4	7.5	7.5	7.9	8.2	8.0	8.2	8.3	8.3
Other Organic Amendments[b]	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Crop Residue N	5.1	4.8	5.1	4.7	5.1	4.7	4.8	4.8	4.9	4.7
Implied Emission Factor for Croplands[c] (kt N_2O-N/kt N)	0.012	0.011	0.011	0.011	0.012	0.011	0.012	0.011	0.011	0.011

Land Use Change Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Cropland Mineral Soil Emission	**173.2**	**182.6**	**182.8**	**184.0**	**183.6**	**180.1**	**175.6**	**181.4**	**179.2**	**180.6**
Tier 3 Cropland	155.3	164.7	164.2	164.4	163.2	161.0	156.4	162.1	160.0	163.2
Inorganic N Fertilizer Application	56.8	57.2	59.2	58.2	57.5	58.0	55.8	60.6	57.2	55.5
Managed Manure Additions	4.5	4.5	4.7	4.5	4.5	4.5	4.5	4.6	4.5	4.7
Crop Residue N	33.8	36.0	36.0	37.0	32.8	35.1	34.7	33.0	33.6	35.1
Min. SOM / Asymbiotic N-Fixation[a]	60.1	66.9	64.2	64.6	68.5	63.3	61.3	63.9	64.6	67.9
Tier 1 Cropland	18.0	17.9	18.7	19.6	20.4	19.1	19.2	19.3	19.2	17.4
Inorganic N Fertilizer Application	4.7	4.7	5.6	6.2	7.2	5.9	5.8	5.8	5.8	4.2
Managed Manure Additions	8.5	8.7	8.7	8.9	8.4	8.6	8.8	8.8	8.8	8.6
Other Organic Amendments[b]	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0
Crop Residue N	4.7	4.5	4.3	4.5	4.8	4.6	4.5	4.6	4.6	4.6
Implied Emission Factor for Croplands[c] (kt N_2O-N/kt N)	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011

Land Use Change Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Cropland Mineral Soil Emission	**182.4**	**180.4**	**172.8**	**193.9**	**203.6**	**196.2**	**187.5**	**187.1**	**191.7**	**193.0**
Tier 3 Cropland	163.5	161.4	154.5	174.2	184.2	171.9	164.5	164.9	170.1	171.9

[126] Reference C stocks are based on cropland soils for the Tier 2 method applied in this Inventory.

Inorganic N Fertilizer Application	54.8	58.8	61.1	62.9	64.2	54.7	60.4	60.5	62.4	63.1
Managed Manure Additions	4.5	5.0	5.0	5.3	5.2	4.0	5.0	5.0	5.2	5.2
Crop Residue N	35.5	36.6	34.5	35.5	37.7	34.3	35.2	35.3	36.4	36.8
Min. SOM / Asymbiotic N-Fixation[a]	68.7	61.0	53.9	70.5	77.1	78.9	64.0	64.1	66.1	66.8
Tier 1 Cropland	18.9	19.1	18.3	19.8	19.4	24.3	22.9	22.1	21.6	21.2
Inorganic N Fertilizer Application	5.8	6.4	5.6	7.0	6.3	10.1	8.5	8.0	7.7	7.4
Managed Manure Additions	8.5	8.4	8.4	8.2	8.4	9.4	9.5	9.3	9.1	9.0
Other Organic Amendments[b]	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Crop Residue N	4.6	4.3	4.3	4.5	4.7	4.7	4.9	4.8	4.8	4.8
Implied Emission Factor for Croplands[c] (kt N_2O-N/kt N)	0.010	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011

Note: For most activity sources data were not available after 2015 and emissions were estimated with a data splicing method. Additional activity data will be collected and the Tier 1, 2 and 3 methods will be applied in a future inventory to recalculate the part of the time series that is estimated with the data splicing methods.

[a] Mineralization of soil organic matter and the asymbiotic fixation of nitrogen gas.

[b] Includes dried blood, tankage, compost, other. Excludes dried manure and bio-solids (i.e., treated sewage sludge) used as commercial fertilizer to avoid double counting.

[c] Annual Implied Emission Factor (kt N_2O-N/kt N) is calculated by dividing total estimated emissions by total activity data for N applied.

Table A-191: Direct Soil N_2O Emissions from Mineral Soils in Grassland (MMT CO_2 Eq.)

Land Use Change Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland Mineral Soil Emission	**84.1**	**84.2**	**83.3**	**84.5**	**80.5**	**83.4**	**85.5**	**86.3**	**87.4**	**82.1**
Tier 3 Grassland	77.1	77.4	76.3	77.6	73.6	76.7	79.1	80.2	81.2	76.2
Inorganic N Fertilizer Application	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.2	0.0
Managed Manure Additions	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pasture, Range, & Paddock N Deposition	7.8	7.7	7.8	8.2	8.5	8.5	8.9	8.4	8.9	8.0
Grass Residue N	29.7	29.0	28.8	29.5	28.1	29.5	30.0	29.8	29.4	30.2
Min. SOM / Asymbiotic N-Fixation[a]	39.5	40.7	39.6	39.8	36.9	38.8	40.1	41.9	42.7	37.9
Tier 1 Grassland	7.0	6.8	7.0	6.9	6.9	6.7	6.5	6.2	6.2	5.9
Pasture, Range, & Paddock N Deposition	6.8	6.5	6.7	6.6	6.6	6.4	6.1	5.8	5.8	5.5
Treated Sewage Sludge Additions	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4
Implied Emission Factor for Grassland[b] (kt N_2O-N/kt N)	0.006	0.006	0.005	0.005	0.005	0.005	0.006	0.005	0.006	0.005

Land Use Change Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Grassland Mineral Soil Emission	**76.8**	**83.1**	**83.7**	**83.2**	**91.6**	**86.4**	**84.9**	**87.1**	**84.5**	**88.2**
Tier 3 Grassland	71.0	77.4	78.1	77.7	86.0	80.8	79.4	81.8	79.2	83.0
Inorganic N Fertilizer Application	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.0
Managed Manure Additions	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pasture, Range, & Paddock N Deposition	7.9	8.4	8.6	8.3	8.6	8.3	8.5	8.2	8.1	8.5
Grass Residue N	28.0	30.2	30.2	30.1	30.2	30.8	30.3	30.6	30.3	30.5
Min. SOM / Asymbiotic N-Fixation[a]	35.0	38.7	39.3	39.2	47.1	41.7	40.5	43.0	40.7	43.9
Tier 1 Grassland	5.8	5.7	5.6	5.6	5.6	5.6	5.5	5.3	5.3	5.2
Pasture, Range, & Paddock N Deposition	5.5	5.3	5.2	5.1	5.1	5.1	5.1	4.8	4.8	4.7
Treated Sewage Sludge Additions	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5
Implied Emission Factor for Grassland[b] (kt N_2O-N/kt N)	0.005	0.005	0.006	0.005	0.006	0.005	0.006	0.005	0.005	0.006

Land Use Change Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Grassland Mineral Soil Emission	**90.4**	**80.9**	**76.2**	**92.0**	**93.3**	**93.0**	**88.1**	**87.4**	**88.4**	**91.5**
Tier 3 Grassland	85.2	75.7	71.1	87.0	88.2	88.0	83.1	82.4	83.3	86.4
Inorganic N Fertilizer Application	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Managed Manure Additions	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pasture, Range, & Paddock N Deposition	8.4	8.0	7.3	8.1	8.2	8.4	8.4	8.3	8.4	8.7
Grass Residue N	31.5	29.6	29.4	31.2	31.8	30.4	31.5	31.2	31.6	32.8
Min. SOM / Asymbiotic N-Fixation[a]	45.2	38.1	34.4	47.6	48.2	49.2	43.2	42.8	43.3	44.9
Tier 1 Grassland	5.2	5.1	5.1	5.1	5.0	5.0	5.0	5.0	5.1	5.1

Pasture, Range, & Paddock N Deposition	4.7	4.6	4.6	4.5	4.5	4.4	4.4	4.4	4.4	4.4
Treated Sewage Sludge Additions	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7
Implied Emission Factor for Grassland[b] (kt N_2O-N/kt N)	0.006	0.005	0.005	0.006	0.006	0.006	0.006	0.006	0.006	0.006

Note: For most activity sources data were not available after 2015 and emissions were estimated with a data splicing method. Additional activity data will be collected and the Tier 1, 2 and 3 methods will be applied in a future inventory to recalculate the part of the time series that is estimated with the data splicing methods.

[a] Mineralization of soil organic matter and the asymbiotic fixation of nitrogen gas.

[b] Annual Implied Emission Factor (kt N_2O-N/kt N) is calculated by dividing total estimated emissions by total activity data for N applied.

Table A-192: Annual Change in Soil Organic Carbon Stocks in Croplands (MMT CO_2 Eq./yr)

Land Use Change Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Cropland Soil Organic C Stock Change	**-55.8**	**-60.3**	**-56.4**	**-43.4**	**-51.0**	**-39.6**	**-55.9**	**-44.5**	**-38.6**	**-40.9**
Cropland Remaining Cropland (CRC)	-58.2	-63.3	-60.0	-45.8	-53.5	-46.1	-61.4	-53.1	-43.5	-46.0
Tier 2	-0.6	-1.5	-1.6	-1.4	-0.4	-0.6	-0.5	-1.8	-0.7	-1.9
Tier 3	-57.6	-61.7	-58.4	-44.4	-53.1	-45.5	-60.8	-51.3	-42.9	-44.1
Grassland Converted to Cropland (GCC)	4.1	4.9	5.8	4.7	4.8	8.9	8.0	11.3	7.6	7.9
Tier 2	3.9	4.2	4.0	4.0	4.3	4.7	5.0	5.0	5.1	5.0
Tier 3	0.2	0.7	1.8	0.7	0.6	4.2	2.9	6.3	2.5	2.9
Forest Converted to Cropland (FCC) (Tier 2 Only)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3
Other Lands Converted to Cropland (OCC) (Tier 2 Only)	-2.3	-2.4	-2.5	-2.7	-2.9	-2.9	-3.0	-3.1	-3.1	-3.2
Settlements Converted to Cropland (SCC) (Tier 2 Only)	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
Wetlands Converted to Cropland (WCC) (Tier 2 Only)	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Land Use Change Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Cropland Soil Organic C Stock Change	**-47.0**	**-56.6**	**-63.6**	**-55.8**	**-58.6**	**-61.1**	**-58.3**	**-61.3**	**-52.7**	**-43.0**
Cropland Remaining Cropland (CRC)	-51.6	-60.7	-65.4	-57.8	-59.9	-62.4	-58.5	-61.8	-55.4	-46.2
Tier 2	-0.9	-3.9	-5.6	-5.1	-4.9	-5.0	-4.5	-4.9	-4.7	-5.1
Tier 3	-50.7	-56.8	-59.8	-52.7	-55.0	-57.4	-53.9	-56.9	-50.7	-41.1
Grassland Converted to Cropland (GCC)	7.8	7.4	4.9	4.8	4.0	4.0	2.8	2.9	5.0	5.3
Tier 2	5.2	5.2	5.0	4.6	4.8	4.8	4.7	4.7	4.5	4.5
Tier 3	2.6	2.2	-0.1	0.2	-0.7	-0.8	-1.9	-1.8	0.4	0.8
Forest Converted to Cropland (FCC) (Tier 2 Only)	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
Other Lands Converted to Cropland (OCC) (Tier 2 Only)	-3.6	-3.6	-3.4	-3.2	-3.1	-2.9	-2.9	-2.7	-2.5	-2.4
Settlements Converted to Cropland (SCC) (Tier 2 Only)	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1
Wetlands Converted to Cropland (WCC) (Tier 2 Only)	0.4	0.3	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.2

Land Use Change Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Cropland Soil Organic C Stock Change	**-46.5**	**-62.7**	**-56.2**	**-43.5**	**-40.3**	**-39.9**	**-51.0**	**-51.7**	**-46.3**	**-44.4**
Cropland Remaining Cropland (CRC)	-51.0	-64.1	-58.7	-46.6	-44.7	-44.9	-54.3	-55.1	-49.4	-47.4
Tier 2	-4.6	-5.2	-3.6	-5.6	-5.5	-6.2	-5.7	-5.4	-5.9	-5.9
Tier 3	-46.4	-58.9	-55.1	-41.0	-39.2	-38.8	-48.6	-49.6	-43.5	-41.5
Grassland Converted to Cropland (GCC)	6.7	3.7	4.5	5.2	6.2	6.9	5.2	5.4	5.1	5.1
Tier 2	4.5	4.6	4.7	4.4	4.3	4.2	4.2	4.3	4.3	4.3
Tier 3	2.2	-0.9	-0.1	0.8	1.9	2.7	1.0	1.1	0.9	0.8
Forest Converted to Cropland (FCC) (Tier 2 Only)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Cropland (OCC) (Tier 2 Only)	-2.4	-2.4	-2.3	-2.3	-2.0	-2.0	-2.1	-2.2	-2.2	-2.3

Settlements Converted to Cropland (SCC) (Tier 2 Only)	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
Wetlands Converted to Cropland (WCC) (Tier 2 Only)	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Table A-193: Annual Change in Soil Organic Carbon Stocks in Grasslands (MMT CO_2 Eq./yr)

Land Use Change Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland Soil Organic C Stock Change	**-25.6**	**-25.4**	**-23.5**	**-23.9**	**-42.7**	**-37.0**	**-41.7**	**-39.4**	**-52.0**	**-52.0**
Grassland Remaining Grassland (GRG)	-2.2	-2.1	-0.5	2.3	-10.7	-2.5	-3.5	0.5	-5.5	-1.3
Tier 2	-0.2	-0.5	-1.1	-1.4	-1.5	-1.4	-0.7	-0.7	-1.5	-1.3
Tier 3	-1.4	-0.9	1.3	4.4	-8.5	-0.4	-2.0	2.1	-3.1	0.9
Treated Sewage Sludge Additions	-0.6	-0.6	-0.7	-0.7	-0.7	-0.8	-0.8	-0.9	-0.9	-0.9
Cropland Converted to Grassland (CCG)	-18.9	-18.7	-18.3	-18.5	-19.8	-19.8	-20.5	-20.1	-24.0	-24.7
Tier 2	-4.0	-3.9	-3.9	-4.3	-4.9	-4.8	-4.8	-4.8	-5.6	-5.9
Tier 3	-15.0	-14.8	-14.4	-14.2	-15.0	-14.9	-15.7	-15.3	-18.3	-18.8
Forest Converted to Grassland (FCG) (Tier 2 Only)	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Other Lands Converted to Grassland (OCG) (Tier 2 Only)	-4.2	-4.3	-4.5	-7.2	-11.4	-14.0	-16.7	-18.8	-21.4	-24.7
Settlements Converted to Grassland (SCG) (Tier 2 Only)	-0.2	-0.2	-0.2	-0.3	-0.5	-0.7	-0.8	-0.9	-1.0	-1.2
Wetlands Converted to Grassland (WCG) (Tier 2 Only)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Land Use Change Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Grassland Soil Organic C Stock Change	**-69.9**	**-61.9**	**-63.7**	**-64.8**	**-58.7**	**-57.4**	**-71.2**	**-55.9**	**-59.9**	**-58.6**
Grassland Remaining Grassland (GRG)	-13.9	-2.5	-4.0	-5.7	0.0	0.8	-12.0	2.2	-5.0	-3.9
Tier 2	-1.4	-1.5	-2.6	-2.6	-0.9	-1.1	-1.3	-1.4	-1.4	-1.6
Tier 3	-11.5	0.0	-0.4	-2.0	1.9	3.0	-9.6	4.8	-2.3	-1.0
Treated Sewage Sludge Additions	-1.0	-1.0	-1.0	-1.0	-1.1	-1.1	-1.2	-1.2	-1.2	-1.3
Cropland Converted to Grassland (CCG)	-26.4	-26.4	-26.8	-26.1	-25.7	-25.0	-26.0	-24.9	-21.7	-21.5
Tier 2	-6.1	-6.3	-6.2	-5.9	-5.8	-5.6	-5.4	-5.2	-5.0	-4.7
Tier 3	-20.3	-20.2	-20.6	-20.1	-19.9	-19.4	-20.6	-19.8	-16.7	-16.8
Forest Converted to Grassland (FCG) (Tier 2 Only)	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Other Lands Converted to Grassland (OCG) (Tier 2 Only)	-28.3	-31.4	-31.4	-31.6	-31.5	-31.7	-31.6	-31.7	-31.7	-31.8
Settlements Converted to Grassland (SCG) (Tier 2 Only)	-1.3	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4
Wetlands Converted to Grassland (WCG) (Tier 2 Only)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Land Use Change Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Grassland Soil Organic C Stock Change	**-43.0**	**-45.0**	**-58.1**	**-41.8**	**-32.5**	**-36.8**	**-40.0**	**-38.9**	**-38.2**	**-34.3**
Grassland Remaining Grassland (GRG)	10.6	7.9	-6.3	6.4	10.0	4.0	0.7	2.2	2.7	5.5
Tier 2	-1.6	-1.5	-0.6	-0.2	1.1	0.1	-0.2	-0.1	0.0	0.0
Tier 3	13.5	10.8	-4.3	8.0	10.3	5.4	2.3	2.5	2.9	5.7
Treated Sewage Sludge Additions	-1.3	-1.3	-1.4	-1.4	-1.4	-1.5	-1.5	-0.2	-0.2	-0.2
Cropland Converted to Grassland (CCG)	-20.3	-19.4	-18.3	-17.5	-15.9	-16.9	-21.3	-21.6	-21.6	-21.1
Tier 2	-4.6	-4.6	-4.5	-4.1	-3.5	-3.4	-5.7	-5.8	-6.0	-6.1
Tier 3	-15.7	-14.8	-13.8	-13.3	-12.4	-13.4	-15.6	-15.8	-15.6	-15.0
Forest Converted to Grassland (FCG) (Tier 2 Only)	-0.1	-0.1	-0.1	-0.1	0.0	-0.1	-0.2	-0.2	-0.2	-0.2
Other Lands Converted to Grassland (OCG) (Tier 2 Only)	-31.8	-32.1	-32.0	-29.5	-25.6	-22.9	-18.4	-18.4	-18.2	-17.7

Settlements Converted to Grassland (SCG) (Tier 2 Only)	-1.4	-1.4	-1.4	-1.3	-1.1	-1.0	-0.9	-0.9	-0.9	-0.8
Wetlands Converted to Grassland (WCG) (Tier 2 Only)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A-194: Methane Emissions from Rice Cultivation (MMT CO_2 Eq.)

Approach	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Rice Methane Emission	**16.0**	**16.1**	**16.1**	**17.1**	**15.7**	**16.5**	**16.7**	**15.4**	**17.1**	**17.7**
Tier 1	2.2	2.3	2.4	2.4	2.5	2.3	2.4	2.3	2.7	4.2
Tier 3	13.8	13.9	13.8	14.7	13.2	14.2	14.3	13.1	14.4	13.5

Approach	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Rice Methane Emission	**19.0**	**15.4**	**17.7**	**14.7**	**15.6**	**18.0**	**14.7**	**15.9**	**14.1**	**16.2**
Tier 1	4.4	2.8	2.5	2.4	2.4	2.2	1.9	2.2	1.8	2.5
Tier 3	14.6	12.6	15.2	12.3	13.2	15.8	12.8	13.8	12.2	13.7

Approach	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Rice Methane Emission	**18.9**	**15.3**	**15.2**	**13.8**	**15.4**	**16.2**	**15.8**	**14.9**	**15.6**	**15.1**
Tier 1	2.4	2.1	2.8	2.1	3.4	2.4	2.4	2.5	2.5	2.5
Tier 3	16.5	13.2	12.4	11.7	12.0	13.8	13.4	12.4	13.1	12.5

Note: Estimates after 2015 are based on a data splicing method (See *Rice Cultivation* section for more information). The Tier 1 and 3 methods will be applied in a future inventory to recalculate the part of the time series that is estimated with data splicing.

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). Table A-195 lists the direct N_2O emissions associated with drainage of organic soils in cropland and grassland.

Table A-195: Direct Soil N_2O Emissions from Drainage of Organic Soils (MMT CO_2 Eq.)

Land Use	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Organic Soil Emissions	**6.3**	**6.2**	**6.2**	**6.3**	**6.3**	**6.3**	**6.3**	**6.2**	**6.2**	**6.2**
Cropland	3.8	3.8	3.7	3.7	3.7	3.8	3.8	3.7	3.7	3.7
Grassland	2.5	2.5	2.5	2.5	2.6	2.5	2.5	2.5	2.5	2.5

Land Use	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Organic Soil Emission	**6.2**	**6.2**	**6.2**	**6.1**	**6.1**	**6.1**	**6.1**	**6.0**	**6.0**	**6.0**
Cropland	3.7	3.8	3.8	3.7	3.7	3.7	3.7	3.6	3.6	3.5
Grassland	2.5	2.4	2.4	2.3	2.4	2.4	2.4	2.4	2.4	2.5

Land Use	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Organic Soil Emission	**6.0**	**6.0**	**6.0**	**5.9**	**5.9**	**5.9**	**5.9**	**5.9**	**5.9**	**5.9**
Cropland	3.5	3.5	3.5	3.5	3.4	3.4	3.4	3.4	3.4	3.4
Grassland	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5

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 organic soils in cropland and grassland are estimated annually from 1990 through 2015, based on the land-use and management activity data in conjunction with appropriate emission factors. The activity data are based on annual data from 1990 through 2015 from the NRI. Organic soil emission factors that are 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-196). 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 soil organic C change for 1,000 iterations 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-197 for croplands and Table A-198 for grasslands.

Table A-196: 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	14.3±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-197: Soil Organic Carbon Stock Changes due to Drainage of Organic Soils in Cropland (MMT CO_2 Eq.)

Land Use Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Cropland Soil Organic C Stock Change	**38.6**	**38.0**	**38.1**	**38.3**	**38.5**	**38.6**	**38.5**	**38.5**	**38.5**	**32.9**
Cropland Remaining Cropland (CRC)	35.0	34.2	34.5	34.2	34.2	34.1	33.9	34.0	33.6	28.0
Grassland Converted to Cropland (GCC)	2.7	2.8	2.8	3.1	3.2	3.5	3.5	3.4	3.8	3.8
Forest Converted to Cropland (FCC)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Cropland (OCC)	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Cropland (SCC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Cropland (WCC)	0.6	0.6	0.6	0.7	0.8	0.9	0.9	0.9	0.9	0.9

Land Use Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Cropland Soil Organic C Stock Change	**32.5**	**39.0**	**38.8**	**38.6**	**38.1**	**37.7**	**37.5**	**36.7**	**36.4**	**36.0**
Cropland Remaining Cropland (CRC)	27.9	33.5	33.5	33.7	33.8	33.4	33.2	32.6	32.4	32.2
Grassland Converted to Cropland (GCC)	3.6	4.5	4.5	4.1	3.6	3.5	3.5	3.3	3.4	3.1
Forest Converted to Cropland (FCC)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
Other Lands Converted to Cropland (OCC)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Cropland (SCC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Cropland (WCC)	0.7	0.7	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.5

Land Use Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Cropland Soil Organic C Stock Change	**36.1**	**36.1**	**36.2**	**35.3**	**36.3**	**35.8**	**35.2**	**36.5**	**36.5**	**36.6**
Cropland Remaining Cropland (CRC)	32.3	32.4	32.3	31.3	32.5	32.1	31.6	32.8	32.8	32.9
Grassland Converted to Cropland (GCC)	3.1	3.1	3.4	3.5	3.4	3.3	3.3	3.3	3.3	3.3
Forest Converted to Cropland (FCC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other Lands Converted to Cropland (OCC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Cropland (SCC)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Cropland (WCC)	0.6	0.6	0.5	0.5	0.3	0.3	0.3	0.3	0.4	0.4

Table A-198: Soil Organic Carbon Stock Changes due to Drainage of Organic Soils in Grasslands (MMT CO_2 Eq)

Land Use Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland Soil Organic C Stock Change	**7.1**	**7.0**	**7.1**	**7.1**	**7.2**	**7.1**	**7.0**	**7.0**	**7.0**	**7.1**
Grassland Remaining Grassland (GRG)	6.3	6.2	6.2	6.1	6.1	6.0	6.0	5.9	5.7	5.7

Cropland Converted to Grassland (CCG)	0.6	0.6	0.7	0.8	0.9	0.9	0.8	0.8	1.0	1.0
Forest Converted to Grassland (FCG)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Other Lands Converted to Grassland (OCG)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Grassland (SCG)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Grassland (WCG)	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Land Use Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Grassland Soil Organic C Stock Change	**7.1**	**7.0**	**7.1**	**6.9**	**7.1**	**7.1**	**7.1**	**7.1**	**7.1**	**7.3**
Grassland Remaining Grassland (GRG)	5.6	5.3	5.3	5.2	5.2	5.2	5.2	5.2	5.3	5.3
Cropland Converted to Grassland (CCG)	1.1	1.2	1.4	1.3	1.5	1.5	1.4	1.4	1.3	1.5
Forest Converted to Grassland (FCG)	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Other Lands Converted to Grassland (OCG)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Grassland (SCG)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Grassland (WCG)	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3

Land Use Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Grassland Soil Organic C Stock Change	**7.3**	**7.3**	**7.3**	**7.3**	**7.3**	**7.3**	**7.3**	**7.3**	**7.2**	**7.2**
Grassland Remaining Grassland (GRG)	5.3	5.3	5.3	5.3	5.5	5.4	5.4	5.4	5.4	5.4
Cropland Converted to Grassland (CCG)	1.5	1.4	1.4	1.4	1.3	1.4	1.4	1.4	1.3	1.3
Forest Converted to Grassland (FCG)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Other Lands Converted to Grassland (OCG)	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Grassland (SCG)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Grassland (WCG)	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.2	0.2	0.2

Step 4: Estimate Indirect Soil N_2O Emissions for Croplands and Grasslands

In this step, soil 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 volatilized 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 indirect soil 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 and implied emission factors are provided in Table A-190 for cropland and in Table A-191 for grassland.

Step 4b: Indirect Soil N_2O Emissions Due to Leaching and Runoff

The amounts 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 water flows are used to calculate indirect emissions from leaching of mineral N from soils and losses in runoff 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 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). The emission estimates are provided in Table A-199 and Table A-200 including the implied Tier 3 emission factors.

Table A-199: Indirect Soil N_2O Emissions for Cropland from Volatilization and Atmospheric Deposition, and from Leaching and Runoff (MMT CO_2 Eq.)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Cropland Indirect Emissions	**34.2**	**31.5**	**33.7**	**37.9**	**29.3**	**34.1**	**33.7**	**32.2**	**36.3**	**32.7**
Volatilization & Atmospheric Deposition	6.5	6.3	6.1	6.4	6.6	6.7	6.7	6.7	6.9	6.9
Leaching & Runoff	27.7	25.3	27.7	31.5	22.7	27.4	27.0	25.5	29.3	25.8
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

Source	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Cropland Indirect Emissions	**30.1**	**35.0**	**32.1**	**33.3**	**36.6**	**31.6**	**33.1**	**35.0**	**36.6**	**35.8**
Volatilization & Atmospheric Deposition	7.0	7.0	7.2	7.2	7.4	7.3	7.2	7.2	7.2	7.1
Leaching & Runoff	23.1	28.0	24.8	26.1	29.2	24.4	25.8	27.8	29.3	28.7
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

Source	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Cropland Indirect Emissions	**36.1**	**35.2**	**28.6**	**37.9**	**37.6**	**42.7**	**38.8**	**37.4**	**42.3**	**43.8**
Volatilization & Atmospheric Deposition	7.6	7.3	6.9	7.7	8.0	8.5	8.1	7.9	8.0	7.9
Leaching & Runoff	28.5	28.0	21.6	30.2	29.6	34.2	30.7	29.5	34.4	35.9
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

Note: Estimates after 2015 are based on a data splicing method (See the *Agricultural Soil Management* section for more information). The Tier 1 and 3 methods will be applied in a future inventory to recalculate the part of the time series that is estimated with the data splicing methods.

Table A-200: Indirect Soil N_2O Emissions for Grassland from Volatilization and Atmospheric Deposition, and from Leaching and Runoff (MMT CO_2 Eq.)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland Indirect Emissions	**9.2**	**9.1**	**9.4**	**9.7**	**9.0**	**9.3**	**9.1**	**9.5**	**10.5**	**9.3**
Volatilization & Atmospheric Deposition	3.6	3.5	3.6	3.5	3.5	3.5	3.6	3.6	3.7	3.5
Leaching & Runoff	5.6	5.5	5.8	6.3	5.6	5.8	5.5	5.9	6.8	5.8
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

Source	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Grassland Indirect Emissions	**8.2**	**9.8**	**9.5**	**9.0**	**10.5**	**9.2**	**9.1**	**10.0**	**9.9**	**10.2**
Volatilization & Atmospheric Deposition	3.2	3.4	3.5	3.5	3.8	3.6	3.6	3.6	3.5	3.5
Leaching & Runoff	5.0	6.4	6.0	5.5	6.7	5.6	5.5	6.5	6.4	6.7
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

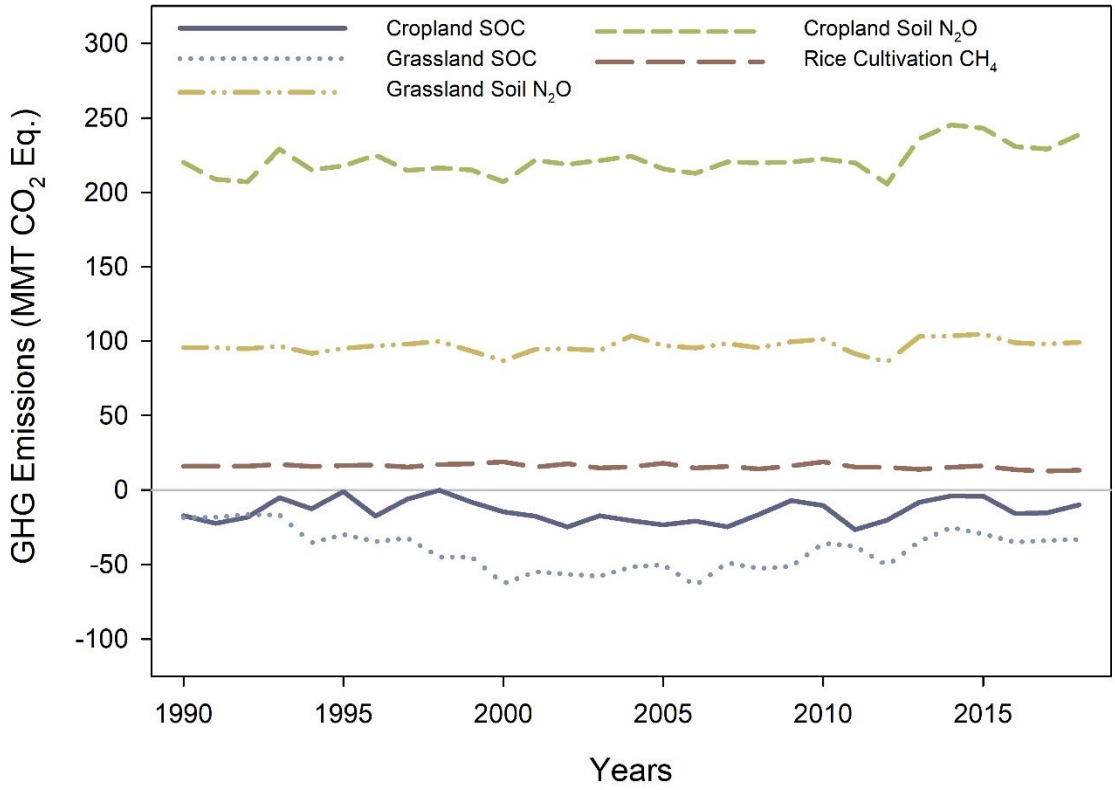
Source	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Grassland Indirect Emissions	**9.8**	**9.5**	**8.8**	**10.2**	**9.3**	**10.8**	**9.9**	**9.8**	**10.0**	**10.4**
Volatilization & Atmospheric Deposition	3.6	3.2	3.3	3.7	3.7	3.7	3.5	3.5	3.5	3.6
Leaching & Runoff	6.2	6.2	5.6	6.5	5.6	7.2	6.4	6.3	6.4	6.8
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

Note: Estimates after 2015 are based on a data splicing method (See the *Agricultural Soil Management* section for more information). The Tier 1 and 3 methods will be applied in a future inventory to recalculate the part of the time series that is estimated with the data splicing methods.

Step 5: Estimate Total Emissions for U.S. Agricultural Soils

Total N_2O emissions are estimated by summing total direct and indirect emissions for croplands and grasslands (both organic and mineral soils). Total soil organic C stock changes for cropland (*Cropland Remaining Cropland* and *Land Converted to Cropland*) and grassland (*Grassland Remaining Grassland* and *Land Converted to Grassland*) are summed to determine the total change in soil organic C stocks (both organic and mineral soils). Total rice CH_4 emissions are estimated by summing results from the Tier 1 and 3 methods. The results are provided in Figure A-7. In general, N_2O emissions from agricultural soil management have been increasing slightly from 1990 to 2019, while CH_4 emissions from rice cultivation have been relatively stable. Agricultural soil organic C stocks have increased for most years in croplands and grasslands leading to sequestration of C in soils, with larger increases in grassland soils.

Figure A-7: GHG Emissions and Removals for Cropland & Grassland



Direct and indirect simulated emissions of soil N_2O vary regionally in croplands and grasslands as a function of N input, other management practices, weather, and soil type. The highest total N_2O emissions for 2015[127] occur in Iowa, Illinois, Kansas, Minnesota, Missouri, Montana, Nebraska, South Dakota, and Texas (Table A-201). These areas are used to grow corn or have extensive areas of grazing with large amounts of PRP manure N inputs. 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 states with largest increases in soil organic C stocks in 2015 include Illinois, Iowa, Missouri, Nebraska, North Dakota (Table A-201). These states tend to have larger amounts of land conversion to grassland and/or more conservation practices such as enrollment in Conservation Reserve Program or adoption of conservation tillage. For rice cultivation, the states with highest CH_4 emissions are Arkansas, California, Louisiana and Texas (Table A-201). 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 flooding, and with the residues left from the initial rice crop, there are additional CH_4 emissions compared to non-ratoon rice management

[127] The emissions data at the state scale is available for 1990 to 2015, but data splicing methods have been applied at national scales to estimate emissions for most emission sub-source categories for 2016 to 2019. Therefore, the final year of emissions data at the state scale is 2015.

systems.

Table A-201: Total Soil N_2O Emissions (Direct and Indirect), Soil Organic C Stock Changes and Rice CH_4 Emissions from Agricultural Lands by State in 2015 (MMT CO_2 Eq.)

	N_2O Emissions[a]		Soil Organic C Stock Change		Rice	Total
State	Croplands	Grasslands	Croplands	Grasslands	CH_4	Emissions
AL	1.34	1.15	-0.39	-1.00	0.00	1.10
AR	5.30	1.37	-0.65	-0.72	6.39	11.69
AZ	0.24	3.82	0.16	-0.27	0.00	3.95
CA	1.08	2.07	0.45	-3.57	4.14	4.17
CO	3.38	4.37	0.06	-2.24	0.00	5.57
CT	0.06	0.02	-0.05	-0.05	0.00	-0.02
DE	0.17	0.02	-0.04	-0.03	0.00	0.12
FL	0.25	1.68	11.88	0.16	0.00	13.97
GA	1.83	0.82	0.35	-0.55	0.00	2.45
HI[b]	NE	NE	0.29	0.53	0.00	0.82
IA	21.23	2.14	-3.83	-1.15	0.00	18.39
ID	2.04	1.01	-0.25	-2.05	0.00	0.76
IL	18.43	0.93	-6.23	-0.65	0.00	12.48
IN	9.02	0.61	0.51	-0.52	0.00	9.63
KS	16.28	4.98	-0.77	-1.30	0.00	19.19
KY	3.66	2.28	-0.30	-0.76	0.00	4.88
LA	3.32	0.92	-0.85	-0.55	2.57	5.41
MA	0.08	0.03	0.21	-0.02	0.00	0.30
MD	0.73	0.16	-0.04	-0.11	0.00	0.74
ME	0.16	0.07	-0.12	0.02	0.00	0.13
MI	3.73	0.70	2.50	-0.25	0.00	6.68
MN	13.26	1.39	5.75	1.18	0.01	21.60
MO	10.71	3.48	-2.93	-0.85	0.00	10.41
MS	3.50	0.84	-1.04	-0.73	1.00	3.57
MT	6.43	6.74	-1.52	1.27	0.00	12.91
NC	2.09	0.60	1.95	-0.63	0.00	4.01
ND	7.80	2.04	-3.12	-1.70	0.00	5.02
NE	13.18	4.94	-2.87	-1.15	0.00	14.10
NH	0.06	0.03	-0.04	0.01	0.00	0.05
NJ	0.14	0.04	-0.01	-0.07	0.00	0.11
NM	0.55	6.63	0.02	2.95	0.00	10.16
NV	0.20	1.10	-0.03	-1.37	0.00	-0.10
NY	2.27	1.04	-0.91	-0.13	0.00	2.28
OH	7.25	0.72	-1.79	-0.84	0.00	5.34
OK	4.56	5.26	0.55	-1.39	0.00	8.98
OR	0.96	1.11	-0.07	-1.65	0.00	0.35
PA	2.70	0.67	-1.33	-0.77	0.00	1.27
RI	0.01	0.01	0.02	-0.01	0.00	0.03
SC	1.09	0.37	-0.18	-0.37	0.00	0.90
SD	10.84	4.66	-1.99	-0.89	0.00	12.62
TN	2.60	1.67	-0.63	-0.60	0.00	3.04
TX	13.66	16.72	2.10	-1.11	1.43	32.80
UT	0.60	1.26	0.22	-3.72	0.00	-1.65
VA	1.43	1.26	-0.73	-0.42	0.00	1.54
VT	0.35	0.16	-0.11	0.01	0.00	0.42
WA	1.69	0.70	-0.03	0.01	0.00	2.37
WI	5.98	1.18	2.18	0.24	0.00	9.58
WV	0.24	0.48	-0.30	-0.29	0.00	0.12
WY	0.77	3.79	-0.22	0.03	0.00	4.38

[a] This table only includes N_2O emissions estimated by DayCent using the Tier 3 method.
[b] N_2O emissions are not reported for Hawaii except from cropland organic soils, which are estimated with the Tier 1 method and therefore not included in this table.

Tier 3 Model Description, Parameterization and Evaluation

The DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011) simulates biogeochemical C and N fluxes between the atmosphere, vegetation, and soil. The model provides a more complete estimation of soil organic C stock changes, CH_4 and N_2O emissions than IPCC Tier 1 or 2 methods by accounting for a broader suite of environmental drivers that influence emissions and C stock changes. These drivers 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 organic 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, and ensuring conservation of mass. For example, plant growth is controlled by nutrient availability, water, and temperature stress. Plant growth, along with residue management, determines C inputs to soils and influences C stock changes. Removal of soil mineral N by microbial organisms influences the amount of production and C inputs, while plant uptake of N influence availability of N for microbial processes of nitrification and denitrification that generate N_2O emissions. 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.

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 United States and extensively tested 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 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, perennial/horticultural crops, and crops that are rotated with these crops). For these latter cases, an IPCC Tier 2 method has been used to estimate soil organic C stock changes, and IPCC Tier 1 method is used to estimate CH_4 and N_2O emissions. The model can also be used to estimate the amount of nitrate leaching and runoff, as well as volatilization of ammonia and nitrogen oxides, which are subject to indirect N_2O emissions.
3) Much of the data needed for the model is available from existing national databases. The exceptions are management of federal grasslands and amendments of biosolids (i.e., treated sewage sludge) to soils, which are not known at a sufficient resolution or detail to use the Tier 3 model. Soil N_2O emissions and C stock changes associated with these practices are addressed with Tier 1 and 2 methods, respectively.

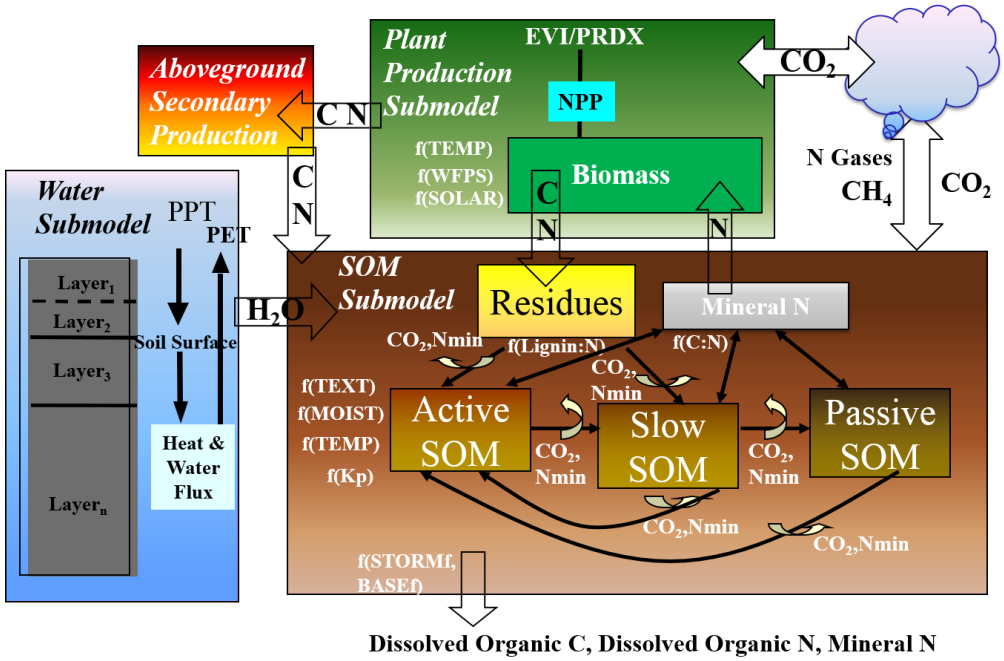
DayCent Model Description

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-8). Each submodel is described 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. The NASA-CASA production algorithm is only used for the following major crops: corn, soybeans, sorghum, cotton, wheat, and other close-grown crops such as

barley and oats.[128] 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 by 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-9.

Figure A-8: DayCent Model Flow Diagram



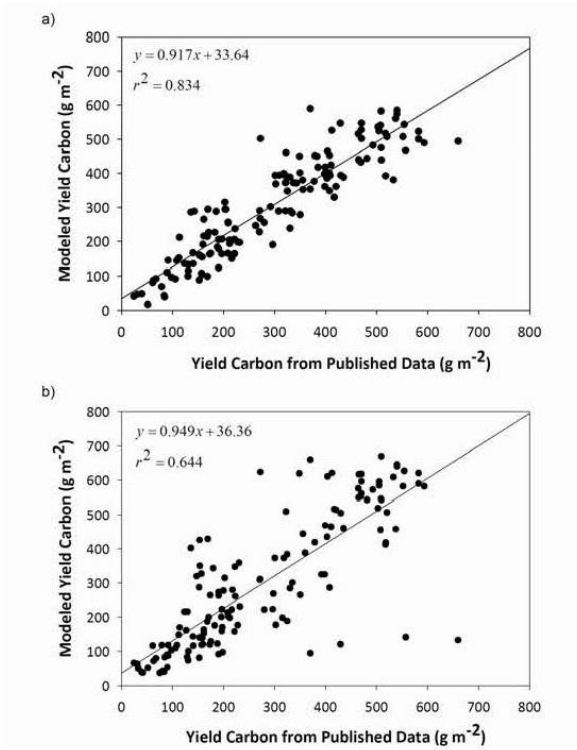
2) Dynamics of soil organic C and N (Figure A-8) are simulated for the surface and belowground litter pools and soil organic matter in the top 30 cm of the soil profile; mineral N dynamics are simulated through the whole soil profile. Organic C and N stocks are represented by two plant litter pools (metabolic 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 be influenced the most by land use and management activity. 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.

3) The soil-water submodel simulates water flows and changes in soil water availability, which influences both plant growth, decomposition and nutrient cycling. Soil moisture content is simulated through a multi-layer

[128] It is a planned improvement to estimate NPP for additional crops and grass forage with the NASA-CASA method in the future.

profile based on precipitation, snow accumulation and melting, interception, soil and canopy evaporation, transpiration, soil water movement, runoff, and drainage.

Figure A-9: Modeled versus measured net primary production



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. Soil 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 A-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 different crop types, crop sequences (e.g., rotation), cover crops, 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. 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.

Box A-2: DayCent Model Simulation of N Gas losses and Nitrate Leaching

The DayCent model simulates the two biogeochemical processes, nitrification and denitrification, that result in N_2O and NOx 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/m2/day)
NH4+	=	the model-derived soil ammonium concentration (g N/m^2)
Kmax	=	the maximum fraction of NH4+ nitrified (Kmax = 0.10/day)
F(t)	=	the effect of soil temperature on nitrification (Figure A-10a)
F(WFPS)	=	the effect of soil water content and soil texture on nitrification (Figure A-10b)
F(pH)	=	the effect of soil pH on nitrification (Figure A-10c)

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:

$$Den = \min[F(CO_2), F(NO3)] \times F(WFPS)$$

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-11a)
F(CO_2)	=	a function relating N gas flux to soil respiration (Figure A-11b)
F(WFPS)	=	a dimensionless multiplier (Figure A-11c)

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-10b). 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.

After calculating and summing N_2O emissions from nitrification and dentification, NOx emissions are calculated using a NOx/N_2O ratio function based on soil gas diffusivity. The NOx/N_2O ratio is high (maximum of about 17) when soil gas diffusivity is high and decreases to a minimum of approximately 0.28 as diffusivity decreases.

Ammonia volatilization is simulated less mechanistically than the other N gas losses. A soil texture specific portion of N excreted from animals ranging from 15-30 percent is assumed to be volatilized with more volatilization as soil texture becomes coarser. In addition, a plant specific portion ranging from 2-15 % of harvested or senesced biomass N is assumed to be volatilized.

A portion of the nitrate is assumed to be dissolved and flows with water between soil layers during saturated and unsaturated water movement. The portion of nitrate that flows from the upper layer to the lower layer increases with increasing sand content and with water flow volume so most movement occurs during saturated flow events triggered by precipitation or irrigation. The amount of nitrate leaching for estimating indirect N2O emissions is based on the nitrate that flows through the entire profile in the model simulation. In addition to sand content, leaching rates are influenced by soil depth, plant N demand, precipitation event size, and other factors.

Figure A-10: Effect of Soil Temperature (a), Water-Filled Pore Space (b), and pH (c) on Nitrification Rates

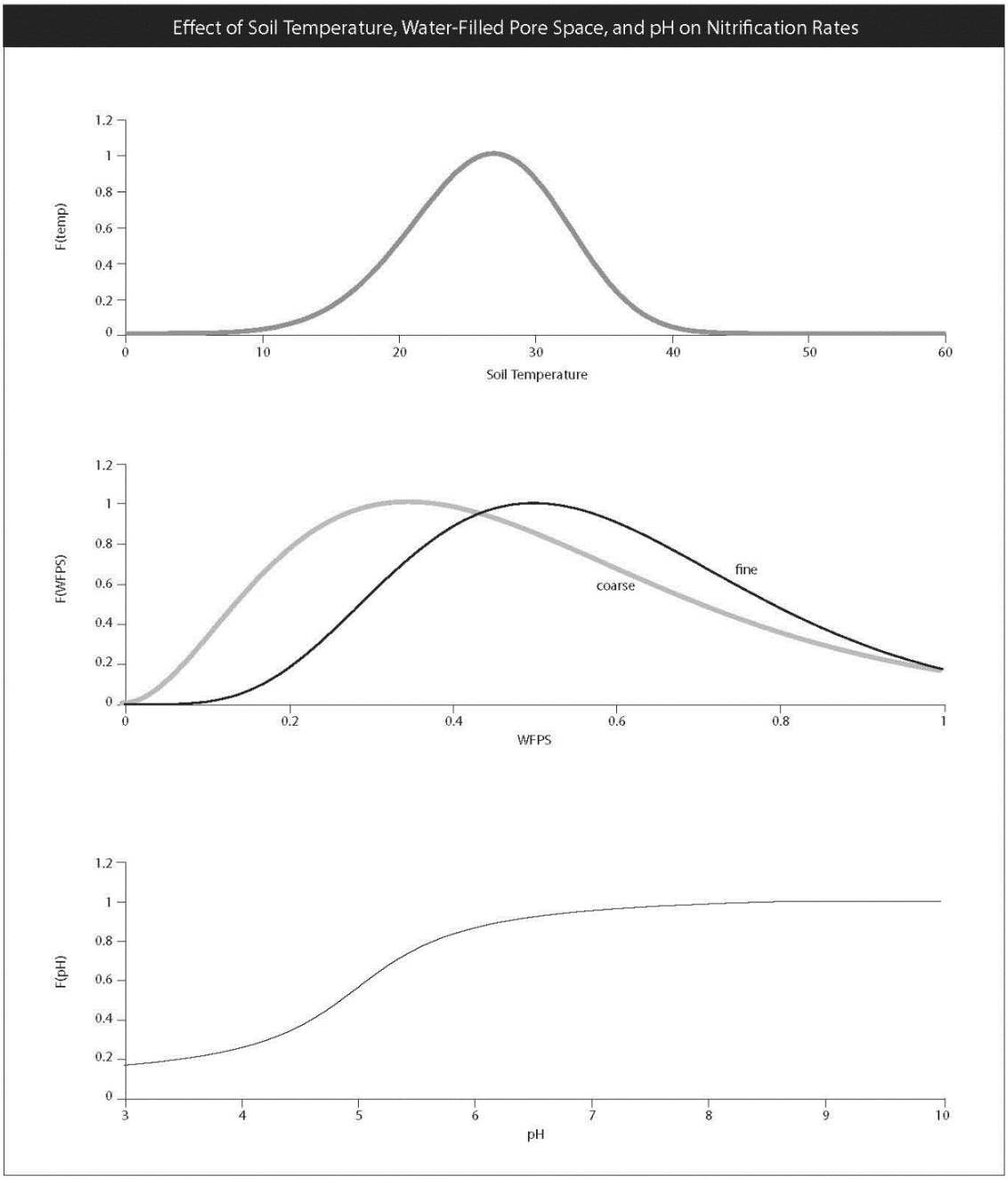
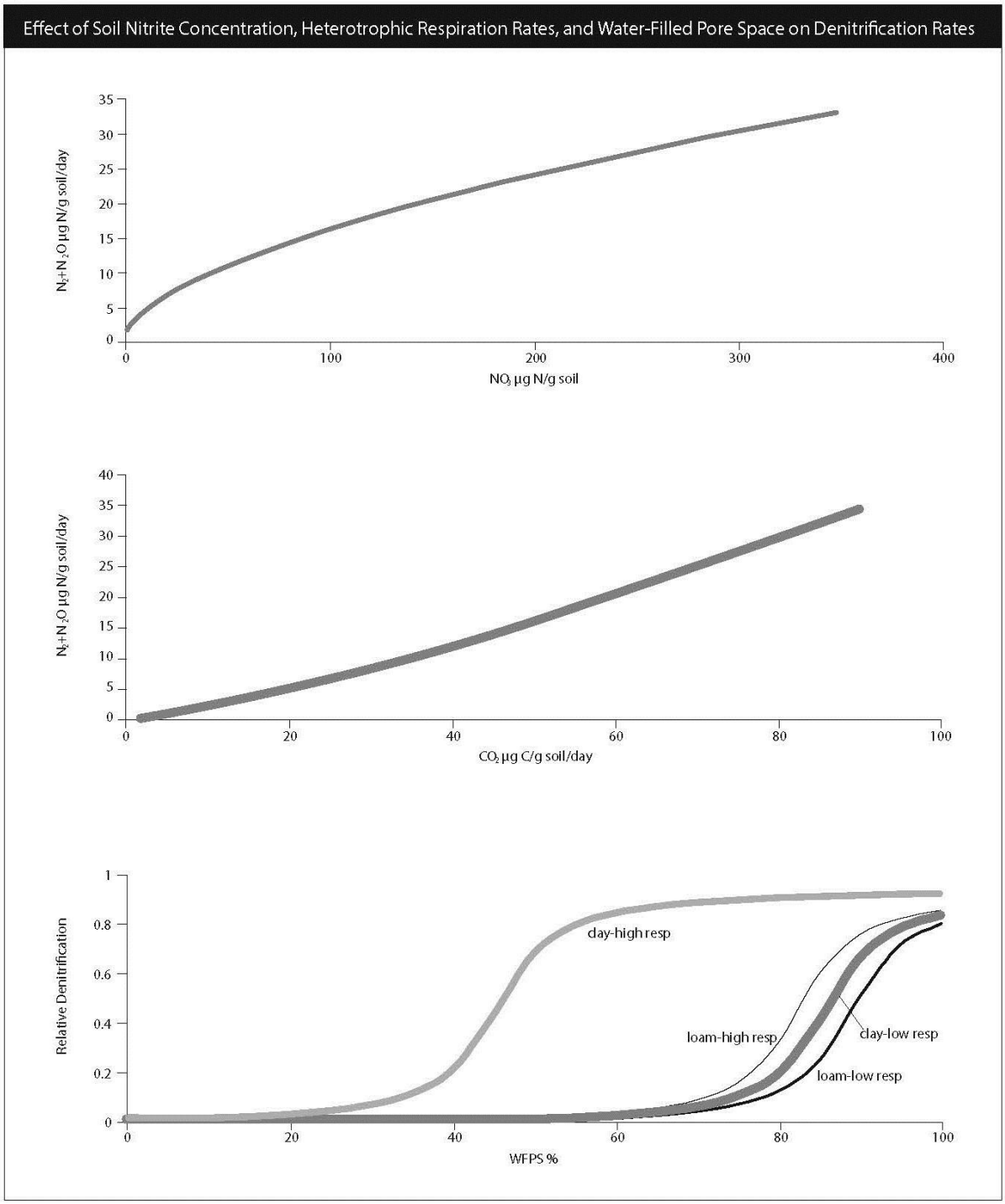


Figure A-11: Effect of Soil Nitrite Concentration (a), Heterotrophic Respiration Rates (b), and Water-Filled Pore Space (c) on Denitrification Rates



Hot moments, or pulses, of N_2O emissions can occur during freeze-thaw events in soils of cold climates, and these events can contribute a substantial portion of annual emissions in northern temperate and boreal regions (Butterbach-Bahl et al. 2017). A recent analysis suggests that not accounting for these events could lead to under-estimation of global agricultural N_2O emissions by 17-28 percent (Wagner-Riddle et al. 2017). The mechanisms responsible for this phenomenon are not entirely understood but the general hypotheses include accumulation of substrates while the soil is frozen that drives denitrification as the soil thaws; impacts on soil gas diffusivity and O_2

availability in pores during freeze-thaw events that influence denitrification rates; and differing temperature sensitives of the enzymatic processes that control the amounts of N_2 and N_2O gases released during denitrification (Congreves et al. 2018). The denitrification routine in DayCent was amended so that periods of thawing of frozen soils in the 2-5 cm layer during the late winter/spring will trigger a hot moment or pulse of N_2O emissions. Specifically, the soil water content and microbial respiration controls on denitrification are relaxed for approximately 3 days upon melting and N_2O from denitrification is amplified by an amount proportional to cumulative freezing degree days during the winter season. DayCent was evaluated using annual high frequency N_2O data collected at research sites in eastern and western Canada (Wagner-Riddle et al. 2017). The results showed less bias with a better match to observed patterns of late winter/spring emissions than the previous version of the DayCent model (Del Grosso et al. 2020).

DayCent Model Parameterization and Evaluation

DayCent has been widely applied and calibrated over the years through manual parameterization (e.g., Parton et al. 1998; Del Grosso et al. 2001). However, manual approaches to parametrization do not necessarily provide the best calibration for a process-based model, and so there is an effort underway to re-parameterize DayCent with Bayesian calibration methods. There are three steps to this calibration method: a) conduct a sensitivity analysis to identify the most influential parameters, b) conduct the Bayesian calibration with the most sensitive parameters, and 3) evaluate the results with independent data. First, the framework uses a global sensitivity analysis to evaluate the importance of parameters given their full parameter space and potential interactions with other parameters (Saltelli et al. 2008). This approach is considered more robust for ranking parameter importance rather than a local sensitivity analysis that focuses on the effect of varying one parameter, generally within a small area of the overall parameter space. The Sobol method is used to conduct the global sensitivity analysis (Sobol 2001), which is appropriate for the complexity in the DayCent model (Saltelli 2002). Second, the model is calibrated using Bayesian logic with the Sampling Importance Resampling (SIR) method (Rubin 1987, Rubin 1988). A set of prior parameter distributions are developed based on the knowledge of the inventory compilers and information in the published literature. The model is then applied in a Monte Carlo analysis by randomly selecting values from the prior parameter distributions using a Latin Hypercube Sampling (LHS) approach. The LHS approach for selecting parameters allows for values that are used in the simulations to be distributed throughout the entire domain of the prior parameter distributions. The posterior distribution is approximated from the results generated by the Monte Carlo analysis using a likelihood function and weighting parameters based on the level of mismatch between modeled and measured emissions or soil organic C stock changes. If the data are informative, the likelihood will update the prior parameter distribution based on the weighting and lead to more resolved joint posterior parameter distribution. Third, the model is applied to simulate experimental sites that are not used in the Bayesian calibration, and the results are evaluated relative to the model application with the prior parameter distributions. If the model has been improved through the calibration process, then the results should have less bias and/or variance than the model application with the prior parameter distributions.

This Bayesian calibration model framework has initially been applied to calibrate DayCent for modeling soil organic C stock changes to a 30 cm depth (Gurung et al. 2020). The analysis reduced uncertainty in model predictions by a factor of 6.6. See Gurung et al. (2020) for more detail about this application. We anticipate expanding the calibration to other model processes in the near future, and eventually using the joint posterior parameter distribution to quantify uncertainty in model predictions. In this Inventory, the *maximum a posterior* value for each parameter from the posterior distribution has been used to simulate soil organic C stock changes.

DayCent has been applied to sites that are independent from model calibration to evaluate the effectiveness of the model for estimating GHG emissions and soil organic C stock changes in the United States inventory. Moreover, these analyses are used to quantify uncertainty with an empirical approach as discussed in Step 2a of this annex (Ogle et al. 2007). Comparison of model results and plot level data show that DayCent simulates soil organic matter levels with reasonable accuracy. The model was tested and shown to capture the general trends in C storage across 948 observations from 72 long-term experiment sites and 142 NRI soil monitoring network sites (Spencer et al. 2011) (Figure A-12). 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-13).

Figure A-12: Comparisons of Results from DayCent Model and Measurements of Soil Organic C Stocks

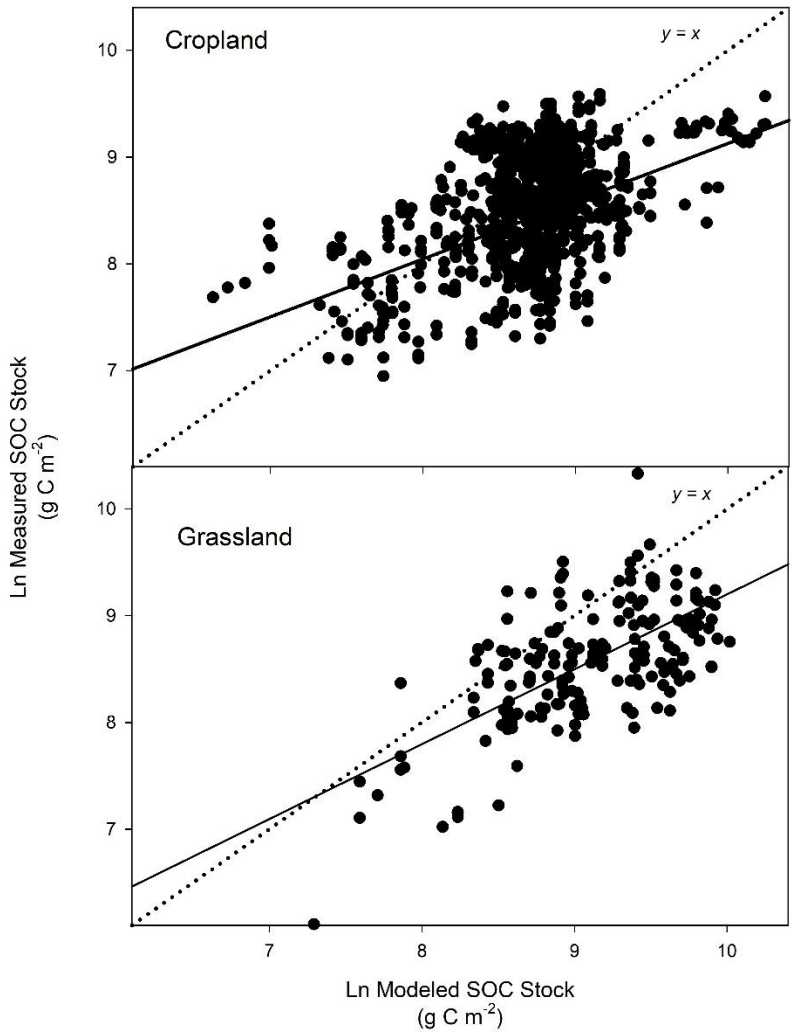
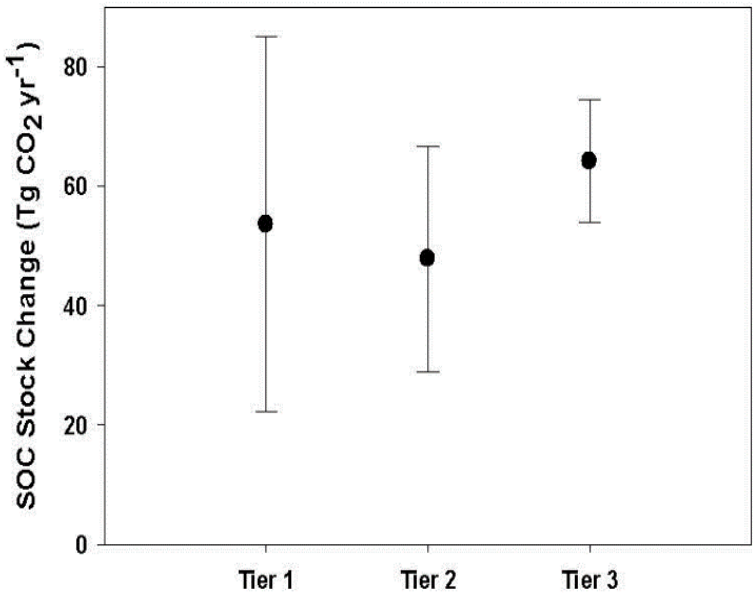


Figure A-13: Comparison of Estimated Soil Organic C Stock Changes and Uncertainties using Tier 1 (IPCC 2006), Tier 2 (Ogle et al. 2003, 2006) and Tier 3 Methods



Similarly, DayCent model results have been compared to trace gas N_2O fluxes for a number of native and managed systems from 41 experimental sites with over 200 treatment observations (Del Grosso et al. 2001, 2005, 2010) (Figure A-14). 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) with higher r^2 values and a fitted line closer to a perfect 1:1 relationship between measured and modeled N_2O emissions (Del Grosso et al. 2005, 2008). This is not surprising, since DayCent includes site-specific factors (climate, soil properties, and previous management) that influence N_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.

DayCent predictions of soil CH_4 emissions have also been compared to experimental measurements from sites in California, Texas, Arkansas, and Louisiana (Figure A-15). There are 17 long-term experiments with data on CH_4 emissions from rice cultivation, representing 238 treatment observations. In general, the model estimates CH_4 emissions with no apparent bias, but there is a lack of precision, which is addressed in the uncertainty analysis.

Figure A-14: Comparisons of Results from DayCent Model and Measurements of Soil Nitrous Oxide Emissions

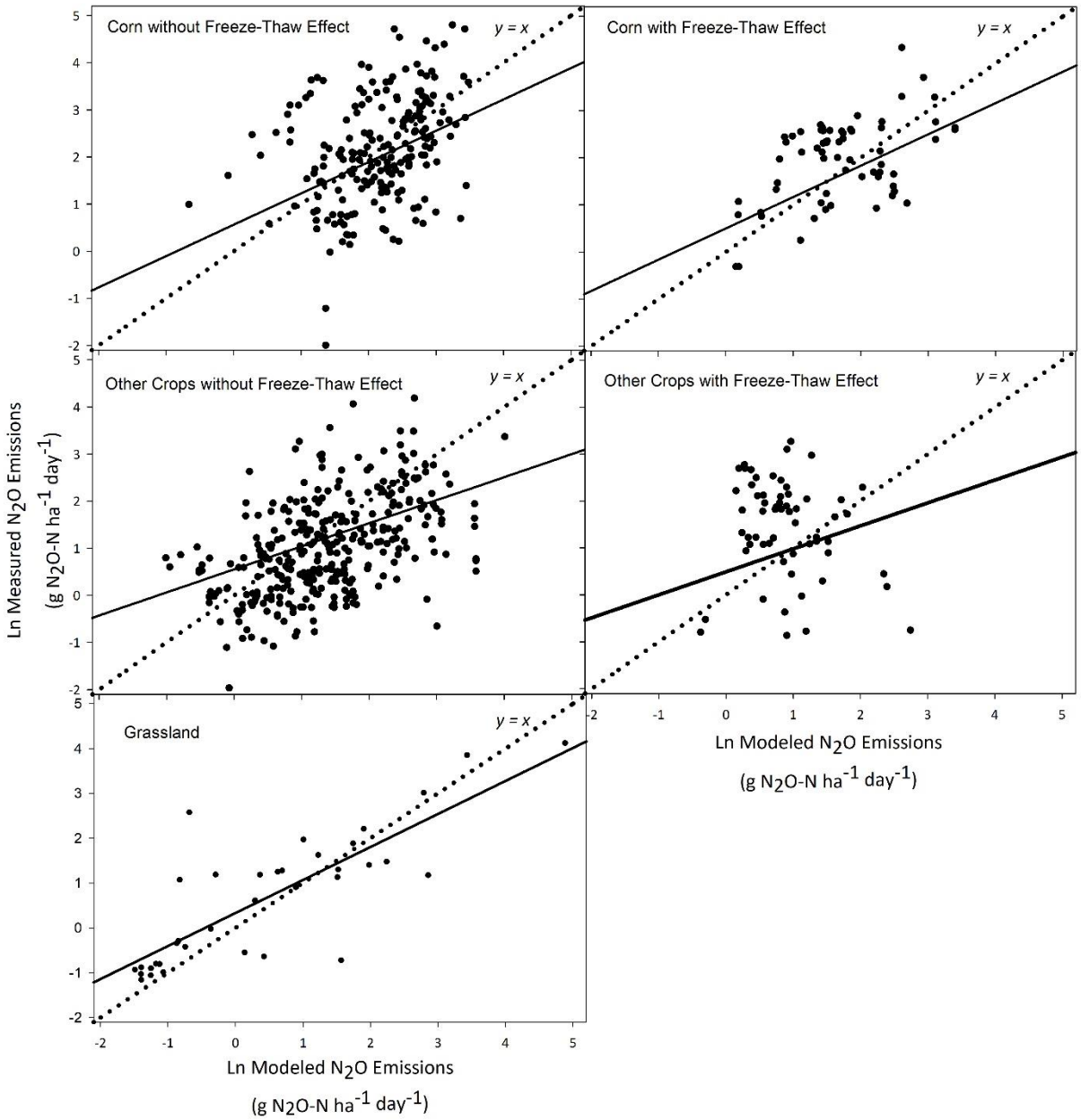
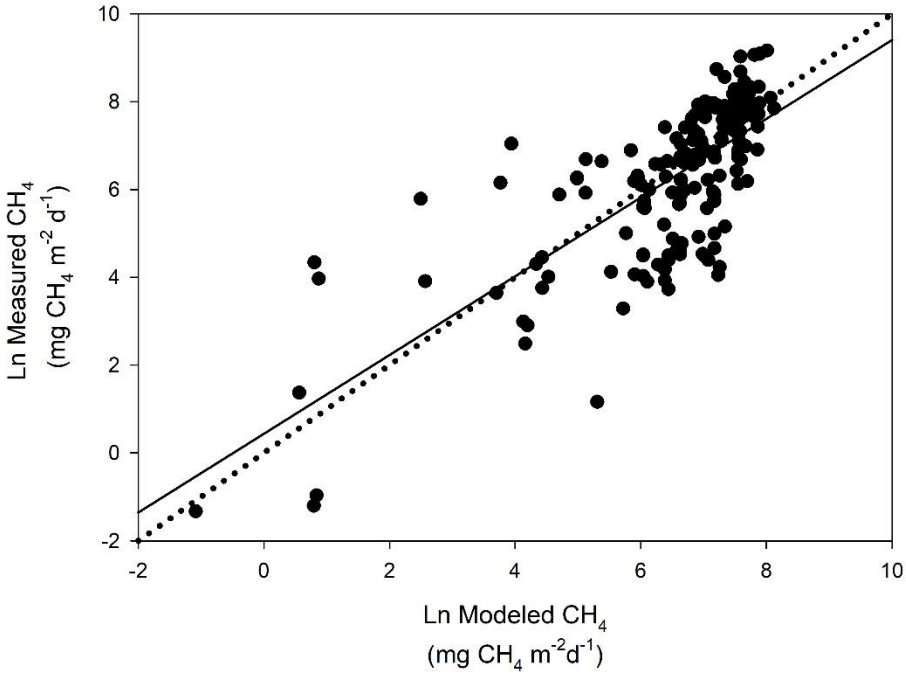


Figure A-15: Comparisons of Results from DayCent Model and Measurements of Soil Methane Emissions



References

AAPFCO (2008 through 2017) Commercial Fertilizers: 2008-2015. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

AAPFCO (1995 through 2000a, 2002 through 2007) Commercial Fertilizers: 1995-2007. Association of American Plant Food Control Officials. University of Kentucky. Lexington, KY.

Abdalla, M., Jones, J. Yeluripati, P. Smith, J. Burke and D M. Williams (2010) Testing DayCent and DNDC model simulations of N_2O fluxes and assessing the impacts of climate change on the gas flux and biomass production from a humid pasture. Atmos. Environ. 44: 2961–2970.

BLM (2014) Rangeland Inventory, Monitoring, and Evaluation Reports. Bureau of Land Management. U.S. Department of the Interior. Available online at: <http://www.blm.gov/wo/st/en/prog/more/rangeland_management/rangeland_inventory.html>.

BOEM (2014) Year 2011 Gulfwide Emissions Inventory Study (BOEM 2014-666) Bureau of Ocean Energy Management, U.S. Department of the Interior (November 2014) <http://www.data.boem.gov/PI/PDFImages/ESPIS/5/5440.pdf>.

Brakebill, J.W. and Gronberg, J.M. (2017) County-Level Estimates of Nitrogen and Phosphorus from Commercial Fertilizer for the Conterminous United States, 1987-2012: U.S. Geological Survey data release, https://doi.org/10.5066/F7H41PKX.

Butterbach-Bahl, K. & Wolf, B. (2017) Greenhouse gases: Warming from freezing soils. Nature Geosci 10(4): 248-249.

Cantens, G. (2004 through 2005) Personal Communication. Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company and ICF International.

Cheng, K., S.M. Ogle, W.J. Parton, G. Pan (2014) “Simulating greenhouse gas mitigation potentials for Chinese croplands using the DAYCENT ecosystem model.” Global Change Biology 20:948-962.

Cheng, K., S.M. Ogle, W.J. Parton and G. Pan (2013) Predicting methanogenesis from rice paddies using the DAYCENT ecosystem model. *Ecological Modelling* 261-262:19-31.

Cheng, B., and D.M. Titterington (1994) "Neural networks: A review from a statistical perspective." Statistical science 9: 2-30.

Cibrowski, P. (1996) Personal Communication. Peter Cibrowski, Minnesota Pollution Control Agency and Heike Mainhardt, ICF Incorporated. July 29, 1996.

Claassen, R., M. Bowman, J. McFadden, D. Smith, and S. Wallander (2018) Tillage intensity and conservation cropping in the United States, EIB 197. United States Department of Agriculture, Economic Research Service, Washington, D.C.

Congreves, K.A., Wagner-Riddle, C., Si, B.C. and Clough, T.J. (2018) “Nitrous oxide emissions and biogeochemical responses to soil freezing-thawing and drying-wetting.” Soil Biology and Biochemistry 117:5-15.

Coulston, J.W., Woodall, C.W., Domke, G.M., and Walters, B.F. (in preparation). Refined Delineation between Woodlands and Forests with Implications for U.S. National Greenhouse Gas Inventory of Forests. *Climatic Change*.

CTIC (2004) 2004 Crop Residue Management Survey. Conservation Technology Information Center. Available online at <http://www.ctic.purdue.edu/CRM/>.

Daly, C., G.H. Taylor, W.P. Gibson, T. Parzybok, G.L. Johnson, and P.A. Pasteris (1998) “Development of high-quality spatial datasets for the United States.” Proc., 1st International Conference on Geospatial Information in Agriculture and Forestry, Lake Buena Vista, FL, I-512-I-519. June 1-3, 1998.

Daly, C., R.P. Neilson, and D.L. Phillips (1994) “A statistical-topographic model for mapping climatological precipitation over mountainous terrain.” Journal of Applied Meteorology, 33:140-158.

Dean, W. E., and E. Gorham (1998) Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. Geology 26:535-538.

Del Grosso, S.J., S.M. Ogle, W.J. Parton, E. Marx, R. Gurung, K. Killian, and C. Nevison (2020) Freeze-thaw events accelerate soil N_2O emissions from U.S. Agricultural Soils. In review.

Del Grosso, S.J., S.M. Ogle, W.J. Parton. (2011) Soil Organic Matter Cycling and Greenhouse Gas Accounting Methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: L. Guo, A. Gunasekara, L. McConnell (Eds.) Understanding Greenhouse Gas Emissions from Agricultural Management, American Chemical Society, Washington, D.C.

Del Grosso, S.J., W.J. Parton, C.A. Keough, and M. Reyes-Fox. (2011) Special features of the DayCent modeling package and additional procedures for parameterization, calibration, validation, and applications, in Methods of Introducing System Models into Agricultural Research, L.R. Ahuja and Liwang Ma, editors, p. 155-176, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI. USA.

Del Grosso, S.J., S.M. Ogle, W.J. Parton, and F.J. Breidt (2010) "Estimating Uncertainty in N_2O Emissions from U.S. Cropland Soils." Global Biogeochemical Cycles, 24, GB1009, doi:10.1029/2009GB003544.

Del Grosso, S.J., T. Wirth, S.M. Ogle, W.J. Parton (2008) Estimating agricultural nitrous oxide emissions. EOS 89, 529-530.

Del Grosso, S.J., A.R. Mosier, W.J. Parton, and D.S. Ojima (2005) "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA." Soil Tillage and Research, 83: 9-24. doi: 10.1016/j.still.2005.02.007.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Schaffer, M., L. Ma, S. Hansen, (eds.); Modeling Carbon and Nitrogen Dynamics for Soil Management. CRC Press. Boca Raton, Florida. 303-332.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, D.S. Ojima, A.E. Kulmala and S. Phongpan (2000) General model for N_2O and N_2 gas emissions from soils due to denitrification. Global Biogeochem. Cycles, 14:1045-1060.

Delgado, J.A., S.J. Del Grosso, and S.M. Ogle (2009) "15N isotopic crop residue cycling studies and modeling suggest that IPCC methodologies to assess residue contributions to N_2O-N emissions should be reevaluated." Nutrient Cycling in Agroecosystems, DOI 10.1007/s10705-009-9300-9.

Deren, C. (2002) Personal Communication and Dr. Chris Deren, Everglades Research and Education Centre at the University of Florida and Caren Mintz, ICF International. August 15, 2002.

Domke, G.M., Woodall, C.W., Smith, J.E., Westfall, J.A., McRoberts, R.E. (2012) Consequences of alternative tree-level biomass estimation procedures on U.S. forest carbon stock estimates. Forest Ecology and Management. 270: 108-116.

Domke, G.M., Smith, J.E., and Woodall, C.W. (2011) Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. *Carbon Balance and Management*. 6:14.

Domke, G.M., Woodall, C.W., Walters, B.F., McRoberts, R.E., Hatfield, M.A. (In Review) Strategies to compensate for the effects of nonresponse on forest carbon baseline estimates from the national forest inventory of the United States. Forest Ecology and Management.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. *PLoS ONE* 8(3): e59949.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (in preparation). Estimation of forest floor carbon using the national forest inventory of the United States. Intended outlet: *Geoderma*.

Easter, M., S. Williams, and S. Ogle. (2008) Gap-filling NRI data for the Soil C Inventory. Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO. Report provided to the U.S. Environmental Protection Agency, Tom Wirth.

Edmonds, L., N. Gollehon, R.L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaeffer (2003) "Costs Associated with Development and Implementation of Comprehensive Nutrient Management Plans." Part 1. Nutrient Management, Land Treatment, Manure and Wastewater Handling and Storage, and Recordkeeping. Natural Resource Conservation Service, U.S. Department of Agriculture.

EIA (2007) Voluntary Greenhouse Gas Reports for EIA Form 1605B (Reporting Year 2006). Available online at <ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/>.

Euliss, N., and R. Gleason (2002) Personal communication regarding wetland restoration factor estimates and restoration activity data. Ned Euliss and Robert Gleason of the U.S. Geological Survey, Jamestown, ND, to Stephen Ogle of the National Resource Ecology Laboratory, Fort Collins, CO. August 2002.

Fleskes, J.P., Perry, W.M., Petrik, K.L., Spell, R., and Reid, F. (2005) Change in area of winter-flood and dry rice in the northern Central Valley of California determined by satellite imagery. California Fish and Game, 91: 207-215.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Gonzalez, R. (2007 through 2014) Email correspondence. Rene Gonzalez, Plant Manager, Sem-Chi Rice Company and ICF International.

Gurung, R. B., Ogle, S.M., Breidt, F.J., Williams, S.A., Parton, W.J. (2020) Bayesian calibration of the DayCent ecosystem model to simulate soil organic carbon dynamics and reduce model uncertainty. Geoderma 376: 114529.

Halvorson, A.D., C.S. Snyder, A.D. Blaylock, and S.J. Del Grosso (2013) Enhanced Efficiency Nitrogen Fertilizers: Potential Role in Nitrous Oxide Emission Mitigation. Agronomy Journal, doi:10.2134/agronj2013.0081

Hardke, J.T. (2015) Trends in Arkansas rice production, 2014. B.R. Wells Arkansas Rice Research Studies 2014. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 626, Arkansas Agricultural Experiment Station, University of Arkansas.

Hardke, J.T., and Wilson, C.E. Jr. (2013) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2012. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 609, Arkansas Agricultural Experiment Station, University of Arkansas.

Hardke, J.T., and Wilson, C.E. Jr. (2014) Trends in Arkansas rice production, 2013. B.R. Wells Arkansas Rice Research Studies 2013. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 617, Arkansas Agricultural Experiment Station, University of Arkansas.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Hollier, C. A. (ed) (1999) Louisiana rice production handbook. Louisiana State University Agricultural Center. LCES Publication Number 2321. 116 pp.

Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis (2005) Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978.

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.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman, et al., eds. August 13, 2004. Available online at <http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm>.

Johnson, D.M., and R. Mueller (2010) The 2009 Cropland Data Layer. Photogrammetric engineering and remote sensing 76:1201-1205.

Kirstein, A. (2003 through 2004, 2006) Personal Communication. Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, FL and ICF International.

Kraft, D.L. and H.C. Orender (1993) "Considerations for Using Sludge as a Fuel." *Tappi Journal*, 76(3): 175-183.

Li, Y., D. Chen, Y. Zhang, R. Edis and H. Ding (2005) Comparison of three modeling approaches for simulating denitrification and nitrous oxide emissions from loam-textured arable soils. Global Biogeochemical Cycles, 19, GB3002.

Little, R. (1988) "Missing-data adjustments in large surveys." *Journal of Business and Economic Statistics* 6: 287–296.

LSU (2015) Louisiana ratoon crop and conservation: Ratoon & Conservation Tillage Estimates. Louisiana State University, College of Agriculture AgCenter. Available online at: <http://www.lsuagcenter.com>.

McGill, W.B., and C.V. Cole (1981) Comparative aspects of cycling of organic C, N, S and P through soil organic matter. Geoderma 26:267-286.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Miller, M.R., Garr, J.D., and Coates, P.S. (2010) Changes in the status of harvested rice fields in the Sacramento Valley, California: Implications for wintering waterfowl. Wetlands, 30: 939-947.

Miner, C. (1998) Harvesting the High Plains: John Kriss and the business of wheat farming, 1920-1950. University Press of Kansas, Lawrence, KS.

Miner, R. (2008) "Calculations documenting the greenhouse gas emissions from the pulp and paper industry." Memorandum from Reid Minor, National Council for Air and Stream Improvement, Inc. (NCASI) to Becky Nicholson, RTI International, May 21, 2008.

Mosier, A.R., Duxbury, J.M., Freney, J.R., Heinemeyer, O., and Minami, K. (1998) Assessing and mitigating N_2O emissions from agricultural soils. Climatic Change 40:7-38.

Nair, P.K.R. and V.D. Nair. (2003) Carbon storage in North American Agroforestry systems. In Kimble J., Heath L.S., Birdsey R.A., Lal R., editors. The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect. CRC Press. Boca Raton, FL, 333–346.

NASS (2004) Agricultural Chemical Usage: 2003 Field Crops Summary. Report AgCh1(04)a, National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdf>.

NASS (1999) Agricultural Chemical Usage: 1998 Field Crops Summary. Report AgCh1(99). National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0599.pdf>.

NASS (1992) Agricultural Chemical Usage: 1991 Field Crops Summary. Report AgCh1(92). National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txt>.

NRAES (1992) On-Farm Composting Handbook (NRAES-54). Natural Resource, Agriculture, and Engineering Service. Available online at <http://compost.css.cornell.edu/OnFarmHandbook/onfarm_TOC.html>.

NRCS (1997) "National Soil Survey Laboratory Characterization Data," Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

NRCS (1981) Land Resource Regions and Major Land Resource Areas of the United States, USDA Agriculture Handbook 296, United States Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Cente., Lincoln, NE, pp. 156.

NRIAI (2003) Regional Budget and Cost Information. U.S. Department of Agriculture, Natural Resources Conservation Service, Natural Resources Inventory and Analysis Institute. Available online at <http://www.economics.nrcs.usda.gov/care/budgets/index.html>.

Nusser, S.M., F.J. Breidt, and. W.A. Fuller (1998) "Design and Estimation for Investigating the Dynamics of Natural Resources, Ecological Applications, 8:234-245.

Nusser, S.M., J.J. Goebel (1997) The national resources inventory: a long term monitoring programme. Environmental and Ecological Statistics, 4, 181-204.

Ogle, S.M., Woodall, C.W., Swan, A., Smith, J., and Wirth. T. (in preparation). Determining the Managed Land Base for Delineating Carbon Sources and Sinks in the United States. *Environmental Science and Policy*.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." Global Change Biology 16:810-822.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian. (2007) "Empirically-Based Uncertainty Associated with Modeling Carbon Sequestration Rates in Soils." Ecological Modeling 205:453-463.

Ogle, S.M., F.J. Breidt, and K. Paustian. (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." Global Change Biology 12:516-523.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." Global Change Biology 9:1521-1542.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." Soil Science Society of America Journal 51:1173-1179.

Parton, W. J., J. M. O. Scurlock, D. S. Ojima, T. G. Gilmanov, R. J. Scholes, D. S. Schimel, T. Kirchner, J.-C. Menaut, T. Seastedt, E. G. Moya, A. Kamnalrut, and J. I. Kinyamario (1993) Observations and modeling of biomass and soil organic matter dynamics for grassland biomes worldwide. Global Biogeochemical Cycles 7:785-809.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, Soil Science Society of America, Madison, WI, 147-167.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". Glob. Planet. Chang. 19: 35-48.

Parton, W.J., E.A. Holland, S.J. Del Grosso, M.D. Hartman, R.E. Martin, A.R. Mosier, D.S. Ojima, and D.S. Schimel (2001) Generalized model for NO_x and N_2O emissions from soils. Journal of Geophysical Research. 106 (D15):17403-17420.

Paustian, K., Collins, H. P. & Paul, E. A. (1997) Management controls on soil carbon. In: *Soil organic matter in temperate agroecosystems: long-term experiments in North America*, ed. E. T. E. Paul E.A., K. Paustian, and C.V. Cole, pp. 15-49. Boca Raton: CRC Press.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P. & Smith, P. (2016) Climate-smart soils. *Nature* **532**(7597): 49-57.

Peer, R., S. Thorneloe, and D. Epperson (1993) "A Comparison of Methods for Estimating Global Methane Emissions from Landfills." *Chemosphere*, 26(1-4):387-400.

Potter, C. S., J.T. Randerson, C.B. Fields, P.A. Matson, P.M. Vitousek, H.A. Mooney, and S.A. Klooster. (1993) "Terrestrial ecosystem production: a process model based on global satellite and surface data." Global Biogeochemical Cycles 7:811-841.

Potter, C., S. Klooster, A. Huete, and V. Genovese (2007) Terrestrial carbon sinks for the United States predicted from MODIS satellite data and ecosystem modeling. Earth Interactions 11, Article No. 13, DOI 10.1175/EI228.1.

PRISM Climate Group (2018) *PRISM Climate Data*, Oregon State University, <http://prism.oregonstate.edu>, downloaded 18 July 2018.

Rubin, D.B. (1988) Using the SIR Algorithm to Simulate Posterior Distributions, in: Bernardo, J.M., Degroot, M.H., Lindley, D. V, Smith, A.F.M. (Eds.), Bayesian Statistics. Oxford University Press, Cambridge, Massachusetts, pp. 395–402.

Rubin, D.B. (1987) The Calculation of Posterior Distributions by Data Augmentation: Comment: A Noniterative Sampling/Importance Resampling Alternative to the Data Augmentation Algorithm for Creating a Few Imputations When Fractions of Missing Information Are Modest: The SIR. J. Am. Stat. Assoc. 82, 543. https://doi.org/10.2307/2289460

Quam, V.C., J. Gardner, J.R. Brandle, and T.K. Boes (1992) Windbreaks in Sustainable Agricultural Systems. EC-91-1772. University of Nebraska Extension. Lincoln, NE.

Saghafi, Abouna (2013) Estimation of fugitive emissions from open cut coal mining and measurable gas content, 13th Coal Operators' Conference, University of Wollongong, The Australian Institute of Mining and Metallurgy & Mine Managers Association of Australia, 2013, 306-313.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., Tarantola, S. (2008) Global Sensitivity Analysis. The Primer, Global Sensitivity Analysis. The Primer. John Wiley & Sons, Ltd, Chichester, UK. https://doi.org/10.1002/9780470725184

Saltelli, A. (2002) Sensitivity analysis for importance assessment. Risk Anal. 22, 579–590. https://doi.org/10.1111/0272-4332.00040

Sanchis, E., Ferrer, M., Torres, A. G., Cambra-López, M. & Calvet, S. (2012) Effect of Water and Straw Management Practices on Methane Emissions from Rice Fields: A Review Through a Meta-Analysis. *Environmental Engineering Science* 29(12): 1053-1062.

Sass, R.L., F.M. Fisher, S.T. Lewis, M.F. Jund, and F.T. Turner (1994) "Methane emissions from rice fields: effect of soil texture." *Global Biogeochemical Cycles* 8:135-140.

Savitzky, A., and M. J. E. Golay (1964) Smoothing and Differentiation of Data by Simplified Least Squares Procedures. Analytical Chemistry 36:1627-1639.

Saxton, K.E., W.J. Rawls, J.S. Romberger, and R.I. Papendick (1986) "Estimating Generalized Soil-Water Characteristics From Texture." Soil Sci. Soc. Am. J. 50:1031-1036.

Schueneman, T. (1997, 1999 through 2001) Personal Communication. Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL and ICF International.

Smith, J. (2008) E-mail correspondence between Jean Kim, ICF, and Jim Smith, U.S. Forest Service, December 3, 2008.

Sobol, I.M. (2001) Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. Math. Comput. Simul. 55, 271–280. https://doi.org/10.1016/S0378-4754(00)00270-6

Soil Survey Staff (2019) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service. Available online at https://gdg.sc.egov.usda.gov/. April, 2019 (FY2019 official release).

Spencer, S., S.M. Ogle, F.J. Breidt, J. Goebel, and K. Paustian (2011) Designing a national soil carbon monitoring network to support climate change policy: a case example for U.S. agricultural lands. Greenhouse Gas Management & Measurement 1:167-178.

Stehfest, E., and C. Müller (2004), Simulation of N_2O emissions from a urine-affected pasture in New Zealand with the ecosystem model DayCent, J. Geophys. Res., 109, D03109, doi:10.1029/2003JD004261.

Strehler, A., and W. Stützle (1987) "Biomass Residues." In Hall, D.O. and Overend, R.P. (eds.). *Biomass*. John Wiley and Sons, Ltd. Chichester, UK.

TAMU (2015) Texas Rice Crop Survey. Texas A&M AgriLIFE Research Center at Beaumont. Online at: <https://beaumont.tamu.edu/>.

Towery, D. (2001) Personal Communication. Dan Towery regarding adjustments to the CTIC (1998) tillage data to reflect long-term trends, Conservation Technology Information Center, West Lafayette, IN, and Marlen Eve, National Resource Ecology Laboratory, Fort Collins, CO. February 2001.

TVA (1992b) Fertilizer Summary Data 1992. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1991 through 1992a, 1993 through 1994) Commercial Fertilizers. Tennessee Valley Authority, Muscle Shoals, AL.

UCCE, 2015. Rice Production Manual. Revised 2015. University of California Cooperative Extension, Davis, in collaboration with the California Rice Research Board.

USDA (2010a) Crop Production 2009 Summary, National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at http://usda.mannlib.cornell.edu.

USDA (2015) Quick Stats: U.S. & All States Data - Crops. National Agricultural Statistics Service, U.S. Department of Agriculture. Washington, DC. U.S. Department of Agriculture, National Agricultural Statistics Service. Washington, D.C., Available online at <http://quickstats.nass.usda.gov/>.

USDA (2003, 2005 through 2006, 2008 through 2009) Crop Production Summary, National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu>.

USDA (1998) Field Crops Final Estimates 1992-1997. Statistical Bulletin Number 947a. National Agricultural Statistics Service, U.S. Department of Agriculture. Washington, DC. Available online at <http://usda.mannlib.cornell.edu>. Accessed July 2001.

USDA (1996) Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH), Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture. July 1996.

USDA (1994) Field Crops: Final Estimates, 1987-1992. Statistical Bulletin Number 896, National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. Available online at <http://usda.mannlib.cornell.edu/data-sets/crops/94896/sb896.txt>.

USDA (1991) *State Soil Geographic (STATSG0) Data Base Data use information*. Miscellaneous Publication Number 1492, National Soil Survey Center, Natural Resources Conservation Service, U.S. Department of Agriculture, Fort Worth, TX.

USDA-ERS (2018) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Available online at: <https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/>.

USDA-ERS (1997) Cropping Practices Survey Data—1995. Economic Research Service, United States Department of Agriculture. Available online at <http://www.ers.usda.gov/data/archive/93018/>.

USDA-FSA (2014) Conservation Reserve Program Monthly Summary – September 2014. U.S. Department of Agriculture, Farm Service Agency, Washington, DC, Available online at https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/Conservation/PDF/summarysept2014.pdf.

USDA-NASS (2019) Quick Stats. National Agricultural Statistics Service, United States Department of Agriculture, Washington, D.C. <http://quickstats.nass.usda.gov/>.

USDA-NRCS (2012) Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi River Basin. US Department of Agriculture, Natural Resources Conservation Service, https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1042093.pdf

USDA-NRCS (2018a) *Summary Report: 2015 National Resources Inventory*. Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

USDA-NRCS (2018b) CEAP Cropland Farmer Surveys. USDA Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/ceap/na/?cid=nrcs143_014163

USDA-NRCS (1996) Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH), Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture. July 1996

USFWS (2010) Strategic Plan: The Partners for Fish and Wildlife Program, Stewardship of Fish and Wildlife Through Voluntary Conservation. U.S. Fish and Wildlife Service, Washington, DC, USA. < http://www.fws.gov/partners/docs/783.pdf>.

Van Buuren, S. (2012) “Flexible imputation of missing data.” Chapman & Hall/CRC, Boca Raton, FL.

Vogelman, J.E., S.M. Howard, L. Yang, C. R. Larson, B. K. Wylie, and J. N. Van Driel (2001) “Completion of the 1990’s National Land Cover Data Set for the conterminous United States.” Photogrammetric Engineering and Remote Sensing, 67:650-662.

Wagner-Riddle, C., Congreves, K.A., Abalos, D., Berg, A.A., Brown, S.E., Ambadan, J.T., Gao, X. and Tenuta, M. (2017) “Globally important nitrous oxide emissions from croplands induced by freeze–thaw cycles.” Nature Geoscience 10(4): 279-283.

Way, M.O., McCauley, G.M., Zhou, X.G., Wilson, L.T., and Morace, B. (Eds.). (2014) 2014 Texas Rice Production Guidelines. Texas A&M AgriLIFE Research Center at Beaumont.

Williams, S.A. (2006) Data compiled for the Consortium for Agricultural Soils Mitigation of Greenhouse Gases (CASMGS) from an unpublished manuscript. Natural Resource Ecology Laboratory, Colorado State University.

Williams, S. and K. Paustian (2005) Developing Regional Cropping Histories for Century Model U.S.-level Simulations. Colorado State University, Natural Resources Ecology Laboratory, Fort Collins, CO.

Wilson, C.E. Jr., and Branson, J.W. (2006) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2005. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 540, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., and Branson, J.W. (2005) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2004. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 529, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., and Runsick, S.K. (2008) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2007. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 560, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., and Runsick, S.K. (2007) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2006. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 550, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., Runsick, S.K., Mazzanti, R. (2009) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2008. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 571, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., Runsick, S.K., and Mazzanti, R. (2010) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2009. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 581, Arkansas Agricultural Experiment Station, University of Arkansas.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Zomer RJ, Trabucco A, Bossio DA, van Straaten O, Verchot LV (2008) Climate Change Mitigation: A Spatial Analysis of Global Land Suitability for Clean Development Mechanism Afforestation and Reforestation. Agric. Ecosystems and Envir. 126: 67-80.

Zomer RJ, Bossio DA, Trabucco A, Yuanjie L, Gupta DC & Singh VP (2007) Trees and Water: Smallholder Agroforestry on Irrigated Lands in Northern India. Colombo, Sri Lanka: International Water Management Institute. pp 45. (IWMI Research Report 122).

3.13. Methodology for Estimating Net Carbon Stock Changes 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.

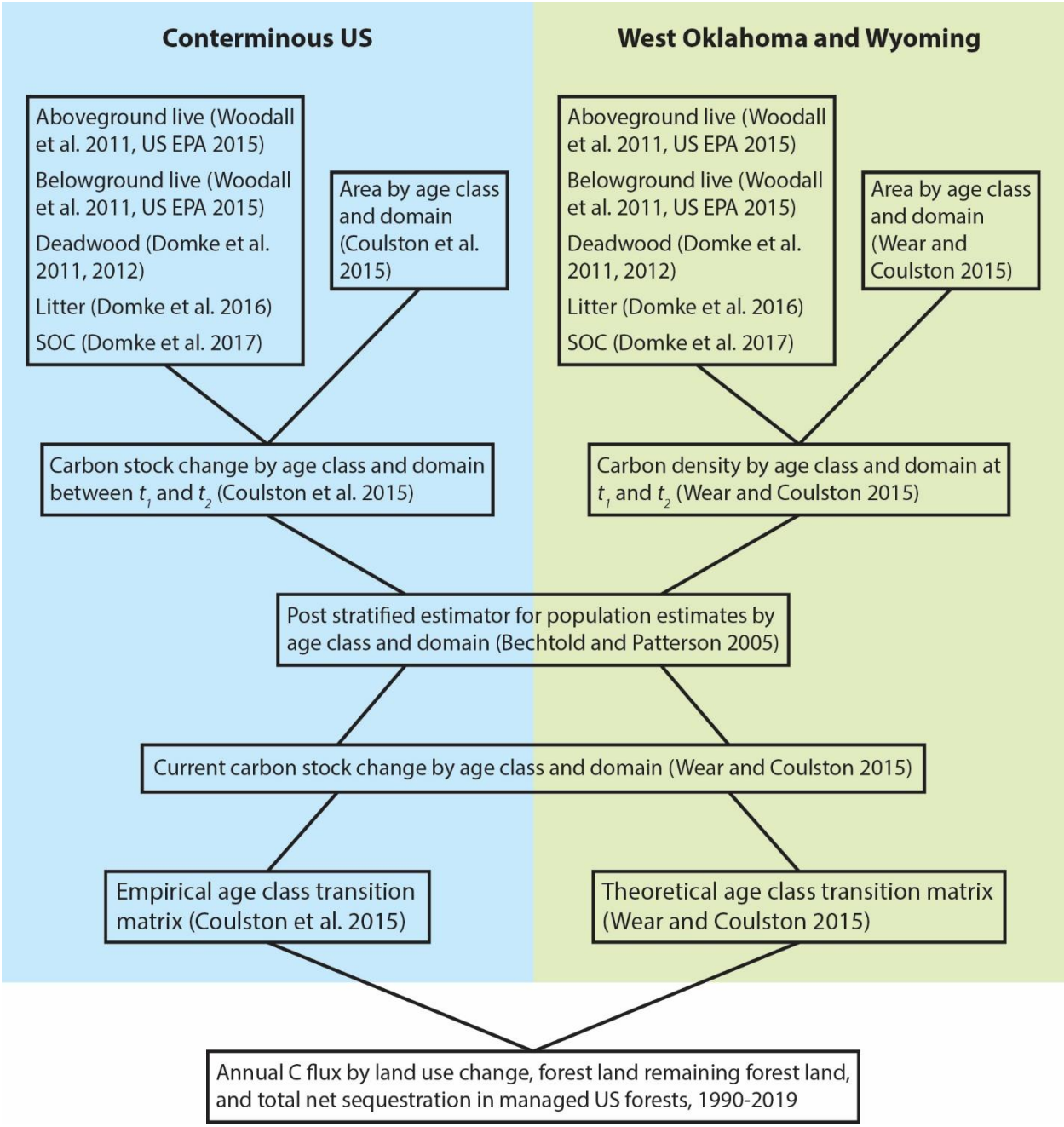
This sub-annex expands on the methodology used to estimate net changes in carbon (C) stocks in forest ecosystems and harvested wood products for *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* as well as non-CO_2 emissions from forest fires. Full details of the C conversion factors and procedures may be found in the cited references. For details on the methods used to estimate changes in mineral 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 the IPCC (2003, 2006) stock-difference (used for the conterminous United States (U.S.)) and gain-loss (used for Alaska) methods. Estimates of ecosystem C are based on data from the network of annual national forest inventory (NFI) plots established and measured by the Forest Inventory and Analysis (FIA) program within the USDA Forest Service; either direct measurements or variables from the NFI are the basis for estimating metric tons of C per hectare in forest ecosystem C pools (i.e., above- and belowground biomass, dead wood, litter, and soil carbon). For the conterminous U.S., 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*. A general description of the land use and stand age transition matrices that are informed by the annual NFI of the U.S. and were used in the estimation framework to compile estimates for the conterminous U.S. in this Inventory are described in Coulston et al. (2015). The annual NFI data in the conterminous U.S. allows for empirical estimation of net change in forest ecosystem carbon stocks within the estimation framework. In contrast, Wyoming and West Oklahoma have limited remeasurement data so theoretical age transition matrices were developed (Figure A-16). The incorporation of all managed forest land in Alaska was facilitated by an analysis to determine the managed land base in Alaska (Ogle et al. 2018), the expansion of the NFI into interior Alaska beginning in 2014, and a myriad of publicly available data products that provided information necessary for prediction of C stocks and fluxes on plots that have yet to be measured as part of the NFI.

The following subsections of this annex describe the estimation system used this year (Figure A-16) including the methods for estimating individual pools of forest ecosystem C in addition to the approaches to informing land use and stand age transitions.

Figure A-16: Flowchart of the inputs necessary in the estimation framework, including the methods for estimating individual pools of forest C in the conterminous United States



Note: An empirical age class transition matrix was used in every state in the conterminous United States with the exception of west Oklahoma and Wyoming where a theoretical age class transition matrix was used due to a lack of remeasurements in the annual NFI.

Forest Land Definition

The definition of forest land within the United States and used for this Inventory is defined in Oswalt et al. (2019) 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

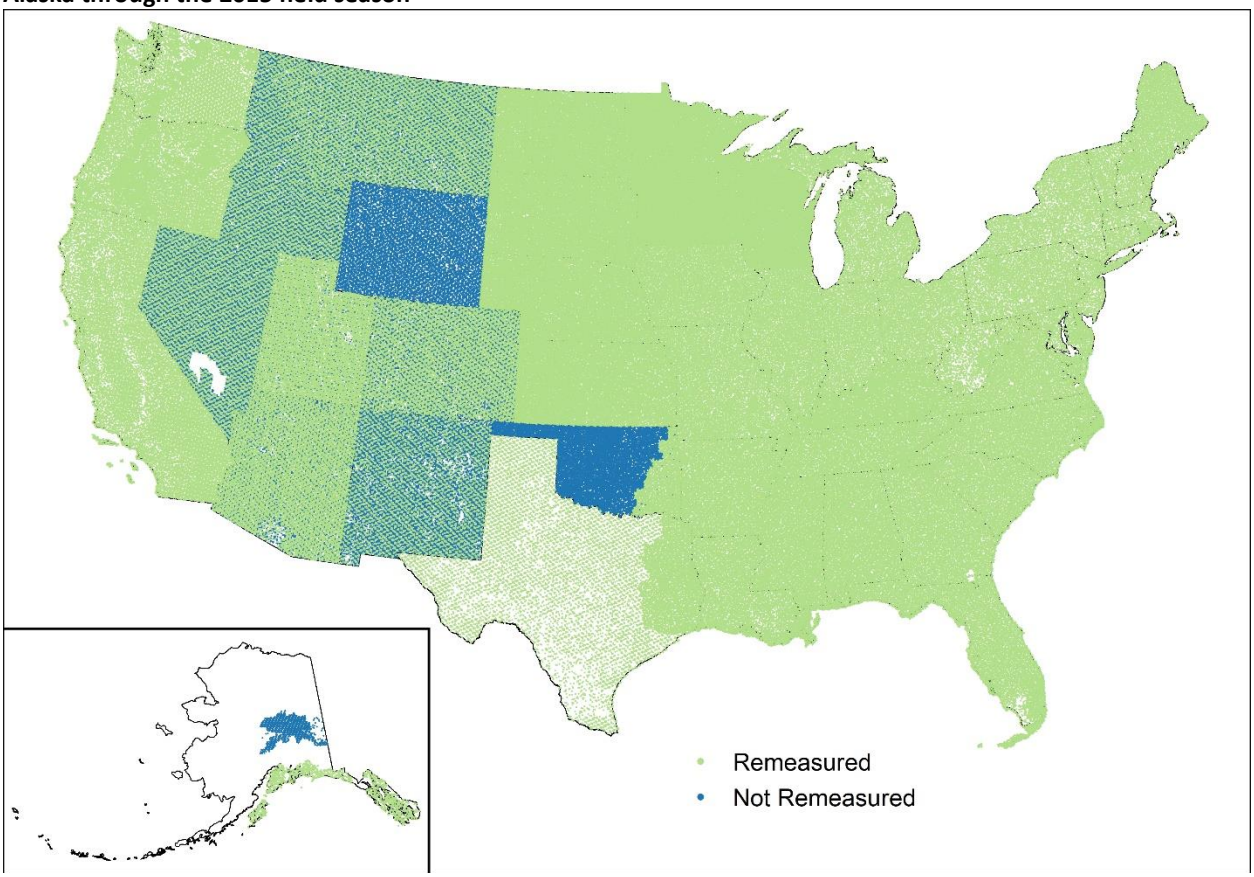
regenerating or capable of attaining such condition in the near future. Forest land also includes transition zones, such as areas between forest and non-forest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Unimproved 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 United States, 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 the annual NFI. NFI data were obtained from the USDA Forest Service, FIA Program (Frayer and Furnival 1999; USDA Forest Service 2020a; USDA Forest Service 2020b). NFI 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, tree height, species, and variables describing tree form and condition. On a subset of plots, additional measurements or samples are taken on downed dead wood, litter, and soil variables. 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. 2017). The field protocols are thoroughly documented and available for download from the USDA Forest Service (2020c). Bechtold and Patterson (2005) provide the estimation procedures for standard NFI results. The data are freely available for download at USDA Forest Service (2011b) as the FIA Database (FIADB) Version 8.0 (USDA Forest Service 2020b; USDA Forest Service 2020c); these are the primary sources of NFI 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 m^2. 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 to classify the land use. Annual NFI data are available for the temperate oceanic ecoregion of Alaska (southeast and south central) from 2004 to present as well as for interior Alaska from a pilot inventory in 2014 which became operational in 2016. Agroforestry systems are 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 2020a) were introduced by FIA with most new annual NFIs beginning after 1998. These are the only NFIs used in the compilation of estimates for this Inventory. These NFIs involve the sampling of all forest land including reserved and lower productivity lands. All states with the exception of Hawaii have annualized NFI data available with substantial remeasurement (with the exception of Wyoming and West Oklahoma) in the conterminous U.S. (Figure A-17). Annualized sampling means that a spatially representative 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 uncertainty 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 three or four cycles of the annualized NFI, and most western states are on their 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 estimates use annual NFI summaries (updates) with unique sets of plot-level data (that is, without redundant sets); the most-recent annual update (i.e., 2019) 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-202 and this list can be compared with the full set of summaries available for download (USDA Forest Service 2020b).

Figure A-17: Annual FIA plots (remeasured and not remeasured) across the United States 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) this will require that 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. In some cases there are NFI plots that do not meet the height component of the definition of forest land (Coulston et al. 2016). These plots are identified as "woodlands" (i.e., not forest land use) and were removed from the forest estimates and classified as grassland.[129] Note that minor differences (approximately 2% less forest land area in the CONUS) in identifying and classifying woodland as "forest" versus "woodland" 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 Inventory reporting (Coulston et al. 2016). Plots in the coastal region of the conterminous U.S. were also evaluated using the National Land Cover Database and the Coastal Change Analysis Program data products to ensure that land areas were completely accounted for in this region and also that they were not included in both the Wetlands category and the Forest Land category. This resulted in several NFI plots or subplots being removed from the Forest Land compilation.

[129] See the *Grassland Remaining Grassland* and *Land Converted to Grassland* sections for details.

Table A-202: Specific annual forest inventories by state used in development of forest C stock and stock change estimate

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	2006 - 2012	2013 - 2019	Oklahoma (West)	2010 - 2012	2013 - 2018
Arizona	2001 - 2008	2009 - 2018	Wyoming	2000	2011 - 2019
Arkansas	2007 - 2014	2014 - 2019			
California	2001 - 2009	2011 - 2019	Alaska (Coastal)[1]	2004 - 2017	
Colorado	2002 - 2008	2009 - 2018	Alaska (Interior)[1]	2014, 2016 - 2017	
Connecticut	2008 - 2013	2013 - 2019			
Delaware	2008 - 2013	2013 - 2019			
Florida	2002 - 2012	2012 - 2017			
Georgia	2005 - 2013	2014 - 2018			
Idaho	2004 - 2008	2009 - 2018			
Indiana	2007 - 2013	2012 - 2019			
Iowa	2008 - 2013	2013 - 2019			
Kansas	2008 - 2013	2013 - 2019			
Kentucky	2008 - 2013	2013 - 2019			
Louisiana	2005 - 2012	2012 - 2017			
Maine	2001 - 2011	2009 - 2017			
Maryland	2010 - 2014	2015 - 2019			
Massachusetts	2008 - 2013	2013 - 2019			
Michigan	2008 - 2013	2013 - 2019			
Minnesota	2008 - 2013	2013 - 2019			
Mississippi	2010 - 2014	2015 - 2019			
Missouri	2006 - 2015	2014 - 2019			
Montana	2008 - 2013	2013 - 2019			
Nebraska	2003 - 2008	2009 - 2018			
Nevada	2008 - 2013	2013 - 2019			
New Hampshire	2004 - 2008	2009 - 2018			
New Jersey	2008 - 2013	2013 - 2019			
New Mexico	2009 - 2014	2015 - 2019			
New York	2005 - 2008	2009 - 2018			
North Carolina	2008 - 2013	2013 - 2019			
North Dakota	2003 - 2013	2011 - 2019			
Ohio	2008 - 2013	2013 - 2019			
Oklahoma (East)	2008 - 2013	2013 - 2019			
Oregon	2008 - 2013	2014 - 2018			
Pennsylvania	2001 - 2009	2011 - 2019			
Rhode Island	2008 - 2013	2013 - 2019			
South Carolina	2008 - 2013	2013 - 2019			
South Dakota	2007 - 2014	2014 - 2018			
Tennessee	2008 - 2013	2013 - 2019			
Texas (East)	2005 - 2012	2012 - 2017			
Texas (West)	2009 - 2014	2015 - 2019			
Utah	2004 - 2012	2014 - 2017			
Vermont	2000 - 2008	2009 - 2018			
Virginia	2008 - 2013	2013 - 2019			
Washington	2008 - 2014	2014 - 2018			
West Virginia	2002 - 2009	2012 - 2019			

Wisconsin	2008 - 2013	2013 - 2019

[1]Plots in Alaska have not been split but are included in this column to conserve space in the Table.
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 forest ecosystem C 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 extension 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 variables for 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 NFI plots which are a systematic sample of all forest attributes and land uses within each state. The results are estimates of C density (T per hectare) for each forest ecosystem C pool. 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 and downed dead wood can be separated into aboveground and belowground components. The live tree and understory C pools are combined into the aboveground and belowground biomass pools 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* and *Land Converted to Forest Land* are reported in forest ecosystem C 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 fraction of 0.5 because biomass is 50 percent of dry weight (USDA Forest Service 2020d). 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 2.54 cm 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-203. 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-203) are set to coefficient A, which is a C density (T C/ha) for these types only.

Table A-203: Coefficients for Estimating the Ratio of C Density of Understory Vegetation (above- and belowground, T C/ha) by Region and Forest Type[a]

Region[b]	Forest Type[b]	A	B	Maximum ratio[c]
NE	Aspen-Birch	0.855	1.032	2.023
	MBB/Other Hardwood	0.892	1.079	2.076
	Oak-Hickory	0.842	1.053	2.057
	Oak-Pine	1.960	1.235	4.203
	Other Pine	2.149	1.268	4.191
	Spruce-Fir	0.825	1.121	2.140
	White-Red-Jack Pine	1.000	1.116	2.098
	Nonstocked	2.020	2.020	2.060
NLS	Aspen-Birch	0.777	1.018	2.023
	Lowland Hardwood	0.650	0.997	2.037
	Maple-Beech-Birch	0.863	1.120	2.129
	Oak-Hickory	0.965	1.091	2.072
	Pine	0.740	1.014	2.046
	Spruce-Fir	1.656	1.318	2.136
	Nonstocked	1.928	1.928	2.117
NPS	Conifer	1.189	1.190	2.114
	Lowland Hardwood	1.370	1.177	2.055
	Maple-Beech-Birch	1.126	1.201	2.130
	Oak-Hickory	1.139	1.138	2.072
	Oak-Pine	2.014	1.215	4.185
	Nonstocked	2.052	2.052	2.072
PSW	Douglas-fir	2.084	1.201	4.626
	Fir-Spruce	1.983	1.268	4.806
	Hardwoods	1.571	1.038	4.745
	Other Conifer	4.032	1.785	4.768
	Pinyon-Juniper	4.430	4.430	4.820
	Redwood	2.513	1.312	4.698
	Nonstocked	4.431	4.431	4.626
PWE	Douglas-fir	1.544	1.064	4.626
	Fir-Spruce	1.583	1.156	4.806
	Hardwoods	1.900	1.133	4.745
	Lodgepole Pine	1.790	1.257	4.823
	Pinyon-Juniper	2.708	2.708	4.820
	Ponderosa Pine	1.768	1.213	4.768
	Nonstocked	4.315	4.315	4.626
PWW	Douglas-fir	1.727	1.108	4.609
	Fir-Spruce	1.770	1.164	4.807
	Other Conifer	2.874	1.534	4.768
	Other Hardwoods	2.157	1.220	4.745
	Red Alder	2.094	1.230	4.745
	Western Hemlock	2.081	1.218	4.693
	Nonstocked	4.401	4.401	4.589
RMN	Douglas-fir	2.342	1.360	4.731
	Fir-Spruce	2.129	1.315	4.749
	Hardwoods	1.860	1.110	4.745
	Lodgepole Pine	2.571	1.500	4.773
	Other Conifer	2.614	1.518	4.821
	Pinyon-Juniper	2.708	2.708	4.820

	Ponderosa Pine	2.099	1.344	4.776
	Nonstocked	4.430	4.430	4.773
RMS	Douglas-fir	5.145	2.232	4.829
	Fir-Spruce	2.861	1.568	4.822
	Hardwoods	1.858	1.110	4.745
	Lodgepole Pine	3.305	1.737	4.797
	Other Conifer	2.134	1.382	4.821
	Pinyon-Juniper	2.757	2.757	4.820
	Ponderosa Pine	3.214	1.732	4.820
	Nonstocked	4.243	4.243	4.797
SC	Bottomland Hardwood	0.917	1.109	1.842
	Misc. Conifer	1.601	1.129	4.191
	Natural Pine	2.166	1.260	4.161
	Oak-Pine	1.903	1.190	4.173
	Planted Pine	1.489	1.037	4.124
	Upland Hardwood	2.089	1.235	4.170
	Nonstocked	4.044	4.044	4.170
SE	Bottomland Hardwood	0.834	1.089	1.842
	Misc. Conifer	1.601	1.129	4.191
	Natural Pine	1.752	1.155	4.178
	Oak-Pine	1.642	1.117	4.195
	Planted Pine	1.470	1.036	4.141
	Upland Hardwood	1.903	1.191	4.182
	Nonstocked	4.033	4.033	4.182

[a] Prediction of ratio of understory C to live tree C is based on the 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 substantially affect C mass are decay, which affects density and thus specific C fraction (Domke et al. 2011; Harmon et al. 2011), and structural loss such as branches and bark (Domke et al. 2011). A C fraction of 0.5 is used for standing dead trees (USDA forest Service 2020d).

Downed dead wood, inclusive of logging residue, are sampled on a subset of NFI 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-221. 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-222. 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-204 (SC, Natural Pine)

C density = 82.99 × 0.068 = 5.67 (T C/ha)

Second, an average logging residue from age and Table A-204 (SC, softwood)

C density = 5.5 × e(−25/17.9) = 1.37 (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

C density = (5.67 + 1.37) × 0.886 = 6.24 (T C/ha)

Table A-204: 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-205: 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 NFI 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 NFI plots, a model (3) was developed to predict C density based on plot/site variables for plots that lacked litter information (Domke et al. 2016):

$$P(FFCFull) = f(lat, lon, elev, fortypgrp, above, ppt, \mathrm{t}max, gmi) + u \quad (3)$$

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.

Due to data limitations in certain regions and inventory periods a series of reduced non-parametric models, which did not include climate variables, were used rather than replacing missing variables with imputation techniques. Database records used to compile estimates for this report were grouped by variable availability and the approaches described herein were applied. Litter C predictions are expressed as density (T ha^{-1}).

Soil organic carbon

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. (2017). The data used to develop the modeling framework to predict SOC on forest land came from the NFI and the International Soil Carbon Network. Since 2001, the FIA program has collected soil samples on every 16th base intensity plot (approximately every 2,428 ha) 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 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 NFI were calculated following O'Neill et al. (2005):

$$\sum SOC_{FIA_TOTAL} = C_i \cdot BD_i \cdot t_i \cdot ucf \qquad (4)$$

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 United States has historically reported SOC estimates to a depth of 100 cm (Heath et al. 2011, USEPA 2015), International Soil Carbon Monitoring Network (ISCN) data from forests in the United States 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 United States. 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:

$$\log_{10} SOC_i = I + \log_{10} Depth \qquad (5)$$

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), $SOC_{20\text{-}100}$ = 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 a non-parametric model, this particular machine learning tool used bootstrap aggregating (i.e., bagging) to develop models to improve prediction (Breimen 2001). It 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 analysis. Due to regional differences in sampling protocols, many of the predictor variables included in the variable selection process were not available for all base intensity plots. To avoid problems with data limitations, pruning was used to reduce the 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 non-parametric 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.

Compilation of population estimates using NFI plot data

Methods for the conterminous United States

The estimation framework is fundamentally driven by the annual NFI. Unfortunately, the annual NFI does not extend to 1990 and the periodic data from the NFI are not consistent (e.g., different plot design) with the annual NFI necessitating the adoption of a system to predict the annual C parameters back to 1990. To facilitate the C prediction parameters, the estimation 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 uptake, 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 NFI database (U.S. Forest Service 2020a-c). Model predictions for before or after the annual NFI period are constructed from the estimation 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 NFIs 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 west Oklahoma and Wyoming 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 model. The overall objective is to estimate unmeasured historical changes and future changes in forest C parameters consistent with annual NFI estimates. For most regions, forest conditions are observed at time t_0 and at a subsequent time $t_1=t_0+s$, where s is the time step (time measured in years) and is indexed by discrete (5 year) forest age classes. The inventory from t_0 is then predicted back to the year 1990 and projected from t_1 to 2019. This prediction 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 all states in the conterminous U.S. (except for Wyoming and west Oklahoma) age class transition matrices are estimated from observed changes in age classes between t_0 and t_1. In west Oklahoma and

Wyoming only one inventory was available (t_0) so transition matrices were obtained from theory but informed by the condition of the observed inventory to predict from t_0 to 1990 and predict from t_0 to 2019.

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 ($\mathbf{T}_{\mathrm{qr}}$) 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:

$$\boldsymbol{T} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{pmatrix} \tag{8}$$

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:

$$\boldsymbol{T} = \begin{pmatrix} 1-t_1-d_1 & d_2 & d_3 & d_4 & d_5 \\ t_1 & 1-t_2-d_2 & 0 & 0 & 0 \\ 0 & t_2 & 1-t_3-d_3 & 0 & 0 \\ 0 & 0 & t_3 & 1-t_4-d_4 & 0 \\ 0 & 0 & 0 & t_4 & 1-d_5 \end{pmatrix} \tag{9}$$

Where 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* ($\mathbf{T}_{\mathrm{qr}}$).

Projections and Backcast for West Oklahoma and Wyoming

Projections of forest C in west Oklahoma and Wyoming are based on a life stage model:

$$\Delta \mathrm{C_t} = \mathrm{C_{t+m}} - \mathrm{C_t} = (\mathbf{F_t T} - \mathbf{F_t}) \cdot \mathbf{Den} + \mathbf{L_t} \cdot \mathbf{Den} \tag{10}$$

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 $\mathbf{F_t T}$-$\mathbf{F_t}$. 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 $\mathbf{L_t}$·**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):

$$\boldsymbol{F}_{t-s} = \boldsymbol{F}_t \cdot \boldsymbol{B} \tag{11}$$

B is constructed based on similar logic used for creating **T**. The matrix cannot simply be derived as the inverse of **T** ($\boldsymbol{F_{t-s}} = \boldsymbol{F_t T^{-1}}$) 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).130 However, **B** can be constructed using observed changes from the inventory and assumptions about transition/accumulation including nonstationary elements of the transition model:

$$\boldsymbol{B} = \begin{pmatrix} 1-\sum_q d_q & \mathrm{b}_2 & 0 & 0 & 0 \\ d_1 & 1-b_2 & \mathrm{b}_3 & 0 & 0 \\ d_2 & 0 & 1-b_3 & \mathrm{b}_4 & 0 \\ d_3 & 0 & 0 & 1-b_4 & \mathrm{b}_r \\ d_4 & 0 & 0 & 0 & 1-\mathrm{b}_r \end{pmatrix} \tag{12}$$

Forest area changes need to be accounted for in the backcasts as well:

$$\boldsymbol{F}_{t-s} = \boldsymbol{F_t B} - \boldsymbol{L_t} \tag{13}$$

Where $\mathbf{L_t}$ is the forest area change between t_1 and t_0 as previously defined.

In west Oklahoma and Wyoming the theoretical life-stage models described by matrices (9) and (10) were applied. The disturbance factors (d) in both **T** and **B** are obtained from the current NFI 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**), the disturbance frequencies implied by the age class distribution for each time step are moved. For areas with empirical transition matrices, change in forest area ($\mathbf{L_t}$) was backcasted/projected using the change in forest area observed for the period t_0 to t_1.

Projections and Backcast for CONUS (excluding west Oklahoma and Wyoming)

For all states in the conterminous United States (with the exception of west Oklahoma and Wyoming) remeasured plots were available. When remeasured data are available, the previously described approach is extended to estimate change more directly; in this case ΔCt=Ft·δC, where ΔC is net stock 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

[130] Simulation experiments show that a population that evolves as a function of **T** can be precisely predicted 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 predictions of negative areas within some stage age classes.

from the observed data directly. Forest C change at the end of the next period is defined as: ΔCt+s = Ft·T·δC. 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:

$$\Delta C_{t+s} = \sum_{d \in L} (A_{td} \cdot T_d \cdot \delta C_d) \tag{14}$$

Where A_{td} = 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), T_d 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.

Predictions 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. Prediction moving back in time 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 2020d). This relationship allowed for the modification of Fcut such that it followed trends described by Oswalt et al. (2014).

Methods for Alaska

Inventory and sampling

The NFI has been measuring plots in southeast and southcentral coastal Alaska as part of the annual NFI since 2004. In 2014, a pilot inventory was established in the Tanana Valley State Forest and Tetlin National Wildlife Refuge in Interior Alaska. This pilot inventory was a collaboration between the USDA Forest Service, FIA program, the National Aeronautical and Space Administration, and many other federal, state, and local partners. This effort resulted in the establishment of 98 field plots which were measured during the summer of 2014 and integrated with NASA's Goddard LiDAR/Hyperspectral/Thermal (G-LiHT) imaging system. Given the remote nature of Interior Alaska forest, the NFI plots in the pilot campaign were sampled at a lower intensity than base NFI plots (1 plot per 2403 ha) in the CONUS and coastal Alaska. Several plot-level protocols were also adapted to accommodate the unique conditions of forests in this region (see Pattison et al. 2018 for details on plot design and sampling protocols). The pilot field campaign became operational in 2016 and plots measured on a 1/5 intensity (1 plot per 12013 ha) from 2014, 2016, and 2017 from the Interior Alaska NFI were used (n = 446) with base-intensity annual NFI plots from coastal AK (n = 2748) in this analysis.

A spatially balanced sampling design was used to identify field sample locations across all of Alaska following standard FIA procedures with a tessellation of hexagons and one sample plot selected per hexagon – 1/5 intensity in interior Alaska and base-intensity in coastal Alaska (Bechtold and Patterson 2005). The sampling locations were classified as forest or non-forest using the NLCD from 2001 and 2011. It is important to note that this is different from how NFI plots are classified into land cover and land use categories in the CONUS where high resolution areal imagery is used. Since the fine-scale remotely sensed imagery (National Agriculture Imagery Program; NAIP 2015) used in the conterminous U.S. were not available for AK and given that the NLCD has been used to classify land use categories in Alaska in the *Representation of the U.S. Land Base* in this Inventory, the NLCD was the most consistent and credible option for classification. Next, the forest land was further classified as managed or unmanaged following the definition in the *Representation of the U.S. Land Base* and using similar procedures (see Ogle et al. 2018 for details on the managed land layer for the U.S.).

While only a subset of the total NFI sample was available at the time of this Inventory, all NFI plot locations within the sampling frame were used in this analysis. Auxiliary climate, soil, structural, disturbance, and topographic variables were harmonized with each plot location and year of occurrence (if relevant and available) over the entire time series (1990 to 2019).

Prediction

The harmonized data were used to predict plot-level parameters using non-parametric random forests (RF) for regression, a machine learning tool that uses bootstrap aggregating (i.e., bagging) to develop models to improve prediction (Breiman 2001). Random forests also relies on random variable selection to develop a forest of uncorrelated regression trees. These trees uncover the relationship between a dependent variable (e.g., live aboveground biomass carbon) and a set of predictor variables. The RF analysis included predictor variables (n > 100) that may influence carbon stocks within each forest ecosystem pool at each plot location over the entire time series. To avoid problems with data limitations over the time series, variable pruning was used to reduce the RF models to the minimum number of relevant predictors without substantial loss in explanatory power or increase in root mean squared error (RMSE; see Domke et al. 2017, Domke et al. In prep for more information). The harmonized dataset used to develop the RF models for each plot-level parameter were partitioned 10 times into training (70 percent) and testing (30 percent) groups and the results were evaluated graphically and with a variety of statistical metrics including Spearman's rank correlation, equivalence tests (Wellek 2003), as well as RMSE. All analyses were conducted using R statistical software (R Core Team 2018).

The RF predictions of carbon stocks for the year 2016 were used as a baseline for plots that have not yet been measured. Next, simple linear regression was used to predict average annual gains/losses by forest ecosystem carbon pool using the chronosequence of plot measurements available at the time of this Inventory. These predicted gains/losses were applied over the time series from the year of measurement or the 2016 base year in the case of plots that have not yet been measured. Since the RF predictions of carbon stocks and the predicted gains/losses were obtained from empirical measurements on NFI plots that may have been disturbed at some point over the time series, the predictions inherently incorporate gains/losses associated with natural disturbance and harvesting. That said, there was no evidence of fire disturbance on the plots that have been measured to date. To account for carbon losses associated with fire, carbon stock predictions for plots that have not been measured but were within a fire perimeter during the Inventory period were adjusted to account for area burned (see Table A-216) and the IPCC (Table 2.6, IPCC 2006) default combustion factor for boreal forests was applied to all live, dead, and litter biomass carbon stocks in the year of the disturbance. The plot-level predictions in each year were then multiplied by the area they represent within the sampling frame to compile population estimates over the time series for this Inventory.

Forest Land Remaining Forest Land Area Estimates

Forest land area estimates in section 6.2 *Forest Land Remaining Forest Land* (CRF Category 4A1) of this Inventory are compiled using NFI data. Forest Land area estimates obtained from these data are also used as part of section 6.1 Representation of the U.S. Land Base (CRF Category 4.1). The Forest Land area estimates in section 6.2 do not include Hawaii as insufficient data is available from the NFI to compile area estimates over the entire time series. The National Land Cover Dataset is used in addition to NFI estimates in section 6.2 Representation of the U.S. Land Base and Forest Land in Hawaii are included in that section. This results in small differences in the managed Forest Land area in sections 6.1 and 6.2 of this Inventory (Table A-214). There are also other factors contributing to the small differences such as harmonization of aspatial and spatial data across all land use categories in section 6.1 over the entire Inventory time series.

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 United States uses the production accounting approach (as in previous years) to report HWP Contribution (Table A-206) but estimates for all three approaches are provides in Table A-207. 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-208. 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-206: Harvested Wood Products from Wood Harvested in the United States—Annual Additions of C to Stocks and Total Stocks under the Production Approach

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	(33.8)	(14.9)	(18.8)	1895	1249	646
1991	(33.8)	(16.3)	(17.4)	1929	1264	665
1992	(32.9)	(15.0)	(17.9)	1963	1280	683
1993	(33.4)	(15.9)	(17.5)	1996	1295	701
1994	(32.3)	(15.1)	(17.2)	2029	1311	718
1995	(30.6)	(14.1)	(16.5)	2061	1326	735
1996	(32.0)	(14.7)	(17.3)	2092	1340	752
1997	(31.1)	(13.4)	(17.7)	2124	1355	769
1998	(32.5)	(14.1)	(18.4)	2155	1368	787
1999	(30.8)	(12.8)	(18.0)	2188	1382	805
2000	(25.5)	(8.7)	(16.8)	2218	1395	823
2001	(26.8)	(9.6)	(17.2)	2244	1404	840
2002	(25.6)	(9.4)	(16.2)	2271	1413	857
2003	(28.4)	(12.1)	(16.3)	2296	1423	873
2004	(28.7)	(12.4)	(16.4)	2325	1435	890
2005	(28.9)	(11.6)	(17.3)	2353	1447	906
2006	(27.3)	(10.0)	(17.4)	2382	1459	923
2007	(20.8)	(3.7)	(17.1)	2410	1469	941
2008	(14.9)	1.8	(16.7)	2430	1473	958
2009	(16.6)	(0.0)	(16.6)	2445	1471	974
2010	(18.8)	(2.0)	(16.8)	2462	1471	991
2011	(19.4)	(2.4)	(17.0)	2481	1473	1008
2012	(20.9)	(3.7)	(17.1)	2500	1475	1025
2013	(22.5)	(5.3)	(17.3)	2521	1479	1042
2014	(23.4)	(6.1)	(17.4)	2543	1484	1059
2015	(24.2)	(6.7)	(17.5)	2567	1490	1076

2016	(25.2)	(7.6)	(17.6)	2591	1497	1094
2017	(26.1)	(8.3)	(17.9)	2616	1505	1112
2018	(26.9)	(8.6)	(18.3)	2642	1513	1129
2019	(29.6)	(10.7)	(18.9)	2669	1521	1148

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Table A-207: 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	(116.6)	(131.4)	(123.8)
1991	(120.2)	(131.6)	(123.8)
1992	(127.1)	(127.8)	(120.7)
1993	(130.3)	(129.9)	(122.5)
1994	(126.0)	(128.0)	(118.4)
1995	(122.3)	(122.5)	(112.2)
1996	(131.3)	(127.4)	(117.3)
1997	(137.2)	(122.8)	(114.2)
1998	(147.1)	(127.2)	(119.0)
1999	(141.2)	(120.2)	(112.9)
2000	(125.0)	(100.3)	(93.4)
2001	(130.7)	(103.3)	(98.2)
2002	(125.8)	(98.5)	(93.7)
2003	(143.2)	(107.9)	(104.1)
2004	(142.1)	(109.7)	(105.4)
2005	(136.6)	(112.0)	(106.0)
2006	(113.6)	(109.8)	(100.3)
2007	(72.6)	(88.1)	(76.1)
2008	(41.8)	(70.0)	(54.5)
2009	(48.2)	(79.8)	(60.8)
2010	(51.4)	(92.2)	(69.1)
2011	(59.0)	(95.2)	(71.0)
2012	(72.4)	(102.9)	(76.5)
2013	(85.7)	(109.4)	(82.6)
2014	(92.8)	(113.2)	(86.0)
2015	(99.4)	(116.2)	(88.7)
2016	(103.2)	(120.1)	(92.4)
2017	(132.1)	(119.9)	(95.7)
2018	(135.0)	(125.5)	(98.8)
2019	(152.7)	(129.8)	(108.5)

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Table A-208: Harvested Wood Products Sectoral Background Data for LULUCF—United States

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	
									MMT C/yr	MMT CO_2/yr
1990	13.2	18.6	14.9	18.8	11.6	15.6	144.4	108.6	110.7	(123.8)
1995	17.0	16.3	14.1	16.5	16.7	16.7	134.5	101.1	103.9	(112.2)
2000	16.5	17.6	8.7	16.8	22.1	15.3	127.9	100.5	102.4	(93.4)
2005	18.7	18.6	11.6	17.3	25.5	18.8	120.1	89.6	91.2	(106.0)
2010	(2.1)	16.1	2.0	16.8	13.9	25.0	102.7	77.5	83.9	(69.1)
2015	10.2	16.9	6.7	17.5	18.5	23.1	119.1	87.4	94.9	(88.7)
2016	11.1	17.0	7.6	17.6	18.5	23.1	122.1	89.3	96.9	(92.4)
2017	18.1	17.9	8.3	17.9	22.6	19.3	108.1	75.4	82.0	(95.7)
2018	17.9	18.9	8.6	18.3	21.6	19.0	110.1	75.9	83.2	(98.8)
2019	21.6	20.0	10.7	18.9	24.7	18.5	105.8	70.4	76.2	(108.5)

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Annual estimates of variables 1A, 1B, 2A and 2B were calculated by tracking the additions to and removals from the pool of products held in end uses (e.g., products in uses such as housing or publications) and the pool of products held in SWDS. In the case of variables 2A and 2B, the pools include products exported and held in other countries and the pools in the United States exclude products made from wood harvested in other countries. Solidwood products added to pools include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end uses. There is one product category and one end-use category for paper. Additions to and removals from pools are tracked beginning in 1900, with the exception that additions of softwood lumber to housing begins in 1800. Solidwood and paper product production and trade data are from USDA Forest Service and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich, 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007, Howard and Jones 2016, Howard and Liang 2019).

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-209. 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-210. 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-206. 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 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 *Land Converted to Forest Land* – Soil C Methods.

Table A-209: 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-life 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-210: 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-211: 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	2005	2010	2015	2016	2017	2018	2019
Forest	**(663.8)**	**(647.1)**	**(624.5)**	**(555.5)**	**(611.8)**	**(582.7)**	**(629.5)**	**(564.0)**	**(599.8)**	**(583.3)**
Aboveground Biomass	(456.4)	(442.3)	(426.0)	(401.3)	(415.4)	(414.2)	(421.3)	(395.1)	(402.4)	(394.0)
Belowground Biomass	(103.7)	(100.7)	(97.3)	(92.0)	(94.2)	(92.6)	(95.0)	(89.2)	(90.9)	(89.2)
Dead Wood	(97.3)	(97.9)	(98.1)	(93.5)	(99.9)	(98.7)	(105.1)	(97.1)	(101.7)	(99.3)
Litter	(8.1)	(7.2)	(3.1)	32.2	0.7	30.5	(3.2)	0.2	(2.3)	(0.5)
Soil (Mineral)	1.5	0.7	(0.5)	(1.5)	(3.0)	(7.3)	(6.8)	14.3	(4.5)	(2.4)
Soil (Organic)	(0.6)	(0.5)	(0.4)	(0.2)	(0.9)	(1.1)	1.2	2.1	1.2	1.2
Drained Organic Soil[a]	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Harvested Wood	**(123.8)**	**(112.2)**	**(93.4)**	**(106.0)**	**(69.1)**	**(88.7)**	**(92.4)**	**(95.7)**	**(98.8)**	**(108.5)**
Products in Use	(54.8)	(51.7)	(31.9)	(42.6)	(7.4)	(24.6)	(27.8)	(30.3)	(31.5)	(39.2)
SWDS	(69.0)	(60.5)	(61.5)	(63.4)	(61.7)	(64.1)	(64.6)	(65.5)	(67.2)	(69.3)
Total Net Flux	**(787.6)**	**(759.3)**	**(717.9)**	**(661.5)**	**(680.9)**	**(671.4)**	**(721.9)**	**(659.7)**	**(698.6)**	**(691.8)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] These estimates include C stock changes from drained organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Note: Parentheses indicate negative values.

Table A-212: Net C Flux from Forest Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

Carbon Pool	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019
Forest	**(181.0)**	**(176.5)**	**(170.3)**	**(151.5)**	**(166.9)**	**(158.9)**	**(171.7)**	**(153.8)**	**(163.6)**	**(159.1)**
Aboveground Biomass	(124.5)	(120.6)	(116.2)	(109.5)	(113.3)	(113.0)	(114.9)	(107.7)	(109.7)	(107.4)
Belowground Biomass	(28.3)	(27.5)	(26.5)	(25.1)	(25.7)	(25.3)	(25.9)	(24.3)	(24.8)	(24.3)
Dead Wood	(26.5)	(26.7)	(26.7)	(25.5)	(27.2)	(26.9)	(28.7)	(26.5)	(27.7)	(27.1)
Litter	(2.2)	(2.0)	(0.8)	8.8	0.2	8.3	(0.9)	0.1	(0.6)	(0.1)
Soil (Mineral)	0.4	0.2	(0.1)	(0.4)	(0.8)	(2.0)	(1.9)	3.9	(1.2)	(0.7)
Soil (Organic)	(0.2)	(0.1)	(0.1)	(0.1)	(0.3)	(0.3)	0.3	0.6	0.3	0.3
Drained Organic Soil[a]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Harvested Wood	**(33.8)**	**(30.6)**	**(25.5)**	**(28.9)**	**(18.8)**	**(24.2)**	**(25.2)**	**(26.1)**	**(26.9)**	**(29.6)**
Products in Use	(14.9)	(14.1)	(8.7)	(11.6)	(2.0)	(6.7)	(7.6)	(8.3)	(8.6)	(10.7)
SWDS	(18.8)	(16.5)	(16.8)	(17.3)	(16.8)	(17.5)	(17.6)	(17.9)	(18.3)	(18.9)
Total Net Flux	**(214.8)**	**(207.1)**	**(195.8)**	**(180.4)**	**(185.7)**	**(183.1)**	**(196.9)**	**(179.9)**	**(190.5)**	**(188.7)**

+ Absolute value does not exceed 0.05 MMT C.

[a] These estimates include C stock changes from drained organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Note: Parentheses indicate negative values.

Table A-213: Forest area (1,000 ha) and C Stocks in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020
Forest Area (1000 ha)	***279,661***	***279,755***	***279,795***	***279,491***	***279,537***	***279,545***	***279,533***	***279,511***	***279,483***	***279,386***	***279,289***
Carbon Pools											
Forest	**50,913**	**51,808**	**52,681**	**53,489**	**54,302**	**55,125**	**55,284**	**55,456**	**55,610**	**55,774**	**55,933**
Aboveground Biomass	11,810	12,424	13,019	13,584	14,144	14,707	14,820	14,935	15,043	15,152	15,260
Belowground Biomass	2,319	2,459	2,594	2,723	2,851	2,979	3,004	3,030	3,054	3,079	3,103
Dead Wood	2,049	2,182	2,316	2,446	2,580	2,716	2,743	2,771	2,798	2,825	2,852
Litter	3,656	3,665	3,673	3,655	3,645	3,644	3,636	3,637	3,637	3,638	3,638
Soil (Mineral)	25,145	25,144	25,143	25,145	25,147	25,145	25,147	25,149	25,145	25,146	25,147
Soil (Organic)	5,934	5,934	5,935	5,936	5,936	5,934	5,935	5,934	5,934	5,933	5,933
Harvested Wood	**1,895**	**2,061**	**2,218**	**2,353**	**2,462**	**2,567**	**2,591**	**2,616**	**2,642**	**2,669**	**2,699**
Products in Use	1,249	1,326	1,395	1,447	1,471	1,490	1,497	1,505	1,513	1,521	1,532
SWDS	646	735	823	906	991	1,076	1,094	1,112	1,129	1,148	1,167
Total Stock	**52,808**	**53,870**	**54,899**	**55,842**	**56,764**	**57,692**	**57,875**	**58,072**	**58,252**	**58,443**	**58,632**

Table A-214: Forest Land Area Estimates and Differences Between Estimates in 6.1 Representation of the U.S. Land Base (CRF Category 4.1) and 6.2 *Forest Land Remaining Forest Land* (CRF Category 4A1) (kha)

Year	Forest Land (managed) - 6.1 Representation of the U.S. Land Base	Forest Land (managed) - 6.2 Forest Land Remaining Forest Land	Difference between Forest Land Areas (managed) – 6.1 and Forest Land Remaining Forest Land – 6.2 area estimates
1990	280,393	279,661	733
1995	280,414	279,755	659
2000	280,518	279,795	723
2005	280,207	279,491	716
2010	280,369	279,537	833
2015	280,528	279,545	983
2016	280,529	279,533	996
2017	280,380	279,511	869
2018	280,274	279,483	791
2019	280,274	279,386	888

Table A-215: State-level Net C Flux from all Forest Pools in Forest Land Remaining Forest Land (MMT C) with Uncertainty Range Relative to Flux Estimate, 2019

State	Stock Change	Lower Bound	Lower Bound (%)	Upper Bound	Upper Bound (%)
Alabama	(12.6)	(14.4)	-15%	(10.8)	15%
Alaska	(4.6)	(6.0)	-31%	(3.1)	31%
Arizona	0.6	0.2	-65%	1.0	65%
Arkansas	(8.2)	(9.7)	-19%	(6.6)	19%
California	(7.3)	(15.3)	-109%	0.7	109%
Colorado	3.2	(5.3)	-268%	11.7	268%
Connecticut	(0.9)	(1.2)	-32%	(0.6)	32%
Delaware	(0.1)	(0.1)	-47%	(0.0)	47%
Florida	(5.4)	(6.0)	-12%	(4.7)	12%
Georgia	(8.2)	(8.7)	-6%	(7.7)	6%
Idaho	1.3	(2.3)	-279%	4.8	279%
Illinois	(1.2)	(2.2)	-82%	(0.2)	82%
Indiana	(1.4)	(3.0)	-112%	0.2	112%
Iowa	(0.7)	(1.0)	-44%	(0.4)	44%
Kansas	(0.6)	(1.0)	-68%	(0.2)	68%
Kentucky	(4.8)	(6.3)	-33%	(3.2)	33%
Louisiana	(6.1)	(6.5)	-8%	(5.6)	8%
Maine	(2.6)	(5.6)	-116%	0.4	116%
Maryland	(1.1)	(1.7)	-46%	(0.6)	46%
Massachusetts	(1.3)	(1.6)	-30%	(0.9)	30%
Michigan	(3.9)	(7.5)	-91%	(0.3)	91%
Minnesota	(3.7)	(6.0)	-63%	(1.4)	63%
Mississippi	(15.9)	(18.8)	-18%	(13.0)	18%
Missouri	(2.9)	(5.5)	-88%	(0.4)	88%
Montana	2.8	(5.1)	-281%	10.8	281%
Nebraska	(0.2)	(0.2)	-33%	(0.1)	33%
Nevada	0.0	(0.2)	-780%	0.3	780%
New Hampshire	(1.4)	(2.0)	-42%	(0.8)	42%
New Jersey	(0.6)	(0.7)	-16%	(0.5)	16%
New Mexico	1.0	(0.9)	-183%	3.0	183%

New York	(6.5)	(8.8)	-35%	(4.2)	35%
North Carolina	(8.3)	(9.5)	-15%	(7.0)	15%
North Dakota	(0.0)	(0.1)	-449%	0.1	449%
Ohio	(1.7)	(3.8)	-122%	0.4	122%
Oklahoma	(1.4)	(2.1)	-44%	(0.8)	44%
Oregon	(9.9)	(12.0)	-21%	(7.8)	21%
Pennsylvania	(5.3)	(9.8)	-84%	(0.9)	84%
Rhode Island	(0.1)	(0.2)	-169%	0.1	169%
South Carolina	(3.4)	(3.9)	-16%	(2.9)	16%
South Dakota	0.1	(0.2)	-280%	0.5	280%
Tennessee	(6.4)	(7.9)	-24%	(4.9)	24%
Texas	(5.5)	(6.0)	-9%	(5.0)	9%
Utah	1.0	(0.4)	-135%	2.4	135%
Vermont	(1.6)	(2.3)	-45%	(0.9)	45%
Virginia	(11.5)	(14.2)	-24%	(8.7)	24%
Washington	(4.7)	(9.4)	-98%	(0.1)	98%
West Virginia	(4.0)	(5.8)	-43%	(2.3)	43%
Wisconsin	(4.4)	(4.9)	-10%	(4.0)	10%
Wyoming	0.8	0.1	-82%	1.4	82%
49 States	**(159.3)**	**(178.0)**	**-12%**	**(140.6)**	**12%**

+ Absolute value does not exceed 0.05 MMT C.
Note: Parentheses indicate negative values.

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 2015 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 United States (USDA Forest Service 2020b, 2020c). 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 (USDA Forest Service 2020d). 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-203. Regions and forest types are the same classifications described in Smith et al. (2003). An example calculation for understory C in aspen-birch forests in the Northeast 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-203) 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 (USDA Forest Service 2020d).

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-204. 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-205. 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 2015 National Resources Inventory (NRI) (USDA-NRCS 2018), and National Land Cover Dataset (NLCD) (Yang et al. 2018). 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-216 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 estimated from the standard deviation of the NRI sampling error and uncertainty associated with the 1000 Monte Carlo simulations (See Annex 3.12). Table A-217

summarizes the total land areas by land use/land use change subcategory that were used to estimate soil C stock changes for mineral soils between 1990 and 2015.

Land Converted to Forest land area estimates

Forest land area estimates in section 6.3 *Land Converted to Forest Land* (CRF Category 4A2) of this Inventory are compiled using NFI data. Forest Land area estimates obtained from these data are also used as part of section 6.1 Representation of the U.S. Land Base (CRF Category 4.1). The Forest Land area estimates in section 6.3 do not include Hawaii as insufficient data is available from the NFI to compile area estimates over the entire time series. The National Land Cover Dataset is used in addition to NFI estimates in section 6.1 Representation of the U.S. Land Base and Forest Land in Hawaii is included in that section. This results in small differences in the managed Forest Land area in sections 6.1 and 6.3 of this Inventory (Table A-218). There are also other factors contributing to the small differences in area such as harmonization of aspatial and spatial data across all land use categories in section 6.1 over the entire Inventory time series.

Table A-216: 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	2010	2015	2016	2017	2018	2019
Cropland Converted to Forest Land	0.08 (0.03 to 0.13)	0.07 (0.03 to 0.12)	0.07 (0.02 to 0.12)	0.07 (0.02 to 0.13)	0.06 (0.01 to 0.11)	0.05 (0.01 to 0.1)	0.06 (-0.02 to 0.13)	0.06 (-0.02 to 0.13)	0.06 (-0.02 to 0.13)	0.06 (-0.02 to 0.13)
Grassland Converted to Forest Land	-0.05 (-0.08 to -0.01)	-0.05 (-0.1 to -0.01)	-0.07 (-0.12 to -0.01)	-0.08 (-0.14 to -0.02)	-0.08 (-0.15 to -0.02)	-0.08 (-0.15 to -0.02)	-0.08 (-0.18 to 0.02)	-0.08 (-0.17 to 0.02)	-0.07 (-0.17 to 0.02)	-0.07 (-0.17 to 0.03)
Other Lands Converted to Forest Land	0.17 (0.13 to 0.21)	0.22 (0.14 to 0.25)	0.24 (0.17 to 0.29)	0.30 (0.22 to 0.36)	0.32 (0.22 to 0.38)	0.31 (0.17 to 0.43)	0.31 (0.13 to 0.5)	0.31 (0.12 to 0.5)	0.31 (0.12 to 0.51)	0.31 (0.11 to 0.51)
Settlements Converted to Forest Land	0.01 (0 to 0.02)	0.01 (0.01 to 0.01)	0.01 (0.01 to 0.01)	0.01 (0.01 to 0.01)	0.01 (0.01 to 0.01)	0.02 (0.02 to 0.02)	0.02 (0.01 to 0.02)	0.02 (0.01 to 0.02)	0.02 (0.01 to 0.02)	0.02 (0.01 to 0.02)
Wetlands Converted to Forest Land	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)
Total Lands Converted to Forest Lands	**0.22**	**0.25**	**0.26**	**0.30**	**0.31**	**0.30**	**0.31**	**0.31**	**0.31**	**0.31**

Note: The range is a 95 percent confidence interval from 50,000 simulations (Ogle et al. 2003, 2006).

Table A-217: Total land areas (hectares) by land use/land use change subcategory for mineral soils between 1990 to 2015

Conversion Land Areas (Hectares x10^6)	1990	1995	2000	2005	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cropland Converted to Forest Land	0.17	0.16	0.17	0.16	0.16	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.14
Grassland Converted to Forest Land	0.75	0.81	0.80	0.81	0.82	0.84	0.84	0.84	0.83	0.84	0.84	0.83	0.80
Other Lands Converted to Forest Land	0.05	0.06	0.07	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Settlements Converted to Forest Land	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
Wetlands Converted to Forest Land	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
Total Lands Converted to Forest Lands	**0.99**	**1.06**	**1.05**	**1.08**	**1.09**	**1.11**	**1.11**	**1.10**	**1.10**	**1.10**	**1.10**	**1.09**	**1.06**

Note: Estimated with a Tier 2 approach and based on analysis of USDA National Resources Inventory data (USDA-NRCS 2018).

Table A-218: *Land Converted to Forest Land* area estimates and differences between estimates in the Representation of the U.S. Land Base (CRF Category 4.1) and *Land Converted to Forest Land* (CRF Category 4A1) (kha)

Year	Cropland Converted to Forest Land - 6.1 Representation of the U.S. Land Base (CRF Category 4.1)	Cropland Converted to Forest Land - 6.3 Land Converted to Forest Land (CRF Category 4A2)	Difference between estimates	Grassland Converted to Forest Land - 6.1 Representation of the U.S. Land Base (CRF Category 4.1)	Grassland Converted to Forest Land - 6.3 Land Converted to Forest Land (CRF Category 4A2)	Difference between estimates	Other Lands Converted to Forest Land - 6.1 Representation of the U.S. Land Base (CRF Category 4.1)	Other Lands Converted to Forest Land - 6.3 Land Converted to Forest Land (CRF Category 4A2)	Difference between estimates	Settlements Converted to Forest Land - 6.1 Representation of the U.S. Land Base (CRF Category 4.1)	Settlements Converted to Forest Land - 6.3 Land Converted to Forest Land (CRF Category 4A2)	Difference between estimates	Wetlands Converted to Forest Land - 6.1 Representation of the U.S. Land Base (CRF Category 4.1)	Wetlands Converted to Forest Land - 6.3 Land Converted to Forest Land (CRF Category 4A2)	Difference between estimates	TOTAL
1990	169	321	(151)	919	476	443	50	22	28	12	174	(162)	77	33	44	202
1995	170	325	(155)	1,077	487	590	66	22	44	20	178	(157)	28	33	(5)	316
2000	176	332	(157)	1,129	495	634	74	23	51	23	178	(155)	27	34	(7)	366
2005	167	317	(150)	1,162	495	667	93	22	71	24	172	(148)	28	33	(5)	435
2010	152	331	(179)	1,195	517	678	100	23	76	24	179	(156)	28	34	(5)	414
2015	139	325	(186)	1,125	515	610	100	24	76	27	179	(153)	25	32	(7)	340
2016	134	322	(188)	989	508	481	93	26	68	26	179	(153)	25	31	(6)	203
2017	135	324	(189)	992	491	501	93	27	66	26	178	(152)	25	31	(6)	220
2018	135	326	(191)	992	465	527	93	29	64	26	182	(156)	25	29	(5)	240
2019	135	326	(191)	992	465	527	93	29	64	26	182	(156)	25	29	(5)	240

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 United States 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:

$$Var(Ct2-Ct1)=Var(Ct2)+Var(Ct1)-2\cdot Cov(Ct2,Ct1) \quad (15)$$

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

$$\%U(Ct)m = 100\cdot MSEm/dt \quad (16)$$

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

$$U(Ct)m=Ct\cdot \%U(Ct)m/100 \quad (17)$$

The model-based uncertainty with respect to stock change is then

$$U(\Delta C)m=(U(Ct1)m + U(Ct2)m - 2\cdot Cov(U(Ct1m,Ct2m)))0.5 \quad (18)$$

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):

$$U(\Delta C)=(U(\Delta C)m2+ U(\Delta C)s2)0.5 \text{ and the 95 percent confidence bounds was } +- 2\cdot U(\Delta C) \quad (19)$$

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 CO_2 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 forest area burned, potential fuel available, and individual fire severity along with IPCC default emission factors and some combustion 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:

Emissions = Area burned × Fuel available × Combustion factor × Emission Factor × 10^{-3}

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 three factors are based on datasets specific to U.S. forests, whereas the emissions factor and in some cases an emission factor employ IPCC (2006) default values. Area burned is based on annual area of forest coincident with fires according to Monitoring Trends in Burn Severity (MTBS) (MTBS Data Summaries 2018; Eidenshink et al. 2007) dataset summaries, 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 (Ogle et al. 2018). Summary information includes fire identity, origin, dates, location, spatial perimeter of the area burned, and a spatial raster mosaic reflecting variability of the estimated fire severity within the perimeter. 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 explicitly included as a part of identifying information for each fire.

Area of forest within the MTBS fire perimeters was determined according to one of the National Land Cover (NLCD) 2016 datasets (Homer et al. 2015; Yang et al. 2018), which include land cover maps for seven of the years over the 2001-2016 interval. Alternate estimates of forest land would provide different estimates; for example Ruefenacht et al. (2008) and the FIADB (USDA Forest Service 2017) provide slightly different estimates and differences vary with location. Some of these differences can be incorporated into the estimates of uncertainty. The choice of NLCD cover for these estimates is because it readily facilitates incorporating the MTBS per-fire severity estimates. The Alaska forest area was allocated to managed and unmanaged areas according to Ogle et al. (2018). The use of the NLCD land cover images to identify forest land within each MTBS-delineated fire identified forest on 15,837 of the 19,558 fires on the 48 conterminous states for 1990-2019 (data for 2019 were unavailable when these estimates were summarized; therefore 2018, the most recent available estimate, is applied to 2019). Similarly, there were 828 of the 1,044 fires in Alaska for 1990-2019 (data for 2019 were unavailable when these estimates were summarized; therefore 2018, the most recent available estimate, is applied to 2019) that included some forest land and are considered managed lands.

The area of forest burned as calculated on some of the individual MTBS-delineated fires are different than the forest areas calculated for the previous inventory; these corrections potentially apply to fires between 1990 and 2016. A minor source of change in calculated forest area is the addition of NLCD land cover images. The NLCD 2016 data (Yang et al. 2018) includes years 2001, 2003, 2006, 2008, 2011, 2013, and 2016, which provide greater temporal resolution relative to the 2001, 2006, and 2011 years used in the previous inventory. This is likely to only have a minor effect on estimated forest area burned. Most of the differences in annual forest area burned (and thus associated emissions) as seen in Table A-219 relative to the same table in the previous inventory are due to improperly adjusting the proportion of forest land

within a fire to account for no-data values in an MTBS raster image rather than a similar modified NLCD raster image that conformed to the spatial extent of the fire. This calculation error only affected some fires; specifically those where the Landsat images included masked areas (such as for cloud cover). The greater the masked area, the greater the error in estimated forest land within the fire bounds.

Estimates of fuel availability are based on plot level forest inventory data, which are summarized by ecological province (see description of the data field 'ecosubcd' in the FIADB, USDA Forest Service 2015). These data are applied to estimates for fires located within the respective regions. Plot level C stocks (Smith et al. 2013; USDA Forest Service 2019) are grouped according to live aboveground biomass (live trees and understory), large dead wood (standing dead and down dead wood), and litter. 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 forest lands. The current forest inventory data and the distribution of metric tons dry matter per hectare are used as the inputs for fuel availability.

Each MTBS defined fire perimeter has an associated burn severity mosaic that includes spatial information on burn severity, which generally varies across the burned area. Combustion is set to similarly vary. Probabilistic definitions are assigned for combustion factors as uniform sampling distributions for each the live, dead wood, and litter fuels. Currently, the uniform distributions for live biomass combustion are defined as 0-0.3, 0.2-0.8, and 0.7-1.0, for burn severity classes 2, 3, and 4 respectively. Similarly, for dead wood combustion, distributions are defined as 0-0.05, 0.05-0.5, 0.3-0.9 and 0.8-1.0, for burn severity classes 1, 2, 3, and 4 respectively. Finally, litter combustion distributions are defined as 0-0.05, 0.-0.1, 0.1-0.7, 0.7-1.0, and 1.0, for burn severity classes 'increased greenness', 1, 2, 3, and 4 respectively (see MTBS documentation for additional information on classifications). Specific classifications not noted above as well as unburned forest within the perimeter are assumed to have zero fire-based emissions. The combustion factors used here for temperate forests are interim probabilistic ranges generally based on MTBS related publications and are subject to change with ongoing improvements (see Planned Improvements in the LULUCF chapter).

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 (2017) forest inventory along the southern coastal portion of the state. The majority of the 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. The few fires that were located in the coastal maritime ecoregion (about 1% of Alaska fires) were assigned fuel and combustion factors as described above. Fuel estimates were not available for the balance of the Alaska fires (on boreal forest) so they were calculated according to default values for boreal forests (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.

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). Table A-219 provides summary values of annual area of forest burned and emissions calculated as described above following 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-237. 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-219, and C emitted per year was based on multiplying by the conversion factor 12/44 (IPCC 2006).

Table A-219: 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	2010	2015	2016	2017	2018	2019[b]
Conterminous 48 States - Wildfires	Forest area burned (1000 ha)	83.5	101.2	508.3	402.1	115.8	954.1	501.5	1128.1	953.8	953.8
	C emitted (MMT/yr)	1.7	1.1	5.0	5.6	2.1	31.7	9.2	37.4	31.5	31.5
	CO_2 emitted (MMT/yr)	6.2	3.9	18.3	20.5	7.8	116.4	33.7	137.2	115.5	115.5
Alaska - Wildfires	Forest area burned (1000 ha)	82.5	1.4	59.6	686.7	103.9	631.3	26.8	23.8	45.5	45.5
	C emitted (MMT/yr)	1.4	0.0	1.0	12.0	1.8	11.1	0.5	0.4	0.8	0.8
	CO_2 emitted (MMT/yr)	5.3	0.1	3.8	44.1	6.7	40.7	1.7	1.5	2.9	2.9
Prescribed Fires (all 49 states)	Forest area burned (1000 ha)	5.0	10.6	15.4	43.5	496.3	150.8	249.9	222.7	206.6	206.6
	C emitted (MMT/yr)	0.1	0.1	0.2	0.4	6.2	1.7	2.7	2.3	2.2	2.2
	CO_2 emitted (MMT/yr)	0.2	0.3	0.8	1.5	22.9	6.1	9.7	8.4	8.0	8.0
Wildfires (all 49 states)	CH_4 emitted (kt/yr)	34.3	12.0	66.2	193.5	43.6	471.0	106.3	415.1	354.5	354.5
	N_2O emitted (kt/yr)	1.9	0.7	3.7	10.7	2.4	26.0	5.9	23.0	19.6	19.6
	CO emitted (kt/yr)	782.9	272.6	1506.6	4405.9	989.7	10718.5	2415.4	9462.2	8078.6	8078.6
	NO_x emitted (kt/yr)	21.9	7.7	42.3	123.5	27.7	300.2	67.9	265.3	226.7	226.7
Prescribed Fires (all 49 states)	CH_4 emitted (kt/yr)	0.7	0.8	2.5	4.6	68.6	18.3	29.2	25.2	24.0	24.0
	N_2O emitted (kt/yr)	0.0	0.0	0.1	0.3	3.8	1.0	1.6	1.4	1.3	1.3
	CO emitted (kt/yr)	16.9	18.0	58.0	105.1	1562.1	417.5	664.5	573.7	547.6	547.6
	NO_x emitted (kt/yr)	0.5	0.5	1.6	2.9	43.8	11.7	18.6	16.1	15.4	15.4

[a] These emissions have already been accounted for in the estimates of net annual changes in C stocks, which accounts for the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.

[b] The data for 2019 were unavailable when these estimates were summarized; therefore 2018, the most recent available estimate, is applied to 2019.

Table A-220: 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] Source: IPCC (2006)
[b] Source: IPCC (2007)

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-237. The summed annual estimates are provided in Table A-236. 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-237.

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). The probabilities used for the factors in equation 2.27 are considered marginal distributions. The distribution for forest area burned is a uniform distribution based on the difference in local estimates of forest area – NLCD versus FIA inventory estimates. Fuel availability is the standard error for the inventory plots within each eco-province. Combustion factor uncertainty is defined above, 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-237) to represent estimates as CO_2 equivalent were not considered uncertain values for these results.

References

AF&PA. (2006a and earlier). Statistical roundup. (Monthly). Washington, DC: American Forest & Paper Association.

AF&PA. (2006b and earlier). Statistics of paper, paperboard and wood pulp. Washington, DC: American Forest & Paper Association.

Amichev, B. Y. and J. M. Galbraith (2004) "A Revised Methodology for Estimation of Forest Soil Carbon from Spatial Soils and Forest Inventory Data Sets." *Environmental Management* 33(Suppl. 1): S74-S86.

Bechtold, W.A.; Patterson, P.L. (2005) The enhanced forest inventory and analysis program—national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 85 p.

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds); *Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions*. American Forests. Washington, DC, 1-26 and 261-379 (appendices 262 and 263).

Bodner, T.E. (2008) What improves with increased missing data imputations? Structural Equation Modeling. 15: 651-675.

Breiman L. (2001) Random forests. Machine Learning. 45(1):5-32.

Caswell, H. (2001) Matrix population models. Sunderland, MA: Sinauer Associates, Inc. 722 p.

Coulston, J.W., Wear, D.N., and Vose, J.M. (2015) Complex forest dynamics indicate potential for slowing carbon accumulation in the southeastern United States. Scientific Reports. 5: 8002.

Coulston, J.W. (In preparation). Tier 1 approaches to approximate the carbon implications of disturbances. On file with J.W. Coulston (jcoulston@fs.fed.us).

Coulston, J.W., Woodall, C.W., Domke, G.M., and Walters, B.F. (in preparation). Refined Delineation between Woodlands and Forests with Implications for U.S. National Greenhouse Gas Inventory of Forests.

Danielson J.J.; Gesch D.B. (2011) Global multi-resolution terrain elevation data 2010 (GMTED2010). Open-file report 2011–1073. Reston, VA: U.S. Department of the Interior, Geological Survey. 26 p.

De Vos, B.; Cools, N.; Ilvesniemi, H.; Vesterdal, L.; Vanguelova, E.; Carnicelli, S. (2015) Benchmark values for forest soil carbon stocks in Europe: results from a large scale forest soil survey. Geoderma. 251: 33-46.

Domke, G.M., Woodall, C.W., Smith, J.E., Westfall, J.A., McRoberts, R.E. (2012) Consequences of alternative tree-level biomass estimation procedures on U.S. forest carbon stock estimates. Forest Ecology and Management. 270: 108-116.

Domke, G.M., Smith, J.E., and Woodall, C.W. (2011) Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. *Carbon Balance and Management*. 6:14.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. *PLoS ONE* 8(3): e59949.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016). A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment. 557–558, 469–478.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., Nave, L., Swanston, C. (2017) Toward inventory-based estimates of soil organic carbon in forests of the United States. Ecological Applications**.** 27(4), 1223-1235.Eidenshink, J., B. Schwind, K. Brewer, Z. Zhu, B. Quayle, and S. Howard. (2007) A project for monitoring trends in burn severity. Fire Ecology 3(1): 3-21.

Domke, G.M., Walters, B.F., Gray, A., Mueller, B. (In prep). Estimating greenhouse gas emissions and removals on managed forest land in Alaska, USA. Intended outlet: *Proceedings of the National Academy of Science*.

Frayer, W.E., and G.M. Furnival (1999) "Forest Survey Sampling Designs: A History." *Journal of Forestry* 97(12): 4-10.

Freed, R. (2004) Open-dump and Landfill timeline spreadsheet (unpublished). ICF International. Washington, D.C.

Hair, D. and A.H. Ulrich (1963) The Demand and price situation for forest products – 1963. U.S. Department of Agriculture Forest Service, Misc Publication No. 953. Washington, DC.

Hair, D. (1958) "Historical forestry statistics of the United States." Statistical Bull. 228. U.S. Department of Agriculture Forest Service, Washington, DC.

Hao, W.M. and N.K. Larkin. (2014) Wildland fire emissions, carbon, and climate: Wildland fire detection and burned area in the United States. Forest Ecology and Management 317: 20–25.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Heath, L.S., M.C. Nichols, J.E. Smith, and J.R. Mills. (2010) FORCARB2: An updated version of the U.S. Forest Carbon Budget Model. Gen. Tech. Rep. NRS-67.USDA Forest Service, Northern Research Station, Newtown Square, PA. 52 p. [CD-ROM].

Heath, L.S., J.E. Smith, K.E. Skog, D.J. Nowak, and C.W. Woodall. (2011) Managed forest carbon estimates for the U.S. Greenhouse Gas Inventory, 1990-2008. *Journal of Forestry* 109(3):167-173.

Homer, C.G., J.A. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N.D. Herold, J.D. Wickham, and K. Megown. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing 81(5): 345-354.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Howard, James L. (2003) *U.S. timber production, trade, consumption, and price statistics 1965 to 2002*. Res. Pap. FPL-RP-615. Madison, WI: USDA, Forest Service, Forest Products Laboratory. Available online at <http://www.fpl.fs.fed.us/documnts/fplrp/fplrp615/fplrp615.pdf>.

Howard, J. L. and Liang, S. (2019). U.S. timber production, trade, consumption, and price statistics 1965 to 2017. Res. Pap. FPL-RP-701. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

Howard, J. L. and Jones, K.C. (2016) U.S. timber production, trade, consumption, and price statistics 1965 to 2013. Res. Pap. FPL-RP-679. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

Howard, J. L. (2007) U.S. timber production, trade, consumption, and price statistics 1965 to 2005. Res. Pap. FPL-RP-637. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

Ince, P.J., Kramp, A.D., Skog, K.E., Spelter, H.N. and Wear, D.N. (2011) U.S. Forest Products Module: a technical document supporting the forest service 2010 RPA assessment. Research Paper-Forest Products Laboratory, USDA Forest Service, (FPL-RP-662).

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

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.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman, et al., eds. August 13, 2004. Available online at <http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm>.

ISCN. (2015) International Soil Carbon Monitoring Network (http://iscn.fluxdata.org/) database.

Jandl, R., Rodeghiero, M., Martinez, C., Cotrufo, M. F., Bampa, F., van Wesemael, B., Harrison, R.B., Guerrini, I.A., deB Richter Jr., D., Rustad, L., Lorenz, K., Chabbi, A., Miglietta, F. 2014. Current status, uncertainty and future needs in soil organic carbon monitoring. Science of the Total Environment, 468, 376-383.

Jenkins, J,C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." *Forest Science* 49(1): 12-35.

Jobbagy, E.G.; Jackson, R.B. (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications. 10: 423-436.

Lal, R. (2005) Forest soils and carbon sequestration. Forest Ecology and Management. 220(1): 242-258.

MTBS Data Summaries. 2018. MTBS Data Access: Fire Level Geospatial Data. (2018, August - last revised). MTBS Project (USDA Forest Service/U.S. Geological Survey). Available online: http://mtbs.gov/direct-download [06Aug2018].

NAIP. (2015) National Agriculture Imagery Program. U.S. Department of Agriculture, Washington, DC. http://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/ <last accessed November 23, 2015>.

Natural Resources Conservation Service [NRCS]. (2015) Soil geography: Description of STATSGO2 database. <http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053629> (accessed October 6, 2015).

Northwest Alliance for Computational Science and Engineering. (2015) PRISM Climate Data. Available at <http://prism.oregonstate.edu> (accessed October 6, 2015).

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." Global Change Biology 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian. (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." Global Change Biology 12:516-523.

Ogle, S. M., G. M. Domke, W. A. Kurz, M. T. Rocha, T. Huffman, A. Swan, J. E. Smith, C. W. Woodall, and T. Krug. 2018. Delineating managed land for reporting national greenhouse gas emissions and removals to the United Nations framework convention on climate change. Carbon Balance and Management 13:9.

O'Neill, K.P., Amacher, M.C., Perry, C.H. (2005) Soils as an indicator of forest health: a guide to the collection, analysis, and interpretation of soil indicator data in the Forest Inventory and Analysis program. Gen. Tech. Rep. NC-258. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 53 p.

Oswalt, S.N.; Smith, W.B; Miles, P.D.; Pugh, S.A. (2014) Forest Resources of the United States, 2012: a technical document supporting the Forest Service 2015 update of the RPA Assessment. Gen. Tech. Rep. WO-91. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office. 218 p.

Perry, C.H., C.W. Woodall, and M. Schoeneberger (2005) Inventorying trees in agricultural landscapes: towards an accounting of "working trees". In: "Moving Agroforestry into the Mainstream." *Proc. 9th N. Am. Agroforestry Conf.*, Brooks, K.N. and Ffolliott, P.F. (eds). 12-15 June 2005, Rochester, MN [CD-ROM]. Dept. of Forest Resources, Univ. Minnesota, St. Paul, MN, 12 p. Available online at <http://cinram.umn.edu/afta2005/> (verified 23 Sept 2006).

R Core Team (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Ruefenacht, B., M.V. Finco, M.D. Nelson, R. Czaplewski, E.H. Helmer, J.A. Blackard, G.R. Holden, A.J. Lister, D. Salajanu, D. Weyermann, K. Winterberger. 2008. Conterminous U.S. and Alaska Forest Type Mapping Using Forest Inventory and Analysis. USDA Forest Service - Forest Inventory and Analysis Program & Remote Sensing Applications Center. Available online at <http://data.fs.usda.gov/geodata/rastergateway/forest_type/>. Accessed 8 September 2015.

Skog, K.E., K. Pingoud, and J.E. Smith (2004) "A method countries can use to estimate changes in carbon stored in harvested wood products and the uncertainty of such estimates." *Environmental Management* 33(Suppl. 1):S65-S73.

Skog, K.E. (2008) "Sequestration of Carbon in harvested wood products for the United States." *Forest Products Journal*, 58(6): 56-72.

Smith, J. E., L. S. Heath, and C. M. Hoover. 2013. Carbon factors and models for forest carbon estimates for the 2005-2011 National Greenhouse Gas Inventories of the United States. For. Ecology and Management 307:7–19.

Smith, J.E., L.S. Heath, and M.C. Nichols (2010). U.S. Forest Carbon Calculation Tool User's Guide: Forestland Carbon Stocks and Net Annual Stock Change. General Technical Report NRS-13 revised, U.S. Department of Agriculture Forest Service, Northern Research Station.

Smith, J.E., L.S. Heath, K.E. Skog, R.A. Birdsey. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. U.S. Department of Agriculture, Forest Service, Northeastern Research Station. Newtown Square, PA.

Smith, J.E., L. S. Heath, and P. B. Woodbury (2004) "How to estimate forest carbon for large areas from inventory data." *Journal of Forestry* 102:25-31.

Smith, J.E., L. S. Heath, and J. C. Jenkins (2003) *Forest Volume-to-Biomass Models and Estimates of Mass for Live and Standing Dead Trees of U.S. Forests.* General Technical Report NE-298, USDA Forest Service, Northeastern Research Station, Newtown Square, PA.

Smith, J.E., and L.S. Heath (2002) "A model of forest floor carbon mass for United States forest types." Res. Paper NE-722. USDA Forest Service, Northeastern Research Station, Newtown Square, PA.

Steer, Henry B. (1948) *Lumber production in the United States*. Misc. Pub. 669, U.S. Department of Agriculture Forest Service. Washington, DC.

Sun, O.J.; Campbell, J.; Law, B.E.; Wolf, V. (2004) Dynamics of carbon stocks in soils and detritus across chronosequences of different forest types in the Pacific Northwest, USA. Global Change Biology. 10(9): 1470-1481.

Tan, Z.X.; Lal, R.; Smeck, N.E.; Calhoun, F.G. (2004) Relationships between surface soil organic carbon pool and site variables. Geoderma. 121(3): 187-195.

Thompson, J.A.; Kolka, R.K. (2005) Soil carbon storage estimation in a forested watershed using quantitative soil-landscape modeling. Soil Science Society of America Journal. 69(4): 1086-1093.

Ulrich, A.H. (1989) *U.S. Timber Production, Trade, Consumption, and Price Statistics, 1950-1987*. USDA Miscellaneous Publication No. 1471, U.S. Department of Agriculture Forest Service. Washington, DC, 77.

Ulrich, A.H. (1985) *U.S. Timber Production, Trade, Consumption, and Price Statistics 1950-1985*. Misc. Pub. 1453, U.S. Department of Agriculture Forest Service. Washington, DC.

United Nations Framework Convention on Climate Change. (2013) Report on the individual review of the inventory submission of the United States of America submitted in 2012. FCCC/ARR/2012/USA. 42 p.

USDC Bureau of Census (1976) *Historical Statistics of the United States, Colonial Times to 1970, Vol. 1*. Washington, DC.

USDA Forest Service (2020a) Forest Inventory and Analysis National Program: Program Features. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: <http://fia.fs.fed.us/program-features/>. Accessed 10 October 2020.

USDA Forest Service. (2020b) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: < https://apps.fs.usda.gov/fia/datamart/datamart.html>. Accessed on 10 October 2020.

USDA Forest Service. (2020c) Forest Inventory and Analysis National Program, FIA library: Field Guides, Methods and Procedures. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: <http://www.fia.fs.fed.us/library/field-guides-methods-proc/>. Accessed on 10 October 2020.

USDA Forest Service (2020d) Forest Inventory and Analysis National Program, FIA library: Database Documentation. U.S. Department of Agriculture, Forest Service, Washington Office. Available online at: <http://fia.fs.fed.us/library/database-documentation/>. Accessed on 10 October 2020.

USDA-NRCS (1997) "National Soil Survey Laboratory Characterization Data," Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

USDA-NRCS (2013) Summary Report: 2010 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1167354.pdf>.

U.S. EPA. (2015) Annex 3.13 Methodology for estimating net carbon stock changes in forest lands remaining forest lands. in Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013. U.S. Environmental Protection Agency. EPA 430-R-15-004.

Wear, D.N., Coulston, J.W. (2015) From sink to source: Regional variation in U.S. forest carbon futures. Scientific Reports. 5: 16518.

Wellek, S. (2003) Testing statistical hypotheses of equivalence. London, England: Chapman & Hall.

Woldeselassie, M.; Van Miegroet, H.; Gruselle, M.C.; Hambly, N. (2012) Storage and stability of soil organic carbon in aspen and conifer forest soils of northern Utah. Soil Science Society of America Journal. 76(6): 2230-2240.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols. (2011) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., B.L. Conkling, M.C. Amacher, J.W. Coulston, S. Jovan, C.H. Perry, B. Schulz, G.C. Smith, S. Will Wolf. (2010). The Forest Inventory and Analysis Database Version 4.0: Database Description and Users Manual for Phase 3. Gen. Tech. Rep. NRS-61. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 180 p.

Woodall, C.W., Coulston, J.W., Domke, G.M., Walters, B.F., Wear, D.N., Smith, J.E., Anderson, H.-E., Clough, B.J., Cohen, W.B., Griffith, D.M., Hagan, S.C., Hanou, I.S.; Nichols, M.C., Perry, C.H., Russell, M.B., Westfall, J.A., Wilson, B.T. (2015a) The U.S. Forest Carbon Accounting Framework: Stocks and Stock change 1990-2016. Gen. Tech. Rep. NRS-154. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 49 pp.

Woodall, C.W., Walters, B.F., Coulston, J.W., D'Amato, A.W., Domke, G.M., Russell, M.B., Sowers, P.A. (2015b) Monitoring network confirms land use change is a substantial component of the forest carbon sink in the eastern United States. Scientific Reports. 5: 17028.

Woodall, C.W., Domke, G.M., MacFarlane, D.W., Oswalt, C.M. (2012) Comparing Field- and Model-Based Standing Dead Tree Carbon Stock Estimates Across Forests of the United States. Forestry 85(1): 125-133.

Woodall, C.W., Walters, B.F., Oswalt, S.N., Domke, G.M., Toney, C., Gray, A.N. (2013) Biomass and carbon attributes of downed woody materials in forests of the United States. Forest Ecology and Management 305: 48-59.

Woodall, C.W., Domke, G.M., MacFarlane, D.W., Oswalt, C.M. (2012) Comparing field- and model-based standing dead tree carbon stock estimates across forests of the United States. Forestry. 85: 125-133.

Woudenberg, S.W. and T.O. Farrenkopf (1995) The Westwide forest inventory data base: user's manual. General Technical Report INT-GTR-317. U.S. Department of Agriculture Forest Service, Intermountain Research Station.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Grannemann, B., Rigge, M. and G. Xian. 2018. A New Generation of the United States National Land Cover Database: Requirements, Research Priorities, Design, and Implementation Strategies, ISPRS Journal of Photogrammetry and Remote Sensing, 146, pp.108-123.

3.14. Methodology for Estimating CH4 Emissions from Landfills

A combination of Tier 2 and 3 approaches are used to calculate emissions from for MSW Landfills. A Tier 2 approach is used to calculate emissions for industrial waste landfills.

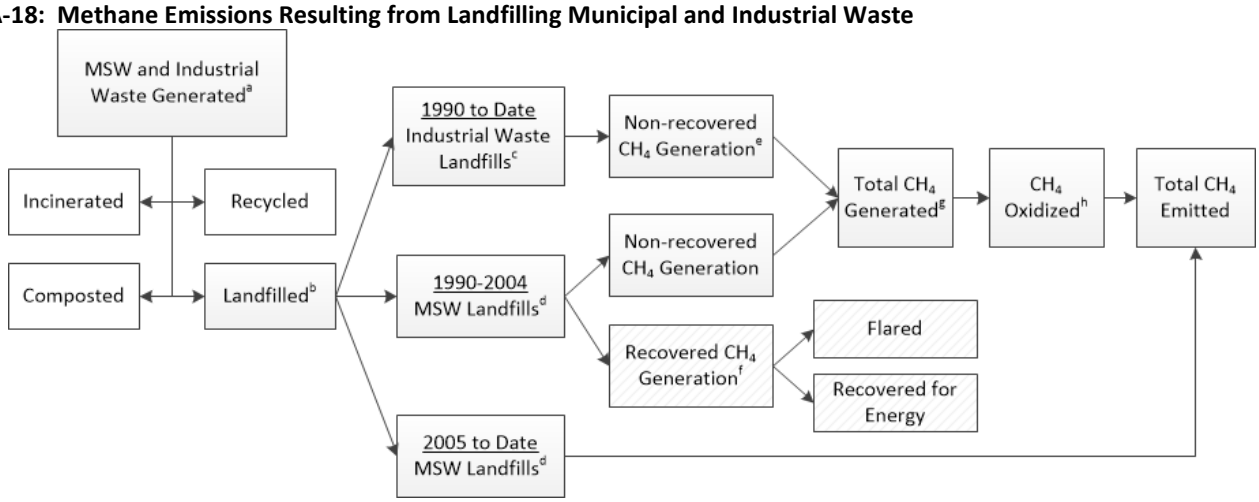
Landfill gas is a mixture of substances generated when bacteria decompose the organic materials contained in solid waste. By volume, landfill gas is about half CH_4 and half CO_2.[131] The amount and rate of CH_4 generation depends upon the quantity and composition of the landfilled material, as well 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 are estimated using two primary methods. The first method uses the first order decay (FOD) 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 second method used to calculate CH_4 emissions from landfills, also called the back-calculation method, is based off directly measured amounts of recovered CH_4 from the landfill gas and is expressed by Equation HH-8 in CFR Part 98.343 of the EPA's Greenhouse Gas Reporting Program (GHGRP).

The current Inventory methodology uses both methods to estimate CH_4 emissions across the time series. The 1990 to 2015 Inventory was the first Inventory to incorporate directly reported GHGRP net CH_4 emissions data for landfills. In previous Inventories, only the first order decay method was used. EPA's GHGRP requires landfills meeting or exceeding a threshold of 25,000 metric tons (MT) 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*. Using EPA's GHGRP data was a significant methodological change and required a merging of the GHGRP methodology with the Inventory methodology used in previous years to ensure time-series consistency.

Figure A-18 presents the CH_4 emissions process—from waste generation to emissions—in graphical format. A detailed discussion of the steps taken to compile the 1990 to 2019 Inventory are presented in the remainder of this Annex.

Figure A-18: Methane Emissions Resulting from Landfilling Municipal and Industrial Waste



[a] MSW waste generation is not calculated because annual quantities of waste landfilled are available through secondary sources as described in figure note b.

[131] 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.

[b] Quantities of MSW landfilled for 1940 through 1988 are based on EPA 1988 and EPA 1993; 1989 through 2004 are based on *BioCycle* 2010; 2005 through 2019 are incorporated through the directly reported emissions from MSW landfills to the Greenhouse Gas Reporting Program. Quantities of industrial waste landfilled are estimated using a disposal factor and industrial production data sourced from Lockwood Post's Directory and the USDA.
[c] The *2006 IPCC Guidelines* – First Order Decay (FOD) Model is used for industrial waste landfills.
[d] Two different methodologies are used in the time series for MSW landfills. For 1990 to 2004, the *2006 IPCC Guidelines* – FOD Model is used. For 2005 to 2019, directly reported net CH_4 emissions from the GHGRP for 2010 to the current Inventory year are used with the addition of a scale-up factor applied to each year's emissions. The scale-up factor accounts for emissions from landfills that do not report to the GHGRP. A scale-up factor of 9 percent is applied to 2005-2016 and a scale-up factor of 11 percent is applied to 2017-2019. The GHGRP emissions from 2010 to the current Inventory year are also used to back-cast emissions for 2005 to 2009 to merge the FOD methodology with the GHGRP methodology for time series consistency. Additional details on how the scale-up factor was developed and the back-casting approach are included in Step 4 of this Annex chapter.
[e] Methane recovery from industrial waste landfills is not incorporated into the Inventory because it does not appear to be a common practice according to the GHGRP dataset.
[f] Methane recovery data are pulled from three recovery databases: EIA 2007, flare vendor database, and EPA (GHGRP) 2015(a). These databases have not been updated past 2015 because the Inventory strictly uses net emissions from the GHGRP data which already accounts for CH_4 recovery.
[g] For years 1990 to 2004, the total CH_4 generated from MSW landfills and industrial waste landfills are summed. For years 2005 to 2019, only the industrial waste landfills are considered because the directly reported GHGRP emissions are used for MSW landfills.
[h] An oxidation factor of 10 percent is applied to all CH_4 generated in years 1990 to 2004 (*2006 IPCC Guidelines*; Mancinelli and McKay 1985; Czepiel et al 1996). For years 2005 to 2019, directly reported CH_4 emissions from the GHGRP are used for MSW landfills. Various oxidation factor percentages are included in the GHGRP dataset (0, 10, 25, and 35) with an average across the dataset of approximately 20 percent.

Step 1: Estimate Annual Quantities of Solid Waste Placed in MSW Landfills for 1940 to 2004

Total national annual waste generation and disposal data back to 1940 are directly used to estimate CH_4 emissions for the 1990 to 2004 Inventory time series. The waste generation and disposal estimates are also made for the rest of the Inventory time series (i.e., 2005 to the current Inventory year) for informational purposes; these data however do not inform the annual CH_4 emission estimates for this portion of the time series. The specific steps are described below (in sections 1a and 1b), followed by a summary of a comparative analysis of datasets that contain or are used to estimate annual waste disposal (in).

1a. Historical Estimates: 1940 to 1988

Historical waste data, preferably from 50 years prior to the first year of the inventory time series (i.e. since 1940 because the time series begins in 1990), are required for the FOD model to estimate CH_4 generation for the Inventory time series (IPCC 2006). States and local municipalities across the United States do not consistently track and report quantities of MSW generated or collected for management, nor do they report end-of-life disposal methods to a centralized system. Therefore, national MSW landfill waste generation and disposal data are obtained from secondary data sources or estimated via proxy data.

Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress (EPA 1993) and an extensive landfill survey by the EPA's Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the FOD model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s.

1b. Inventory Time Series Estimates: 1990 to the Current Inventory Year

For 1989 to 2008, estimates of the annual quantity of MSW generated were developed from a survey of state agencies as reported in the State of Garbage (SOG) in America surveys (BioCycle 2001, 2004, 2006, 2010), adjusted to include U.S. Territories.[132] The SOG surveys collected data from state agencies and then applied the principles of mass balance where all MSW generated is equal to the amount of MSW landfilled, combusted in waste-to-energy plants, composted, and/or recycled (BioCycle 2006; Shin 2014). This approach assumes that all waste management methods are

[132] 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 2020) and the per capita rate for waste landfilled from BioCycle (2010).

tracked and reported to state agencies. Survey respondents were asked to provide a breakdown of MSW generated and managed by landfilling, recycling, composting, and combustion (in waste-to-energy facilities) in actual tonnages as opposed to reporting a percent generated under each waste disposal option. The data reported through the surveys have typically been adjusted to exclude non-MSW materials (e.g., industrial and agricultural wastes, construction and demolition debris, automobile scrap, and sludge from wastewater treatment plants) that may be included in survey responses. While non-municipal solid wastes may have been disposed of in MSW landfills, they were not the primary type of waste material disposed and are typically inert. In last survey (BioCycle 2010), state agencies were asked to provide MSW-only data. Where this was not possible, they were asked to provide comments to better understand the data being reported. Methodological changes have occurred over the time frame the SOG surveys have been published, which directly impacted the fluctuating trends observed in the waste disposal data and emission estimates from 1990 to 2004 (RTI 2013).

The SOG survey is voluntary and not all states provided data in each survey year. To estimate waste generation for states that did not provide data in any given reporting year, one of the following methods was used (RTI 2013):

- For years when a state-specific waste generation rate was available from the previous SOG reporting year submission, the state-specific waste generation rate for that state was used.

  – or –

- For years where a state-specific waste generation rate was not available from the previous SOG reporting year submission, the waste amount is generated using the national average waste generation rate. In other words, Waste Generated = Reporting Year U.S. Population × the National Average Waste Generation Rate
  - The National Average Waste Generation Rate is determined by dividing the total reported waste generated across the reporting states by the total population for reporting states.
  - This waste generation rate may be above or below the waste generation rate for the non-reporting states and contributes to the overall uncertainty of the annual total waste generation amounts used in the model.

Use of these methods to estimate solid waste generated by states is a key aspect of how the SOG data was manipulated and why the results differ for total solid waste generated as presented in the SOG reports and in the Inventory. In the early years (2002 data in particular), SOG made no attempt to fill gaps for non-survey responses. For the 2004 data, the SOG team used proxy data (mainly from the Waste Business Journal [WBJ]) to fill gaps for non-reporting states and survey responses.

Although some fluctuation in waste generation data reported by states to the SOG survey is expected, for some states, the year-to-year fluctuations are quite significant (>20 percent increase or decrease in some case) (RTI 2013). The SOG survey reports for these years do not provide additional explanation for these fluctuations and the source data are not available for further assessment. Although exact reasons for the large fluctuations are difficult to obtain without direct communication with states, staff from the SOG team that were contacted speculated that significant fluctuations are present because the particular state could not gather complete information for waste generation (i.e., they are missing part of recycled and composted waste data) during a given reporting year. In addition, SOG team staff speculated that some states may have included C&D and industrial wastes in their previous MSW generation submissions but made efforts to exclude that (and other non-MSW categories) in more recent reports (RTI 2013).

The SOG surveys provide state-specific landfill waste generation data used in the Inventory for select years – 1989 to 2000, 2002, 2004, 2006, and 2008. In-between year waste generation is interpolated using the prior and next SOG report data. For example, waste generated in 2003 = (waste generation in 2002 + waste generation in 2004)/2.

For the Inventory year 2010 and later, EREF's 2016 report entitled, *MSW Management in the United States*, is used as the primary data source because BioCycle ceased preparing the SOG surveys. EREF (2016) includes state-specific landfill MSW generation and disposal data for 2010 and 2013 using a similar methodology as the SOG surveys. Waste generation data were interpolated for 2009, the year in-between the 2008 SOG survey data and the 2010 EREF data. Waste generation data were also extrapolated for 2011 and 2012 using the EREF data for 2010 and 2013. Waste generation data for 2014 and the current year were extrapolated based on the EREF 2013 data and population increases from the U.S. Census (U.S. Census Bureau 2020). No data source on annual waste generation by state or nationally (similar to an SOG or EREF report) has been published since EREF (2016).

For each year in the time series, estimates of the quantity of waste landfilled are determined by applying a waste disposal factor to the total amount of waste generated. A waste disposal factor was determined for each year a SOG survey was 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 report and extrapolated for years after the last year of EREF data (i.e., 2013). The waste disposal factor has ranged from approximately 77 percent in 1990 to 65.3 percent from 2015 to 2019.

Table A-221 shows estimates of MSW generated and landfilled, and industrial waste landfilled. A description of the data sources used to estimate industrial waste landfilled is included in Step 7. Estimates for MSW generated and landfilled are presented for various years after 2004 for informational purposes only. As described in Step 4, after 2004, the Inventory methodology relies on the GHGRP net reported CH_4 emissions data, replacing the need for the now discontinued SOG surveys and intermittent EREF estimates.

Table A-221: Solid Waste in MSW and Industrial Waste Landfills Contributing to CH_4 Emissions (MMT unless otherwise noted)

	1990	2005	2015	2016	2017	2018	2019
Total MSW Generated[a]	270	368	322	324	326	328	329
Percent of MSW Landfilled	77%	64%	65%	65%	65%	65%	65%
Total MSW Landfilled	**205**	**234**	**208**	**209**	**211**	**212**	**212**
MSW last 30 years[b]	4,876	5,992	6,455	6,476	6,497	6,515	6,531
MSW since 1940[c]	6,808	9,925	12,085	12,294	12,505	12,716	12,929
Total Industrial Waste Production Data	**196**	**221**	**209**	**209**	**209**	**209**	**209**
Pulp and Paper Sector[d]	129	139	122	121	121	121	119
Food and Beverage Sector[e]	67	82	87	87	88	88	90
Percent Total Industrial Waste Landfilled	**5%**	**5%**	**5%**	**5%**	**5%**	**5%**	**5%**
Total Industrial Waste Landfilled	**9.7**	**10.9**	**10.3**	**10.3**	**10.3**	**10.1**	**10.3**
Pulp and Paper Sector[d]	6.5	6.9	6.1	6.1	6.1	6.0	6.0
Food and Beverage Sector[e]	3.3	4.0	4.2	4.2	4.3	4.3	4.4

[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 2009 (1981 to 2004, and 2006 to 2011 are not presented in table). Values for years 2010 to 2019 are based on EREF (2016) and annual population data from the U.S. Census Bureau (2020).

[b] This estimate is the cumulative amount of waste that has been placed in landfills for the 30 years prior 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; EREF 2016; and extrapolated data based on annual population increases (U.S. Census Bureau 2020).

[c] 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; EREF 2016; and extrapolated data based on annual population increases (U.S. Census Bureau 2020).

[d] A disposal factor of 0.050 MT/MT of product is applied to total pulp and paper production data to estimate the annual amount landfilled. See Step 7 for the references and rationale for this method. The same disposal factor is applied to every year of the time series. Production data from 1990 and 2001 are from Lockwood-Post's Directory, 2002. Production data from 2002 to 2019 are from the FAOStat database available at: http://faostat3.fao.org/home/index.html#DOWNLOAD. Accessed on May 20, 2020.

[e] A disposal factor of 0.046 MT/MT of product is applied to total food production data to estimate the annual amount landfilled. See Step 7 for the references and rationale for this method. The same disposal factor is applied to every year of the time series. Food production values for 1990 to 2019 are from ERG 2020. 2020 USDA-NASS Ag QuickStats available at http://quickstats.nass.usda.gov (FAO 2019).

Box A-3: Comparison of Annual Waste Disposal Estimates Aross Available Data Sources

In 2019, EPA compared the available data on estimates of total waste generated and landfilled as presented in Table A-221 for the year 2017 and found inconsistencies between the estimates of MSW landfilled between the data sources. Data sources directly compared include the EREF-extrapolated estimate for 2017 to the Advancing Sustainable Materials Management: Facts and Figures report (EPA 2019b, Table 2, latest year of data is 2017). These inconsistencies are expected, as the data sources use two different methodologies to estimate MSW landfilled. While there are differences in the methods used between these data sources, the uncertainty factors for MSW Landfills are intended to account for these variabilities in the emission estimates for 1990 to 2004.

The EREF-extrapolated estimate of total MSW landfilled for 2017 is based on a bottom-up approach using information at the facility-level to estimate MSW for the sector as a whole, while the Facts and Figures report uses a top-down (materials flow mass balance) approach to estimate the same quantity. The materials flow methodology is generally based on production data for each material at the state- (recycling, composting) or national- (waste generation) level. Discarded or landfilled material is Subtitle D waste only and assumed to be the calculated difference between generation and recovery through recycling and composting (EPA 2019a). Subtitle D wastes do not include construction and demolition waste, for example, which many GHGRP-reporting facilities accept and include in their greenhouse gas reports.

As a quality check, EPA also compared the MSW landfilled estimates from the EREF-extrapolated data, the Facts and Figures report, and the estimated waste disposed by facilities reporting to EPA's GHGRP under Subpart HH (MSW Landfills) for 2017 plus a 9 percent scale-up factor to account for landfills that do not report to Subpart HH.

- On average, the EREF-extrapolated value was 36 percent less than GHGRP-based estimated waste disposal amount (including a scale-up factor of 9 percent) for the year 2017.
- Estimates of MSW landfilled from the Facts and Figures report for the year 2017 were, on average, 60 percent less than the GHGRP + scale-up factor waste quantity.

While this percent difference is large, it is not unexpected. The GHGRP uses a facility-specific, bottom-up approach to estimating emissions while the Facts and Figures report uses a top-down approach which incorporates many assumptions about disposal and recycling at a national level. The Facts and Figures report also specifically omits certain types of waste that are explicitly included in the GHGRP reports, such as construction and demolition waste, biosolids (sludges), and other inert wastes (EPA 2019a). The exclusion of these waste categories likely accounts for much of the discrepancies between these two data sets.

Step 2: Estimate CH_4 Generation at MSW Landfills for 1990 to 2004

The FOD method is exclusively used for 1990 to 2004. For the FOD method, methane generation is based on nationwide MSW generation data, to which a national average disposal factor is applied; it is not landfill-specific.

The FOD method is presented below and is similar to Equation HH-6 in CFR Part 98.343 for MSW landfills, and Equation TT-6 in CFR Part 98.463 for industrial waste landfills.

$$CH_{4,\text{Solid Waste}} = [G_{CH4,MSW} - R] - Ox$$

where,

$CH_{4,\text{Solid Waste}}$ = Net CH_4 emissions from solid waste
$G_{CH4,MSW}$ = CH_4 generation from MSW landfills
R = CH_4 recovered and combusted
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) as a function of methane generation potential (Lo), and the decay rate constant (k). The equation below provides additional detail on the activity data and emission factors used in the $CH_{4,MSW}$ equation presented above.

$$CH_{4,MSW} = \left[\sum_{x=S}^{T-1}\left\{W_x \times Lo \times \frac{16}{12} \times \left(e^{-k(T-x-1)} - e^{-k(T-x)}\right)\right\}\right]$$

where,

$CH_{4,MSW}$	=	Total CH_4 generated from MSW landfills
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-222)

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),
L0	=	CH_4 generation potential (100 m3 CH_4/Mg waste; EPA 1998, 2008),
6.74 × 10-4	=	CH_4 density (Mg/m3),
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[133] of 100 m^3 CH_4/Mg waste (EPA 2008) as described below.

The DOC value used in the CH_4 generation estimates from MSW landfills for 1990 to 2004 is 0.2028, which 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 L_o 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

[133] 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.

precipitation; consequently, average values of k were developed for three precipitation ranges, shown in Table A-222 and recommended in EPA's compilation of emission factors (EPA 2008).

Table A-222: 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 25 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-223.

Table A-223: Percent of U.S. Population within Precipitation Ranges by Decade (%)

Precipitation Range (inches/year)	1950	1960	1970	1980	1990	2000
<20	10	13	14	16	19	20
20-40	40	39	37	36	34	33
>40	50	48	48	48	48	48

Totals may not add to 100% due to rounding.
Note: The precipitation range data are no longer used in the IPCC waste model (i.e., the FOD method) for 2010 and later years.
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.

The *2006 IPCC Guidelines* also require annual proportions of waste disposed of in managed landfills versus unmanaged and uncategorized sites 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 unmanaged and uncategorized sites 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 uncategorized sites. The uncategorized sites represent those sites where not enough information was available to assign a percentage to unmanaged shallow versus unmanaged deep solid waste disposal sites. 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 the uncategorized sites, a methane correction factor (MCF) of 0.6 was used based on the recommended IPCC default value for uncharacterized land disposal (IPCC 2006). 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 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 four 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 LFGE projects that is primarily based on information compiled by EPA LMOP (EPA 2016),
- the flare vendor database (contains updated sales data collected from vendors of flaring equipment), and the

- EPA's GHGRP MSW landfills database (EPA 2015a).[134]

The EPA's GHGRP MSW landfills database was first introduced as a source for recovery data for the 1990 to 2013 Inventory. The 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 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 landfills in this database, methane recovery data reported data for 2010 and later were linearly back-casted to 1990, or the date the landfill gas collection system at a facility began operation, whichever is earliest.

A destruction efficiency of 99 percent was applied to amounts of CH_4 recovered to estimate CH_4 emissions avoided for all recovery databases. 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 3a: Estimate CH_4 Emissions Avoided Through Landfill Gas-to-Energy (LFGE) and Flaring Projects for 1990 to 2004

The quantity of CH_4 avoided due to LFGE 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 LFGE database for the purposes of this inventory (EPA 2016); and (3) the GHGRP MSW landfills dataset (EPA 2015a). The EIA database included location information for landfills with LFGE 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 LFGE 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 LFGE project. The GHGRP MSW landfills database contains the most detailed data on landfills that reported under EPA's GHGRP for years 2010 through 2015, however the amount of CH_4 recovered is not specifically allocated to a flare versus a LFGE project. The allocation into flares or LFGE was performed by matching landfills to the EIA and LMOP databases for LFGE 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 LFGE databases; consequently, it was straightforward to identify landfills that were in both databases against those in EPA's GHGRP MSW landfills database.

The same landfill may be included one or more times across these four databases. To avoid double- or triple-counting CH_4 recovery, the landfills across each database were compared and duplicates identified. A hierarchy of recovery data is used based on the certainty of the data in each database. In summary, the GHGRP > EIA > LFGE > flare vendor database.

If a landfill in the GHGRP MSW landfills database was also in the EIA, LFGE, and/or flare vendor database, the avoided emissions were only based on EPA's GHGRP MSW landfills database to avoid counting the recovery amounts multiple times across the different databases. In other words, the CH_4 recovery from the same landfill was not included in the total recovery from the EIA, LFGE, or flare vendor databases. While the GHGRP contains facility-reported information on MSW Landfills starting in the year 2010, EPA has back-casted GHGRP emissions to the year 2005 in order to merge the two methodologies (more information provided in Steps 4a and 4b). Prior to 2005, if a landfill in EPA's GHGRP was also in the LFGE or EIA databases, the landfill gas project information, specifically the project start year, from either the LFGE or EIA databases was used as the cutoff year for the estimated CH_4 recovery in the GHGRP database. For example, if a landfill reporting under EPA's GHGRP was also included in the LFGE database under a project that started in

[134] The 2015 GHGRP dataset is used in the GHGRP MSW landfills dataset described in Step 3a. This database is no longer updated because the methodology has changed such that the directly reported net methane emissions are used. The GHGRP dataset is available through Envirofacts <http://www.epa.gov/enviro/facts/ghg/search.html>.

2002 that is still operational, the CH_4 recovery data in the GHGRP database for that facility was back-casted to the year 2002 only.

If a landfill in the EIA database was also in the LFGE 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 EPA's GHGRP.

If both the flare data and LFGE recovery data were available for any of the remaining landfills (i.e., not in the EIA or EPA's GHGRP databases), then the CH_4 recovered were based on the LFGE data, which provides reported landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The LFGE 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 have not been collected since 2015 because these data are not used for estimates beyond 2005 in the time series. Given that each LFGE project is likely to also have a flare, double counting reductions from flares and LFGE projects in the LFGE database was avoided by subtracting emission reductions associated with LFGE projects for which a flare had not been identified from the emission reductions associated with flares (referred to as the flare correction factor).

Step 3b: Estimate CH_4 Emissions Avoided Through Flaring for the Flare Database for 1990 to 2004

To avoid double counting, flares associated with landfills in EPA's GHGRP, EIA and LFGE databases were not included in the total quantity of CH_4 recovery from the flare vendor database. As with the LFGE 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 LFGE 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 since the 1990 to 2015 Inventory year, when the net CH_4 emission directly reported to EPA's GHGRP began to be used to estimate emission from MSW landfills.

To estimate a median flare gas flow rate for flares associated with these vendors, the size of the flare was matched with the size and corresponding flow rates provided by other vendors. Some flare vendors reported the maximum capacity of the flare. An analysis of flare capacity versus measured CH_4 flow rates from the EIA database showed that the flares operated at 51 percent of capacity when averaged over the time series and at 72 percent of capacity for the highest flow rate for a given year. For those cases when the flare vendor supplied maximum capacity, the actual flow was estimated as 50 percent of capacity. Total CH_4 avoided through flaring from the flare vendor database was estimated by summing the estimates of CH_4 recovered by each flare for each year.

Step 3c: Reduce CH_4 Emissions Avoided Through Flaring for 1990 to 2004

If comprehensive data on flares were available, each LFGE project in EPA's GHGRP, EIA, and LFGE databases would have an identified flare because it is assumed that most LFGE 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 LFGE projects. These LFGE 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 LFGE project would be counted. To avoid overestimating emissions avoided from flaring, the CH_4 avoided from LFGE 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 LFGE projects in the EIA and LFGE databases. Each flare in the flare vendor database not

associated with a LFGE project in the EIA, LFGE, or EPA's 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, LFGE 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 LFGE database that are currently flaring but are also considering LFGE. These landfills projects considering a LFGE project are labeled as candidate, potential, or construction in the LFGE 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 LFGE 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 (RTI 2010).

Step 4: Estimate CH_4 Emissions from MSW Landfills for 2005 to 2009

During preparation of the 1990 to 2015 Inventory, EPA engaged with stakeholders both within and outside of the landfill industry on the methodology used in the Inventory, the data submitted by facilities under EPA's GHGRP Subpart HH for MSW Landfills, and the application of this information as direct inputs to the MSW landfill methane emissions estimates in the 1990 to 2015 Inventory. Based on discussions with stakeholders, EPA developed several options for improving the Inventory through methodological changes and moved forward with using the directly reported net GHGRP methane emissions from 2010 to 2015 for MSW landfills in the 1990 to 2015 Inventory.

The Inventory methodology now uses directly reported net CH_4 emissions for the 2010 to 2019 reporting years from EPA's GHGRP to back-cast emissions for 2005 to 2009. The emissions for 2005 to 2009 are recalculated each year the Inventory is published to account for the additional year of reported data and any revisions that facilities make to past GHGRP reports. When EPA verifies the greenhouse gas reports, comparisons are made with data submitted in earlier reporting years and errors may be identified in these earlier year reports. Facility representatives may submit revised reports for any reporting year in order to correct these errors. Facilities reporting to EPA's GHGRP that do not have landfill gas collection and control systems use the FOD method. Facilities with landfill gas collection and control must use both the FOD method and a back-calculation approach. The back-calculation approach starts with the amount of CH_4 recovered and works back through the system to account for gas not collected by the landfill gas collection and control system (i.e., the collection efficiency).

Including the GHGRP net emissions data was a significant methodological change from the FOD method previously described in Steps 1 to 3 and only covered a portion of the Inventory time series. Therefore, EPA needed to merge the previous method with the new (GHGRP) dataset to create a continuous time series and avoid any gaps or jumps in. estimated emissions in the year the GHGRP net emissions are first included (i.e., 2010).

To accomplish this, EPA back-casted GHGRP net emissions to 2005 to 2009 and added a scale-up factor to account for emissions from landfills that do not report to the GHGRP. A description of how the scale-up factor was determined and why the GHGRP emissions were back-casted are included below as Step 4a and Step 4b, respectively. The methodology described in this section was determined based on the good practice guidance in Volume 1: Chapter 5 Time Series Consistency of the *2006 IPCC Guidelines*. Additional details including other options considered are included in RTI 2017a and RTI 2018.

Step 4a: Developing and Applying the Scale-up Factor for MSW Landfills for 2005 to 2009

Landfills that do not meet the reporting threshold are not required to report to the GHGRP. As a result, the GHGRP dataset is only partially complete when considering the universe of MSW landfills. In theory, national emissions from MSW landfills equals the emissions from landfills that report to the GHGRP plus emissions from landfills that do not report to the GHGRP. Therefore, for completeness, a scale-up factor had to be developed to estimate the amount of emissions from the landfills that do not report to the GHGRP.

To develop the scale-up factor, EPA completed four main steps:

1. EPA determined the number of landfills that do not report to the GHGRP (hereafter referred to as the non-reporting landfills). Source databases included the LMOP database 2017 (EPA 2017) and the WBJ Directory 2016 (WBJ 2016). This step identified 1,544 landfills that accepted MSW between 1940 and 2016 and had never reported to the GHGRP. These landfills and the data collected were compiled into the 2016 Non-Reporting Landfills Database.
2. EPA estimated annual waste disposed and the total waste-in-place (WIP) at each non-reporting landfill as of 2016. Both databases include critical details about individual landfills to estimate annual methane emissions, including the year waste was first accepted, the year the landfill closed (as applicable), and the estimated amount of waste disposed. But not all details are included for all landfills. A total of 969 of the 1,544 landfills (63 percent) contained the critical information necessary to estimate WIP.
    a. For 234 non-reporting landfills, there was not enough information in the source databases to estimate WIP.
    b. For 341 of the non-reporting landfills, WIP could be estimated with assumptions that either (i) "forced" the year that waste was first accepted as 30 years prior to the landfill closure year (if a closure date was included); or (ii) "forced" a closure year of 2016 if the landfill was known to be closed and a closure year was not included in the source database.
    c. The database was reviewed by industry and staff from LMOP at this stage to help fill data gaps and rectify discrepancies between individual landfills across the source databases, which improved the WIP estimates by landfill and overall.
3. EPA summed the total WIP for the non-reporting landfills. Using the assumptions mentioned above, the total WIP in 2016 across the non-reporting landfills was approximately 0.922 billion MT.
4. EPA calculated the scale-up factor (9%) by dividing the non-reporting landfills WIP (0.92 billion MT) by the sum of the GHGRP WIP and the non-reporting landfills WIP (10.0 billion MT).

Table A-224: Revised Waste-in-Place (WIP) for GHGRP Reporting and Non-reporting Landfills in 2016

Category	Estimated WIP (billion metric tons)	Percentage
Non-reporting facilities	0.92	9 percent (the applied scale-up factor)
GHGRP facilities	9.1	91 percent
Total	10.0	100 percent

The same 9 percent scale-up factor is applied in each year the GHGRP reported emissions are used in the Inventory.

Step 4b: Back-casting GHGRP Emissions for MSW Landfills for 2005 to 2009 to Ensure Time Series Consistency

Regarding the time series and as stated in *2006 IPCC Guidelines Volume 1: Chapter 5 Time Series Consistency* (IPCC 2006), "the time series is a central component of the greenhouse gas inventory because it provides information on historical emissions trends and tracks the effects of strategies to reduce emissions at the national level. All emissions in a time series should be estimated consistently, which means that as far as possible, the time series should be calculated using the same method and data sources in all years" (IPCC 2006). Chapter 5 however, does not recommend back-casting emissions to 1990 with a limited set of data and instead provides guidance on techniques to splice, or join methodologies together. One of those techniques is referred to as the overlap technique. The overlap technique is recommended when new data becomes available for multiple years, which was the case with the GHGRP data, where directly reported net CH_4 emissions data became available for more than 1,200 MSW landfills beginning in 2010. The GHGRP emissions data had to be merged with emissions from the FOD method to avoid a drastic change in emissions in 2010, when the datasets were combined. EPA also had to consider that according to IPCC's good practice, efforts should be made to reduce uncertainty in Inventory calculations and that, when compared to the GHGRP data, the FOD method presents greater uncertainty.

In evaluating the best way to combine the two datasets, EPA considered either using (1) the FOD method from 1990 to 2009, or (2) using the FOD method for a portion of that time series and back-casting the GHGRP emissions data to a year where emissions from the two methodologies aligned. Plotting the back-casted GHGRP emissions against the emissions estimates from the FOD method showed an alignment of the data in 2004 and later years which facilitated the use of the overlap technique while also reducing uncertainty. Therefore, EPA decided to back-cast the GHGRP emissions from 2009 to 2005 only, to merge the datasets and adhere to the IPCC good practice guidance.

EPA used the Excel Forecast function to back-cast net methane emissions using the GHGRP data. The forecast function is used to predict a future value by using existing values, but EPA has applied it to predict previous values. Although it is not ideal, it allowed for expeditious implementation. In the forecast function, the known values are existing x-values and y-values (i.e., the years and data for the GHGRP, 2010 to 2015). The unknown y-values are the years to be estimated (i.e., all years prior to 2009). The following Excel formula was used: =FORECAST(year to back-cast, GHGRP data for 2010 to 2015, years 2010 to 2015). The forecast function is a linear regression; thus, it will not account for annual fluctuations in CH_4 emissions when used for multiple years.

The years to back-cast the GHGRP data were first determined for the 1990 to 2015 Inventory when a 12.5 percent scale-up factor was used. EPA plotted the net CH_4 emissions from the adjusted 1990 to 2014 methodology against the back-casted GHGRP emissions for 1990 to 2009 and directly reported CH_4 emissions for 2010 to 2015 with a scale-up factor of 12.5 percent applied to all years the GHGRP data are used, 2005 to 2014) as presented in Figure A-19. The results for the two methods are nearly identical for the years 2005 to 2010, which provides a basis for back-casting the GHGRP emissions data to 2005 only. However, after applying the 12.5 percent scale-up factor across the time series, the GHGRP emissions data were now larger than the revised Inventory estimates for the years 2010 to 2015. This difference was addressed through revisions to the scale-up factor after a more detailed review of the non-reporting landfills, resulting in a revised scale-up factor of 9 percent (described above in Step 4a), which more closely aligns emissions estimates between the two methodologies as presented in Figure A-20. EPA therefore decided to maintain back-casting of the GHGRP emissions from 2005 to 2009 only.

Figure A-19: Comparison of the revised 1990-2014 Inventory methodology against the GHGRP emissions (back-casted from 2009 to 1990) and directly reported emissions for 2010 to 2014 with a 12.5% scale-up factor

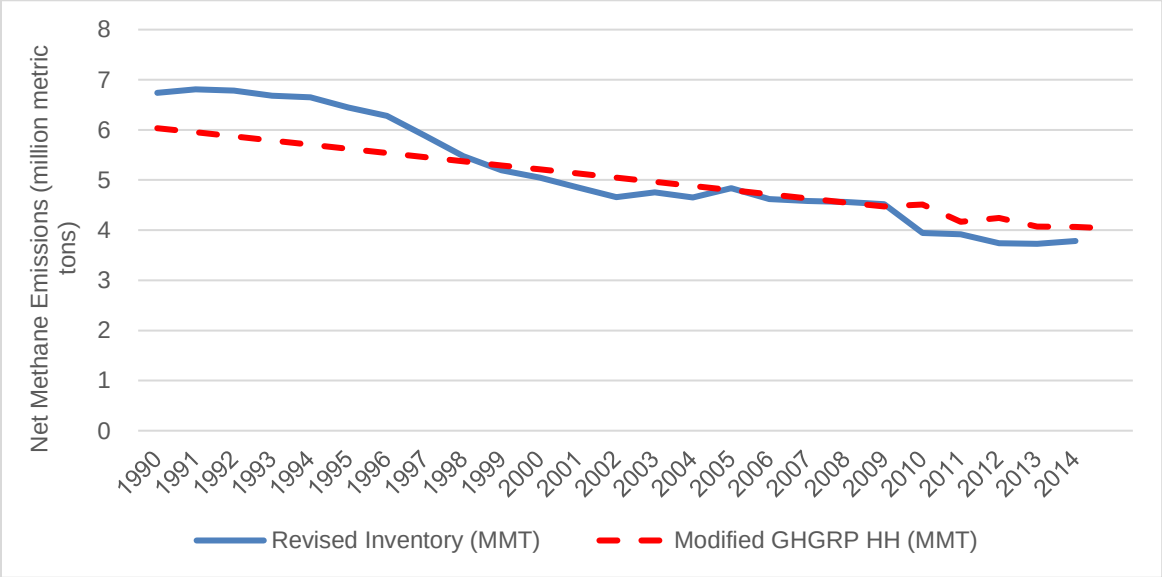
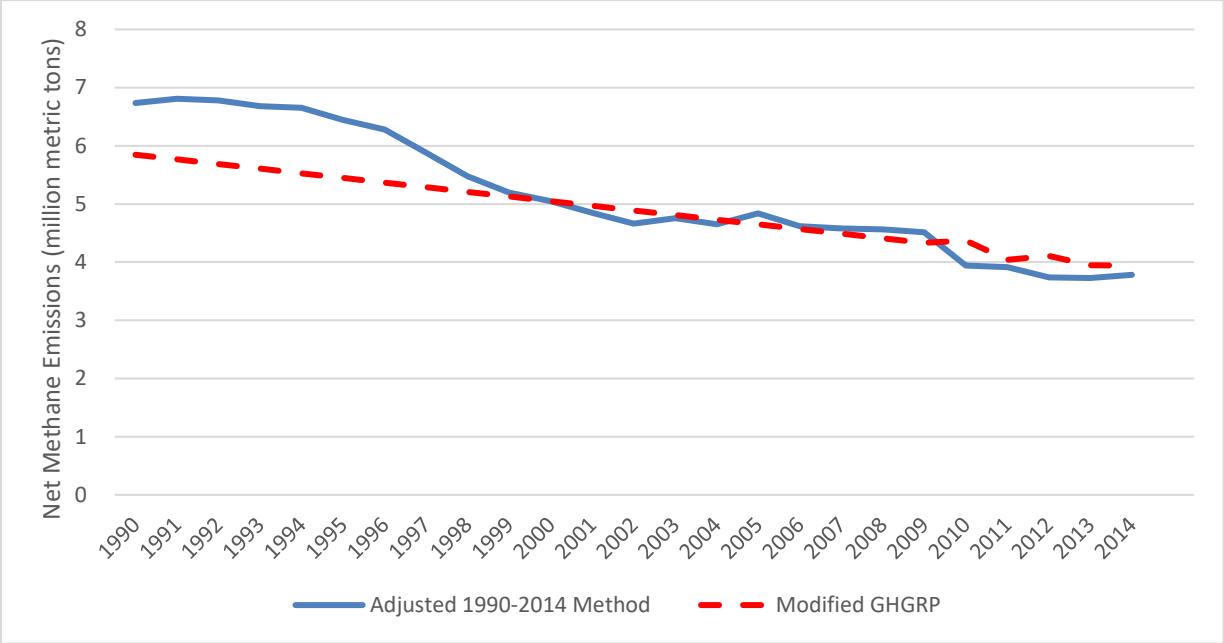


Figure A-20: Comparison of the revised 1990-2014 Inventory methodology against the GHGRP emissions (back-casted from 2009 to 1990) and directly reported emissions for 2010 to 2014 with a 9% scale-up factor



An important factor in this approach is that the back-casted emissions for 2005 to 2009 are subject to change with each Inventory because the GHGRP dataset may change as facilities revise their annual reports. The revisions are generally minor considering the entire GHGRP dataset and EPA has not determined any revisions to the back-casting approach or scale-up factor are necessary to date.

Step 5: Estimate CH_4 Emissions from MSW Landfills for 2010 to 2016

CH_4 emissions directly reported to EPA's GHGRP are used for 2010 to 2019. Inherent in these direct emissions are the use of various GHGRP default emission factors such as the gas collection and control system collection efficiencies (where applicable), decay rate (k), and degradable organic carbon (DOC).

Facilities reporting to Subpart HH of the GHGRP can report their k and DOC values under one of three waste type options: (1) Bulk waste option, where all waste is accounted for within one bulk k and DOC value; (2) Modified bulk waste option, where waste disposed of at the landfill can be binned into bulk MSW excluding inerts and construction and demolition waste, construction and demolition waste, and inerts; and (3) Waste Composition option, where waste disposed of can be delineated into specific waste streams (i.e., food waste, garden waste, textiles, etc.) OR where facilities report a known quantity of inert waste and consider the remaining waste as bulk MSW (using the same k and DOC value for MSW as the bulk waste option).

The GHGRP requires facilities with a gas collection and control system to report their emissions using both a forward-estimating (i.e., using a first order decay approach, accounting for soil oxidation) and a back-calculating (i.e., using methane recovery and collection efficiency data, accounting for soil oxidation) method as described in Chapter 7 of this Inventory. To determine collection efficiency, facilities are required to report the amount of waste-in-place (surface area and soil depth) at their landfill as categorized by one of five area types (see Table A-225).

Table A-225: Table HH-3 to Subpart HH of the EPA's Greenhouse Gas Reporting Program, Area Types Applicable to the Calculation of Gas Collection Efficiency

Description	Landfill Gas Collection Efficiency
A1: Area with no waste-in-place	Not applicable, do not use this area in the calculation
A2: Area without active gas collection, regardless of cover type	CE2: 0%
A3: Area with daily soil cover and active gas collection	CE3: 60%

A4: Area with an intermediate soil cover, or a final soil cover not meeting the criteria for A5 below, and active gas collection	CE4: 75%
A5: Area with a final soil cover of 3 feet or thicker of clay or final cover (as approved by the relevant agency) and/or geomembrane cover system and active gas collection	CE5: 95%
Weighted average collection efficiency for landfills:	
Area weighted average collection efficiency for landfills	CEave1 = (A2*CE2) + A3*CE3 + A4*CE4 + A5*CE5) / (A2 + A3 + A4 + A5)

If facilities are unable to bin their waste into these area types, they are instructed to use 0.75, or 75 percent as a default value. In the EPA's original rulemaking for the GHGRP, the EPA proposed this default collection efficiency of 75 percent because it was determined to be a reasonable central-tendency default considering the availability of data such as surface monitoring under the EPA's New Source Performance Standards for MSW Landfills (40 CFR Part 60 Subpart WWW), which suggested that gas collection efficiencies generally range from 60 to 95 percent. This 75 percent default gas collection efficiency value only applies to areas at the landfill that are under gas collection and control; for areas of the landfill that are not under gas collection and control, a gas collection efficiency of 0 percent is applied.

The 9 percent scale-up factor is applied to the net annual emissions reported to the GHGRP for 2010 to 2016 as is done for 2005 to 2009 because the GHGRP does not capture emissions from all landfills in the United States.

Step 6: Estimate CH_4 Emissions from MSW Landfills for 2017 to 2019

The scale-up factor was initially developed to use the GHGRP reported data and account for the remaining subset of landfills that are not required to report to the GHGRP. The EPA acknowledges there are uncertainties associated with the 9 percent scale-up factor and underlying landfill-specific data used to develop the Non-Reporting Landfills database. Specifically, the GHGRP allows facilities to off-ramp (i.e., stop reporting to the GHGRP) after meeting certain criteria; therefore, the number of facilities and WIP reported under the GHGRP will vary year to year. Nearly 200 facilities have off-ramped from the GHGRP to date, which means there is now more WIP for non-reporting landfills than there was in the 2016 scale-up factor analysis. Reassessment of the scale-up factor at regular intervals to account for changes in the GHGRP dataset and LMOP database is considered good practice and was therefore included in the Planned Improvements section for the previous (1990 to 2018) Inventory.

The methodology used to revise the scale-up factor largely followed that to develop the 2016 Non-Reporting Landfills Database, as summarized below:

1. EPA streamlined the layout of the 2016 Non-Reporting Landfills Data to remove extraneous columns, clearly present the landfill-specific data from the main sources (i.e., the 2017 LMOP Database [EPA 2017] and the WBJ Directory 2016 [WBJ, 2016]), and the calculation columns that yield the start year, closure year, and WIP data used to estimate the total WIP at all non-reporting landfills. The database is hereafter referred to as the 2018 Non-Reporting Landfills Database.
2. EPA added in new or updated data for existing non-reporting landfills and added in entries for new non-reporting landfills.
    a. We added the 194 landfills that have off-ramped from the GHGRP as of 2019 (EPA 2020a) into the Non-Reporting Landfills Database.
    b. We cross-referenced and updated the 2017 LMOP Database (EPA 2017) information with the 2020 LMOP Database (EPA 2020b) information. New cases from the 2020 LMOP Database were added, LMOP IDs were updated for some landfills, and 27 landfills from the 2017 LMOP Database were removed because they were determined not to be MSW landfills.
    c. These revisions increased the count of non-reporting landfills from 1,544 landfills to 1,672 landfills, a net increase of 128 landfills from the 2016 Non-Reporting Landfills Database.
3. EPA conducted additional quality control checks on calculations in the 2016 Non-Reporting Landfills Database and rectified identified errors, which resulted in an increase of 38,498,070 MT of waste from the 2016 Non-Reporting Landfills Database.

a. We identified a formula error that under-estimated the WIP for landfills with a permitted end year after 2016, especially for those landfills that had reported closure dates in 2030 or later. For example, if the start year was 1980 and the permitted closure year was 2040, the formula was estimating 50 years when, for the purposes of this exercise, the number of years should have been 36 years. Dividing the WIP by 60 years results in a lower annual waste disposal value than dividing the WIP by 36 years (2016-1980). The methodology calculates an annual disposal rate for each landfill and then applies the annual disposal rate to 2016 minus the start year.

b. We did not pull in the year the WIP data were from in the 2017 LMOP Database and assumed the WIP data were from 2016 unless otherwise noted. The WIP year is now included in the 2018 Non-Reporting Landfills Database. The WBJ Directory does not present the year the WIP data are from, thus we assumed each data point was from 2016. These assumptions underestimate the amount of WIP for a large majority of the landfills where the WIP data year is not reported.

4. EPA estimated annual waste disposed and the total WIP at each non-reporting landfill as of 2018. Where available, the databases include details about individual landfills to estimate annual methane emissions, including the year waste was first accepted, the year the landfill closed (as applicable), and the estimated amount of waste disposed. When enough data were available, EPA estimated WIP by calculating an annual waste disposal rate and multiplied that by the number of operating years up to the closure year, or 2018 (if the landfill was known or assumed to be open). EPA used a tiered methodology when a landfill with critical information was included in more than one database:

Tier 1: If the landfill has off-ramped from the GHGRP, use the Subpart HH WIP value

Tier 2. If the landfill is in the 2020 LMOP Database, use the 2020 LMOP WIP value

Tier 3. Otherwise, EPA used the average of the estimated WIP value that was forced or provided from the 2016 Non-reporting Landfill Database industry and LMOP reviewers.

a. A total of 1,027 of the 1,672 landfills (61 percent) contained enough critical information necessary to estimate the 2018 WIP (i.e., first year of operation, either total WIP or annual waste disposal data, and either an indication the landfill was still operating or the closure date). It is important to note that the WIP estimates are estimates. The quality of the source data for WIP and annual waste disposed have not been individually verified by the EPA team. In the case of the GHGRP data, the annual waste disposal quantities are either estimates using defined methodologies or actual waste disposed from tipping receipts. In general, most landfills have relied on tipping receipts for the past decade, meaning that annual waste disposed several decades ago are estimates.

b. For 325 of the 1,672 landfills (19 percent), WIP could be estimated with assumptions that either (i) “forced” the year that waste was first accepted as 30 years prior to the landfill closure year (if a closure year was included); or (ii) forced a closure year of 2018 if the landfill was known or thought to be open and a closure year was not included in the source database. These are the same general assumptions applied in the 2016 Non-Reporting Landfills Database.

c. For 320 of the 1,672 landfills (19 percent), there was not enough information in the source databases to estimate WIP, thus no WIP data was calculated for these facilities, which underestimates the total WIP for the non-reporting landfills.

5. EPA summed the total WIP for the non-reporting landfills, yielding 1.2 billion MT of WIP, which is an increase of approximately 0.27 billion MT of WIP (30 percent increase) from the 2016 Non-Reporting Landfills Database where the total WIP for non-reporting landfills was estimated at 0.92 billion MT.

6. EPA calculated the scale-up factor (11 percent) by dividing the non-reporting landfills WIP (1.2 billion MT) by the sum of the GHGRP WIP and the non-reporting landfills WIP (10.8 billion MT).

Table A-226: Revised Waste-in-Place (WIP) for GHGRP Reporting and Non-reporting Landfills in 2018

Category	Estimated WIP (billion metric tons)	Percentage
Non-reporting facilities	1.2	11 percent (the applied scale-up factor)
GHGRP facilities	9.6	89 percent
Total	10.8	100 percent

An 11 percent scale-up factor is applied annually for 2017 to 2019 as is done for 2010 to 2016 because the GHGRP does not capture emissions from all landfills in the United States. In future inventories, the scale-up factor will be reassessed annually to include additional facilities that off-ramp from the GHGRP and revisions to the LMOP Database.

Step 7: Estimate CH_4 Generation at Industrial Waste Landfills for 1990 to the Current Inventory Year

A Tier 2 approach (IPCC 2006) is used to estimate annual emissions from industrial waste landfills. A tailored IPCC waste model, based on the FOD method and country-specific defaults, is exclusively used for 1990 to 2019. For the FOD method, methane generation is based on nationwide industrial production data from two major sectors – pulp and paper, and food and beverage manufacturing – to which a national average disposal factor is applied, separately for each sector. The same disposal factor and emission factors are applied to every year in the time series. The methodology is not Tier 3 (i.e., it is not landfill-specific) because data for individual landfills are limited. Table A-235 presents the amount of industrial production data and estimated amount of industrial waste landfilled for select years.

The FOD method is presented below and is similar to Equation HH-6 in CFR Part 98.343 for MSW landfills, and Equation TT-6 in CFR Part 98.463 for industrial waste landfills.

$$CH_{4,\text{Solid Waste}} = [G_{CH4,MSW} - R] - Ox$$

where,

$CH_{4,\text{Solid Waste}}$ = Net CH_4 emissions from solid waste
$G_{CH4,MSW}$ = CH_4 generation from MSW landfills
R = CH_4 recovered and combusted
Ox = CH_4 oxidized from MSW and industrial waste landfills before release to the atmosphere

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 most of the organic waste placed in industrial waste landfills originated from two sectors: food processing (meat, vegetables, fruits) and pulp and paper (EPA 1993). Data for annual nationwide production for the food and beverage processing and pulp and paper sectors were taken from industry and government sources for recent years and 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 Food and Agriculture Organization were used for years 2002 through 2019. An extrapolation based on U.S. real gross domestic product was used for years 1940 through 1964.

For the food and beverage processing sector, production data were obtained from the U.S. Department of Agriculture for the years 1990 through 2019 (ERG 2020). An extrapolation based on U.S. population was used for the years 1940 through 1989.

In addition to production data for the pulp and paper and food processing 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 emission factors were applied to estimates of annual production to estimate annual waste disposal in industrial waste landfills (see Table A-235 for select years). 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 2015a). 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 (RTI 2014). 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.[135] 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 EPA's 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. 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 unmanaged landfills, or open dumps to managed landfills was expected for industrial waste landfills; therefore, the same timeline that was developed for MSW landfills was applied to the industrial landfills to estimate the average MCF. That is, between 1940 and 1980, the fraction of waste 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 unmanaged sites, 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 8: 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 LFGE projects, 10 percent was oxidized in the soil (Jensen and Pipatti 2002; Mancinelli and McKay 1985; Czepiel et al 1996). The literature was reviewed in 2011 (RTI 2011) and 2017 (RTI 2017b) 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. IPCC (2006) notes that test results from field and laboratory studies may lead to over-estimations of oxidation in landfill cover soils because they largely determine oxidation using uniform and homogeneous soil layers. In addition, several 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.

An oxidation factor of 0.10 (IPCC 2006) is applied for industrial waste landfills for the entire time series. A variety of oxidation factors (0.0, 0.10, 0.25, or 0.35) are applied for MSW landfills as described below. The oxidation factors applied for MSW landfills are based on IPCC 2006 (0.10) and scientific literature reviewed for the development of the GHGRP regulations (40 CFR Part 98).

[135] 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.

MSW landfills 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 IPCC (2006) 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 and for industrial waste landfills for the full time series.

For years 2005 to 2018, net CH_4 emissions from MSW landfills as directly reported to EPA's GHGRP, which include the adjustment for oxidation, are used. Subpart HH of the GHGRP includes default values for oxidation which are dependent on the mass flow rate of CH_4 per unit at the bottom of the surface soil prior to any oxidation, also known as methane flux rate. The oxidation factors included in the GHGRP (0, 0.10, 0.25, 0.35) are based on published, peer-reviewed literature and facility data provided through external stakeholder engagement. The EPA concluded, during review of both the literature and facility-reported emissions data, that simply revising the IPCC's Tier 1 oxidation default of 10 percent to a new singular default oxidation value would not take into account the key variable - methane flux rate - entering the surface soil layer. More information regarding analysis of methane oxidation fractions can be found in the memorandums entitled "Review of Oxidation Studies and Associated Cover Depth in the Peer Reviewed Literature", June 17, 2015 (RTI 2015b). More information about the landfill specific conditions required to use higher oxidation factors can be found in Table HH-4 of 40 CFR Part 98, Subpart HH, as shown below.

Table A-227: Table HH-4 to Subpart HH of Part 98—Landfill Methane Oxidation Fractions

Under these conditions:	Use this landfill methane oxidation fraction:
I. For all reporting years prior to the 2013 reporting year	
C1: For all landfills regardless of cover type or methane flux	0.10
II. For the 2013 reporting year and all subsequent years	
C2: For landfills that have a geomembrane (synthetic) cover or other non-soil barrier meeting the definition of final cover with less than 12 inches of cover soil for greater than 50% of the landfill area containing waste	0.10
C3: For landfills that do not meet the conditions in C2 above and for which you elect not to determine methane flux	0.10
C4: For landfills that do not meet the conditions in C2 or C3 above and that do not have final cover, or intermediate or interim cover[a] for greater than 50% of the landfill area containing waste	0.10
C5: For landfills that do not meet the conditions in C2 or C3 above and that have final cover, or intermediate or interim cover[a] for greater than 50% of the landfill area containing waste and for which the methane flux rate[b] is less than 10 grams per square meter per day (g/m2/d)	0.35
C6: For landfills that do not meet the conditions in C2 or C3 above and that have final cover or intermediate or interim cover[a] for greater than 50% of the landfill area containing waste and for which the methane flux rate[b] is 10 to 70 g/m2/d	0.25
C7: For landfills that do not meet the conditions in C2 or C3 above and that have final cover or intermediate or interim cover[a] for greater than 50% of the landfill area containing waste and for which the methane flux rate[b] is greater than 70 g/m2/d	0.10

[a] Where a landfill is in a state that does not have an intermediate or interim cover requirement, the landfill must have soil cover of 12 inches or greater in order to use an oxidation fraction of 0.25 or 0.35.

[b] Methane flux rate (in grams per square meter per day; $g/m^2/d$) is the mass flow rate of methane per unit area at the bottom of the surface soil prior to any oxidation and is calculated as follows:

For Equation HH-5 of this subpart, or for Equation TT-6 of subpart TT of this part,

$$MF = K \times G_{CH4} / SArea$$

For Equation HH-6 of this subpart,

$$MF = K \times \left(G_{CH4} - \sum_{n=1}^{N} R_n \right) \Big/ SArea$$

For Equations HH-7 of this subpart,

$$MF = K \times \left(\frac{1}{CE} \sum_{n=1}^{N} \left[\frac{R_n}{f_{Rec,n}} \right] \right) \Big/ SArea$$

For Equation HH-8 of this subpart,

$$MF = K \times \left(\frac{1}{CE} \left\{ \sum_{n=1}^{N} \left[\frac{R_n}{f_{Rec,n}} \right] \right\} - \sum_{n=1}^{N} R_n \right) \Big/ SArea$$

The EPA's GHGRP also requires landfills to report the type of cover material used at their landfill as: organic cover, clay cover, sand cover, and/or other soil mixtures.

Step 9: Estimate Total CH_4 Emissions for the Inventory

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-228. A different methodology is applied for 2005 to 2019 where directly reported net CH_4 emissions to EPA's GHGRP plus a scale-up factor to account for landfills that do not report to the GHGRP was applied. For 2005 to 2009, the directly reported GHGRP net emissions from 2010 to 2018 were used to back-cast emissions for 2005 to 2009. Note that the emissions values for 2005 to 2009 are re-calculated for each Inventory and are subject to change if facilities reporting to the GHGRP revise their annual greenhouse gas reports for any year. A 9 percent scale-up factor was applied annually to the net CH_4 reported to the GHGRP for 2005 to 2016, and an 11 percent scale-up factor was applied to the net CH_4 reported to the GHGRP for 2016 to 2019.

Table A-228: CH_4 Emissions from Landfills (kt)

	1990	1995	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
MSW CH_4 Generation	8,109	8,303	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Industrial CH_4 Generation	484	538	638	641	645	650	655	658	659	660	663	664	665	666	667	668	669
MSW CH_4 Recovered	**(718)**	**(1,935)**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
MSW CH_4 Oxidized	(739)	(637)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Industrial CH_4 Oxidized	(48)	(54)	(64)	(64)	(64)	(65)	(66)	(66)	(66)	(66)	(66)	(66)	(66)	(67)	(67)	(67)	(67)
MSW Net CH_4 Emissions	**6,652**	**5,732**	**4,681**	**4,593**	**4,506**	**4,419**	**4,331**	**4,372**	**4,023**	**4,070**	**3,924**	**3,907**	**3,858**	**3,722**	**3,775**	**3,881**	**3,978**
Industrial Net CH_4 Emissions	**436**	**485**	**575**	**577**	**580**	**585**	**590**	**592**	**593**	**594**	**596**	**597**	**598**	**599**	**600**	**601**	**602**
Net Emissions[a]	**7,088**	**6,216**	**5,255**	**5,171**	**5,087**	**5,004**	**4,921**	**4,964**	**4,616**	**4,664**	**4,520**	**4,504**	**4,456**	**4,321**	**4,375**	**4,482**	**4,580**

"-" Not applicable due to methodology change.

Notes: MSW and Industrial CH_4 generation in Table A-228 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 2010 to 2019 are directly reported CH_4 emissions to the EPA's GHGRP for MSW landfills and are back-casted to estimate emissions for 2005 to 2009. A scale-up factor of 9 percent of each year's emissions from 2005 to 2016, and a scale-up factor of 11 percent of each year's emissions from 2016 to 2019 is applied to account for landfills that do not report annual methane emissions to the GHGRP. Emissions for years 1990 to 2004 are calculated by the FOD methodology.

References

Barlaz, M.A. (2006) “Forest Products Decomposition in Municipal Solid Waste Landfills.” Waste Management, 26(4): 321-333.

Barlaz, M.A. (1998) “Carbon Storage During Biodegradation of Municipal Solid Waste Components in Laboratory-scale Landfills.” Global Biogeochemical Cycles, 12(2): 373-380, June 1998.

BioCycle (2010) "The State of Garbage in America" By L. Arsova, R. Van Haaren, N. Goldstein, S. Kaufman, and N. Themelis. BioCycle. December 2010. Available online at <http://www.jgpress.com/archives/_free/002191.html>.

BioCycle (2006) "The State of Garbage in America" By N. Goldstein, S. Kaufman, N. Themelis, and J. Thompson Jr. BioCycle. April 2006. Available online at: <https://www.biocycle.net/2006/04/21/the-state-of-garbage-in-america-2/>.

BioCycle (2004) “The State of Garbage in America” By S. Kaufman, N. Goldstein, K. Millrath, and N. Themelis. January 2004. Available online at: <https://www.biocycle.net/2004/01/30/the-state-of-garbage-in-america/>.

BioCycle (2001) “The State of Garbage in America” By S. Kaufman, N. Goldstein, and N. Themelis. December 2001.

Chartwell (2004) Municipal Solid Waste Directory. The Envirobiz Group.

Czepiel, P., B. Mosher, P. Crill, and R. Harriss (1996) “Quantifying the Effect of Oxidation on Landfill Methane Emissions.” Journal of Geophysical Research, 101(D11):16721-16730.

EIA (2007) Voluntary Greenhouse Gas Reports for EIA Form 1605B (Reporting Year 2006). Available online at <ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/>.

EPA (2020a) Greenhouse Gas Reporting Program (GHGRP). 2019 Amazon S3 Data. Subpart HH: Municipal Solid Waste Landfills.

EPA (2020b) Landfill Methane Outreach Program (LMOP). 2019 Landfill and Project Level Data. September 2019. Available online at: < https://www.epa.gov/lmop/landfill-gas-energy-project-data>.

EPA (2019a) Methodology for MSW Characterization Numbers. Available online at: < https://www.epa.gov/sites/production/files/2015-09/documents/06numbers.pdf >.

EPA (2019b) Advancing Sustainable Materials Management: 2017 Fact Sheet. November 2019. Available online at: <https://www.epa.gov/sites/production/files/2019-11/documents/2017_facts_and_figures_fact_sheet_final.pdf>.

EPA (2017) Landfill Gas-to-Energy Project Database. Landfill Methane and Outreach Program. June 2017.

EPA (2016) Landfill Gas-to-Energy Project Database. Landfill Methane and Outreach Program. August 2015.

EPA (2015a) Greenhouse Gas Reporting Program (GHGRP). 2015 Envirofacts. Subpart HH: Municipal Solid Waste Landfills. Available online at: <http://www.epa.gov/enviro/facts/ghg/search.html>.

EPA (2015b) Greenhouse Gas Reporting Program (GHGRP). 2015 Envirofacts. Subpart TT: Industrial Waste Landfills. Available online at: <http://www.epa.gov/enviro/facts/ghg/search.html>.

EPA (2008) Compilation of Air Pollution Emission Factors, Publication AP-42, Draft Section 2.4 Municipal Solid Waste Landfills. October 2008.

EPA (1998) Compilation of Air Pollution Emission Factors, Publication AP-42, Section 2.4 Municipal Solid Waste Landfills. November 1998.

EPA (1993) Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress, U.S. Environmental Protection Agency, Office of Air and Radiation. Washington, D.C. EPA/430-R-93-003. April 1993.

EPA (1988) National Survey of Solid Waste (Municipal) Landfill Facilities, U.S. Environmental Protection Agency. Washington, D.C. EPA/530-SW-88-011. September 1988.

EREF (The Environmental Research & Education Foundation) (2016). Municipal Solid Waste Management in the United States: 2010 & 2013.

ERG (2020) Draft Production Data Supplied by ERG for 1990-2018 for Pulp and Paper, Fruits and Vegetables, and Meat. August 2019.

FAO (2019). FAOStat database 2019. Available at http://faostat3.fao.org/home/index.html#DOWNLOAD, Accessed on May 20, 2019.

Flores, R.A., C.W. Shanklin, M. Loza-Garay, S.H. Wie (1999) "Quantification and Characterization of Food Processing Wastes/Residues." Compost Science & Utilization, 7(1): 63-71.

Heath, L.S. et al. 2010. Greenhouse Gas and Carbon Profile of the U.S. Forest Products Industry Value Chain. Environmental Science and Technology 44(2010) 3999-4005.

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.

Jensen, J.E.F., and R. Pipatti (2002) "CH4 Emissions from Solid Waste Disposal." Background paper for the Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.

Kraft, D.L. and H.C. Orender (1993) "Considerations for Using Sludge as a Fuel." Tappi Journal, 76(3): 175-183.

Lockwood-Post Directory of Pulp and Paper Mills (2002). Available for purchase at <http://www.risiinfo.com/product/lockwood-post/>.

Mancinelli, R. and C. McKay (1985) "Methane-Oxidizing Bacteria in Sanitary Landfills." Proc. First Symposium on Biotechnical Advances in Processing Municipal Wastes for Fuels and Chemicals, Minneapolis, MN, 437-450. August.

Miner, R. (2008). "Calculations documenting the greenhouse gas emissions from the pulp and paper industry." Memorandum from Reid Minor, National Council for Air and Stream Improvement, Inc. (NCASI) to Becky Nicholson, RTI International, May 21, 2008.

Mintz C., R. Freed, and M. Walsh (2003) "Timeline of Anaerobic Land Disposal of Solid Waste." Memorandum to T. Wirth (EPA) and K. Skog (USDA), December 31, 2003.

National Council for Air and Stream Improvement, Inc. (NCASI) (2008) "Calculations Documenting the Greenhouse Gas Emissions from the Pulp and Paper Industry." Memorandum to R. Nicholson (RTI).

National Council for Air and Stream Improvement, Inc. (NCASI) (2005) "Calculation Tools for Estimating Greenhouse Gas Emissions from Pulp and Paper Mills, Version 1.1." July 8, 2005.

Peer, R., S. Thorneloe, and D. Epperson (1993) "A Comparison of Methods for Estimating Global Methane Emissions from Landfills." Chemosphere, 26(1-4):387-400.

RTI (2018) Methodological changes to the scale-up factor used to estimate emissions from municipal solid waste landfills in the Inventory. Memorandum prepared by K. Bronstein and M. McGrath for R. Schmeltz (EPA). In progress.

RTI (2017a) Methodological changes to the methane emissions from municipal solid waste landfills as reflected in the public review draft of the 1990-2015 Inventory. Memorandum prepared by K. Bronstein and M. McGrath for R. Schmeltz (EPA). March 31, 2017.

RTI (2017b) Options for revising the oxidation factor for non-reporting landfills for years 1990-2004 in the Inventory time series. Memorandum prepared by K. Bronstein, M, McGrath, and K. Weitz for R. Schmeltz (EPA). August 13, 2017.

RTI (2015a) Investigate the potential to update DOC and k values for the Pulp and Paper industry in the US Solid Waste Inventory. Memorandum prepared by K. Bronstein and M. McGrath for R. Schmeltz (EPA), December 4, 2015.

RTI (2015b) Review of Oxidation Studies and Associated Cover Depth in the Peer-Reviewed Literature. Memorandum prepared by K. Bronstein, M. McGrath, and J. Coburn (RTI) for R. Schmeltz (EPA). June 17, 2015.

RTI (2014) Analysis of DOC Values for Industrial Solid Waste for the Pulp and Paper Industry and the Food Industry. Memorandum prepared by J. Coburn for R. Schmeltz (EPA), October 28, 2014.

RTI (2013) Review of State of Garbage data used in the U.S. Non-CO2 Greenhouse Gas Inventory for Landfills. Memorandum prepared by K. Weitz and K. Bronstein (RTI) for R. Schmeltz (EPA). November 25, 2013.

RTI (2011) Updated Research on Methane Oxidation in Landfills. Memorandum prepared by K. Weitz (RTI) for R. Schmeltz (EPA), January 14, 2011.

RTI (2010) Revision of the flare correction factor to be used in the EPA Greenhouse Gas Inventory. Memorandum prepared by K. Bronstein, K. Weitz, and J. Coburn for R. Schmeltz (EPA), January 8, 2010.

RTI (2009) GHG Inventory Improvement – Construction & Demolition Waste DOC and Lo Value. Memorandum prepared by J. Coburn and K. Bronstein (RTI) for R. Schmeltz, April 15, 2010.

RTI (2006) Methane Emissions for Industrial Landfills. Memorandum prepared by K. Weitz and M. Bahner for M. Weitz (EPA), September 5, 2006.

RTI (2004) Documentation for Changes to the Methodology for the Inventory of Methane Emissions from Landfills. Memorandum prepared by M. Branscome and J. Coburn (RTI) to E. Scheehle (EPA), August 26, 2004.

Shin, D. (2014) Generation and Disposition of Municipal Solid Waste (MSW) in the United States – A National Survey. Master of Science thesis submitted to the Department of Earth and Environmental Engineering Fu Foundation School of Engineering and Applied Science, Columbia University. January 3, 2014. Available online at: <http://www.seas.columbia.edu/earth/wtert/sofos/Dolly_Shin_Thesis.pdf>.

Skog, K.E. (2008) "Sequestration of Carbon in harvested wood products for the United States." Forest Products Journal, 58(6): 56-72.

Skog, K. and G.A. Nicholson (2000) "Carbon Sequestration in Wood and Paper Products." USDA Forest Service Gen. Tech. Rep. RMRS-GTR-59.

Solid Waste Association of North America (SWANA) (1998) Comparison of Models for Predicting Landfill Methane Recovery. Publication No. GR-LG 0075. March 1998.

Sonne, E. (2006) "Greenhouse Gas Emissions from Forestry Operations: A Life Cycle Assessment." J. Environ. Qual. 35:1439-1450.

Upton, B., R. Miner, M. Spinney, L.S. Heath (2008) "The Greenhouse Gas and Energy Impacts of Using Wood Instead of Alternatives in Residential Construction in the United States." Biomass and Bioenergy, 32: 1-10.

U.S. Census Bureau (2020) Annual Estimates of the Resident Population: April 1, 2010 to July 1, 2019. Available online at <https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=PEP_2018_PEPANNRES&prodType=table>.

Waste Business Journal (WBJ) (2016) Directory of Waste Processing & Disposal Sites 2016.

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 Annex 2.1 Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion. 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 Intergovernmental Panel on Climate Change (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 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 modify 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 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 third modification adjusts for consumption of bunker fuels, which refer to quantities of fuels used for international transportation estimated separately from U.S. totals. The fourth 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-229.

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-229 for 2019), 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-230. The resulting fuel type-specific energy data for 2019 are provided in Table A-231.

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-230.

Step 3: Estimate Carbon Emissions

Once apparent consumption is estimated, the remaining calculations are similar to those for the "bottom-up" Sectoral Approach (see Annex 2.1 Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion). Potential CO_2 emissions were estimated using fuel-specific C coefficients (see Table A-231).[136] The C in products from non-energy uses of fossil fuels (e.g., plastics or asphalt) that is stored was then estimated and subtracted (see Table A-232). This step differs from the Sectoral Approach in that emissions from both fuel combustion and non-energy uses are accounted for directly in the Reference Approach. As a result, the Reference Approach emission estimates are comparable to those of the Sectoral Approach, with the exception that the NEU source category emissions are included in the Reference Approach and reported separately in the Sectoral 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 Annex 2.1 Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion).

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-232.

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

[136] 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-232 for more specific source information.

compared to the aggregation of fuel use and emission totals from Annex 2.1 Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion and Annex 2.3 Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels. 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.

Differences in Total Amount of Energy Consumed

Table A-235 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 1.2 percent lower than the Sectoral Approach for 2019. The greatest differences lie in lower estimates for petroleum and coal consumption for the Reference Approach (2.5 percent and 1.7 percent, respectively) and higher estimates for natural gas consumption for the Reference Approach (0.5 percent).

There are several potential sources for the discrepancies in consumption estimates:

- *Product Definitions.* The fuel categories in the Reference Approach are different from those used in the Sectoral Approach, particularly for petroleum.[137] 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 (e.g., anthracite, bituminous).
- *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. Furthermore, Hydrocarbon Gas Liquids (HGL) is a blend of multiple paraffinic hydrocarbons: ethane, propane, isobutane, and normal butane, and their associated olefins: ethylene, propylene, isobutylene, and butylene, each with their own heat content. HGL also includes pentanes plus. The heat content for HGL varies annually depending upon the components of the blend.
- *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.

[137] For the 1990-2019 Inventory year, the United States revised the Sectoral Approach and Reference Approach to report consumption of all HGL components (i.e., ethane, propane, isobutane, normal butane, ethylene, propylene, isobutylene, butylene, and pentanes plus). Pentanes plus is accounted for separately from other HGL components in the Sectoral Approach but is included in HGL in the Reference Approach. Carbon contents and heat contents of HGL were also updated accordingly for each 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-236 summarizes the differences between the two methods in estimated C emissions.

As mentioned above, for 2019, the Reference Approach resulted in a 1.2 percent lower estimate of energy consumption in the United States than the Sectoral Approach. The resulting emissions estimate for the Reference Approach was 0.1 percent lower. Estimates of natural gas and petroleum emissions from the Reference Approach are higher (0.6 percent each), and coal emission estimates are lower (2.0 percent) than the Sectoral Approach. Potential reasons for these differences may include:

- *Product Definitions.* Coal data are 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.

Table A-229: 2019 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	2,611	[1]	[1]	[1]			
	Bituminous Coal	338,955	[1]	[1]	[1]			
	Sub-bituminous Coal	311,552	[1]	[1]	[1]	367		
	Lignite	53,192	[1]	[1]	[1]	1,539		
	Coke		116	967	440			
	Unspecified Coal		6,697	93,765	35,542	20,280		1,217
Gas Fuels (Million Cubic Feet)	Natural Gas	33,551,098	2,741,717	4,656,324	557,803	399,049		46,433
Liquid Fuels (Thousand Barrels)	Crude Oil	4,470,528	2,482,332	1,088,345	(23,901)			
	HGL	1,760,945	75,438	667,957	27,835			1,658
	Other Liquids	0	506,447	148,647	9,113			
	Motor Gasoline	(24,781)	34,148	297,306	360	238,678		20,779
	Aviation Gasoline		347	0	196			
	Kerosene		703	1,735	205			80
	Jet Fuel		59,900	80,401	(1,118)		198,850	5,425
	Distillate Fuel		73,886	476,657	(79)	55	16,710	13,793
	Residual Fuel		54,299	83,539	2,206	9,000	53,480	7,341
	Naphtha for petrochemical feedstocks		5,117	0	(195)			
	Petroleum Coke		2,312	198,555	1,160	10,182		
	Other Oil for petrochemical feedstocks		1,011	0	(55)	1,240		
	Special Naphthas		6,453	0	(234)			
	Lubricants		16,336	37,321	(1,269)			172
	Waxes		1,822	1,486	50			
	Asphalt/Road Oil		16,000	9,459	(3,963)			
	Still Gas[a]		0	0	0			
	Misc. Products		12	660	9			1,658

Note: Parentheses indicate negative values.

[1] Included in Unspecified Coal

Sources: Solid and Gas Fuels: EIA (2020a and 2020b); Liquid Fuels: EIA (2020c).

[a] Still gas is reported as petroleum product (liquid fuel) in this report. However, still gas physically exists as a gas, consisting primary of methane and ethane, and some hydrogen and other trace gases (EIA 2020d).

Table A-230: 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				25.83		
	Lignite	12.87				12.87		
	Coke		20.56	24.58	20.56			
	Unspecified		25.00	25.97	20.86	21.72		25.14
Natural Gas (BTU/Cubic Foot)		1,038	1,025	1,009	1,038	1,038		1,038
Liquid Fuels (Million Btu/Barrel)	Crude Oil	5.70	6.06	5.71	5.71		5.71	5.71
	HGL	4.21	4.21	4.21	4.21		4.21	4.21
	Other Liquids	5.83	5.83	5.83	5.83		5.83	5.83
	Motor Gasoline	5.05	5.05	5.05	5.05	5.05	5.05	5.05
	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[a]		5.67	5.67	5.67		5.77	5.67
	Distillate Fuel		5.76	5.76	5.76	5.76	5.76	5.76
	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[b]		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); Coke, Natural Gas Crude Oil, HGL, and Motor Gasoline: EIA (2020b); Unspecified Solid Fuels: EIA (2011).

[a] Jet fuel used in bunkers has a different heating value based on data specific to that source. When physical values are converted based on a combined heating value across all sources of jet fuel (as shown in Table 1.A(b) of CRF) it will not necessarily match jet fuel bunker data (as shown in Table 1.D of CRF). The energy value for bunker fuel in Table 1.D is based on bunkers only and the values in Table 1.A(b) are based on apparent consumption including imports, exports, etc. and average heating value.

[b] Still gas is reported as petroleum product (liquid fuel) in this report. However, still gas physically exists as a gas, consisting primary of methane and ethane, and some hydrogen and other trace gases (EIA 2020d).

Table A-231: 2019 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	58.9							58.9
	Bituminous Coal	8,097.6							8,097.6
	Sub-bituminous Coal	5,340.0				9.5			5,330.5
	Lignite	684.4				19.8			664.6
	Coke		2.4	23.8	9.0				(30.4)
	Unspecified		167.4	2,435.3	741.4	440.5		30.6	(3,419.1)
Gas Fuels	Natural Gas	34,826.0	2,810.3	4,698.2	579.0	414.2		48.2	31,993.1
Liquid Fuels	Crude Oil	25,473.1	15,045.4	6,212.3	(136.4)				34,442.6
	HGL	7,421.4	317.9	2,815.1	117.3			7.0	4,813.9
	Other Liquids		2,950.1	865.9	53.1				2,031.1
	Motor Gasoline	(125.2)	172.6	1,502.6	1.8			105.0	(1,352.0)
	Aviation Gasoline		1.8		1.0				0.8
	Kerosene		4.0	9.8	1.2			0.5	(6.6)
	Jet Fuel		339.6	455.9	(6.3)		1,147.1	30.8	(1,226.3)
	Distillate Fuel		425.8	2,746.7	(0.5)	0.3	96.3	79.5	(2,337.6)
	Residual Oil		341.4	525.2	13.9	56.6	336.2	46.2	(544.4)
	Naphtha for petrochemical feedstocks		26.9		(1.0)				27.9
	Petroleum Coke		13.9	1,196.1	7.0	61.3			(1,250.5)
	Other Oil for petrochemical feedstocks		5.9		(0.3)	7.2			(1.0)
	Special Naphthas		33.9		(1.2)				35.1
	Lubricants		99.1	226.4	(7.7)			1.0	(118.5)
	Waxes		10.1	8.2	0.3				1.6
	Asphalt/Road Oil		106.2	62.8	(26.3)				69.7
	Still Gas[a]								
	Misc. Products		0.1	3.8	0.1			9.6	5.8
Total		81,776.2	22,874.5	23,787.9	1,345.2	1,009.4	1,579.6	358.3	77,286.8

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

[a] Still gas is reported as petroleum product (liquid fuel) in this report. However, still gas physically exists as a gas, consisting primary of methane and ethane, and some hydrogen and other trace gases (EIA 2020d).

Table A-232: 2019 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	0.06	28.28	6.1
	Bituminous Coal	8.10	25.41	754.5
	Sub-bituminous Coal	5.33	26.49	517.7
	Lignite	0.66	26.75	65.2
	Coke	(0.03)	31.00	(3.5)
	Unspecified	(3.42)	25.34	(317.6)
Gas Fuels	Natural Gas	31.99	14.43	1,692.2
Liquid Fuels	Crude Oil	34.44	20.31	2,564.4
	HGL	4.81	18.58	328.0
	Other Liquids	2.03	20.31	151.2
	Motor Gasoline	(1.35)	19.46	(96.5)
	Aviation Gasoline	+	18.86	0.1
	Kerosene	(0.01)	19.96	(0.5)
	Jet Fuel	(1.23)	19.70	(88.6)
	Distillate Fuel	(2.34)	20.22	(173.3)
	Residual Oil	(0.54)	20.48	(40.9)
	Naphtha for petrochemical feedstocks	0.03	18.55	1.9
	Petroleum Coke	(1.25)	27.85	(127.7)
	Other Oil for petrochemical feedstocks	(+)	20.17	(0.1)
	Special Naphthas	0.04	19.74	2.5
	Lubricants	(0.12)	20.20	(8.8)
	Waxes	+	19.80	0.1
	Asphalt/Road Oil	0.07	20.55	5.3
	Still Gas[a]	0.00	18.20	0.0
	Misc. Products	0.01	0.00	0.0
Total				**5,231.8**

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.
+ Does not exceed 0.005 QBtu or 0.05 MMT CO_2 Eq.
Sources: C content coefficients by coal rank from USGS (1998), PSU (2010), Gunderson (2019), IGS (2019), ISGS (2019), and EIA (2020a); natural gas C content coefficients from EPA (2010) and EIA (2020b); unspecified solid fuel and liquid fuel C content coefficients from EPA (2010) and ICF (2020).
[a] Still gas is reported as petroleum product (liquid fuel) in this report. However, still gas physically exists as a gas, consisting primary of methane and ethane, and some hydrogen and other trace gases (EIA 2020d).

Table A-233: 2019 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	132.8	31.00	4.12	0.10	2.1
Natural Gas	299.1	14.43	4.31	0.67	10.7
Asphalt & Road Oil	843.9	20.55	17.34	1.00	63.3
HGL	2,523.7	16.85	42.53	0.67	105.1
Lubricants	250.7	20.20	5.06	0.09	1.7
Pentanes Plus	153.5	18.24	2.80	0.67	6.9
Petrochemical Feedstocks	[1]	[1]	[1]	[1]	34.1
Petroleum Coke	0.0	27.85	0.00	0.30	0.0
Special Naphtha	88.7	19.74	1.75	0.67	4.3
Waxes/Misc.	[1]	[1]	[1]	[1]	0.7
Misc. U.S. Territories Petroleum	[1]	[1]	[1]	[1]	0.1
Total					**229.0**

Note: Totals may not sum due to independent rounding.
[1] Values for Misc. U.S. Territories Petroleum, Petrochemical Feedstocks, and Waxes/Misc. are not shown because these categories are aggregates of numerous smaller components.

Table A-234: 2019 Reference Approach CO_2 Emissions from Fossil Fuel Consumption (MMT CO_2 Eq.)

Fuel Category	Potential Emissions	Carbon Sequestered	Net Emissions	Fraction Oxidized	Total Emissions
Coal	1,022.4	2.1	1,020.3	100.0%	1,020.3
Petroleum	2,517.2	216.2	2,301.0	100.0%	2,301.0
Natural Gas	1,692.2	10.7	1,681.5	100.0%	1,681.5
Total	**5,231.8**	**229.0**	**5,002.8**		**5,002.8**

Note: Totals may not sum due to independent rounding.

Table A-235: Fuel Consumption in the United States by Estimating Approach (TBtu)[a]

Approach	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Sectoral	**69,634**	**74,688**	**82,554**	**83,937**	**82,689**	**83,921**	**81,084**	**76,258**	**78,689**	**77,201**	**75,387**	**77,324**	**78,034**	**77,120**	**76,286**	**75,752**	**79,028**	**78,196**
Coal	18,098	19,210	21,772	22,215	21,864	22,106	21,792	19,271	20,307	19,110	16,866	17,488	17,407	15,079	13,812	13,404	12,798	10,882
Natural Gas	19,173	22,173	23,395	22,283	21,961	23,371	23,594	23,193	24,313	24,679	25,832	26,562	27,145	27,932	28,153	27,742	30,801	31,824
Petroleum	32,363	33,305	37,386	39,439	38,864	38,444	35,699	33,794	34,069	33,412	32,688	33,274	33,483	34,109	34,322	34,607	35,430	35,490
Reference (Apparent)	**68,869**	**74,148**	**82,003**	**83,963**	**82,484**	**84,406**	**80,749**	**76,802**	**78,171**	**76,804**	**75,835**	**76,453**	**77,215**	**76,373**	**75,493**	**75,362**	**78,388**	**77,287**

Coal	17,598	18,591	20,982	22,015	21,565	21,616	21,430	19,283	19,662	18,796	16,682	17,134	17,248	14,836	13,576	13,136	12,562	10,702
Natural Gas	19,280	22,277	23,487	22,350	22,030	23,442	23,666	23,277	24,409	24,778	25,924	26,639	27,228	28,011	28,236	27,862	30,931	31,993
Petroleum	31,990	33,280	37,534	39,599	38,889	39,348	35,653	34,242	34,100	33,230	33,229	32,681	32,738	33,527	33,681	34,363	34,895	34,592
Difference	**-1.1%**	**-0.7%**	**-0.7%**	**0.0%**	**-0.2%**	**0.6%**	**-0.4%**	**0.7%**	**-0.7%**	**-0.5%**	**0.6%**	**-1.1%**	**-1.1%**	**-1.0%**	**-1.0%**	**-0.5%**	**-0.8%**	**-1.2%**
Coal	-2.8%	-3.2%	-3.6%	-0.9%	-1.4%	-2.2%	-1.7%	0.1%	-3.2%	-1.6%	-1.1%	-2.0%	-0.9%	-1.6%	-1.7%	-2.0%	-1.8%	-1.7%
Natural Gas	0.6%	0.5%	0.4%	0.3%	0.3%	0.3%	0.3%	0.4%	0.4%	0.4%	0.4%	0.3%	0.3%	0.3%	0.3%	0.4%	0.4%	0.5%
Petroleum	-1.2%	-0.1%	0.4%	0.4%	0.1%	2.4%	-0.1%	1.3%	0.1%	-0.5%	1.7%	-1.8%	-2.2%	-1.7%	-1.9%	-0.7%	-1.5%	-2.5%

Note: Totals may not sum due to independent rounding.

[a] Includes U.S. Territories. Does not include international bunker fuels.

Table A-236: CO_2 Emissions from Fossil Fuel Combustion by Estimating Approach (MMT CO_2 Eq.)[a]

Approach	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Sectoral	**4,844**	**5,144**	**5,740**	**5,884**	**5,795**	**5,871**	**5,669**	**5,279**	**5,444**	**5,302**	**5,099**	**5,227**	**5,277**	**5,119**	**5,015**	**4,970**	**5,134**	**4,998**
Coal	1,720	1,825	2,073	2,123	2,085	2,108	2,079	1,839	1,938	1,824	1,611	1,670	1,661	1,441	1,320	1,282	1,224	1,041
Natural Gas	1,007	1,164	1,228	1,172	1,157	1,231	1,243	1,222	1,279	1,299	1,359	1,397	1,426	1,466	1,477	1,456	1,618	1,671
Petroleum	2,117	2,155	2,440	2,589	2,553	2,531	2,347	2,218	2,227	2,179	2,128	2,160	2,189	2,212	2,219	2,232	2,292	2,287
Reference (Apparent)	**4,812**	**5,149**	**5,721**	**5,931**	**5,821**	**5,932**	**5,688**	**5,370**	**5,444**	**5,320**	**5,186**	**5,216**	**5,263**	**5,126**	**5,023**	**5,002**	**5,150**	**5,003**
Coal	1,656	1,757	1,990	2,089	2,051	2,056	2,039	1,834	1,870	1,791	1,589	1,629	1,641	1,413	1,290	1,244	1,196	1,020
Natural Gas	1,014	1,171	1,234	1,176	1,160	1,235	1,247	1,227	1,285	1,305	1,365	1,402	1,431	1,470	1,482	1,463	1,626	1,682
Petroleum	2,142	2,221	2,498	2,665	2,610	2,641	2,401	2,308	2,289	2,224	2,232	2,185	2,191	2,242	2,251	2,296	2,328	2,301
Difference	**-0.7%**	**0.1%**	**-0.3%**	**0.8%**	**0.5%**	**1.1%**	**0.3%**	**1.7%**	**0.0%**	**0.3%**	**1.7%**	**-0.2%**	**-0.3%**	**0.1%**	**0.2%**	**0.7%**	**0.3%**	**0.1%**
Coal	-3.8%	-3.7%	-4.0%	-1.6%	-1.6%	-2.5%	-1.9%	-0.2%	-3.5%	-1.8%	-1.4%	-2.5%	-1.2%	-1.9%	-2.3%	-3.0%	-2.3%	-2.0%
Natural Gas	0.7%	0.6%	0.5%	0.3%	0.3%	0.3%	0.3%	0.4%	0.5%	0.5%	0.4%	0.3%	0.3%	0.3%	0.4%	0.5%	0.5%	0.6%
Petroleum	1.2%	3.0%	2.4%	3.0%	2.2%	4.4%	2.3%	4.0%	2.8%	2.1%	4.9%	1.2%	0.1%	1.4%	1.5%	2.8%	1.6%	0.6%

Note: Totals may not sum due to independent rounding

[a] Includes U.S. Territories. Does not include international bunker fuels.

References

EIA (2020a). *Annual Coal Report 2019,* Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0584(2019).

EIA (2020b). *Monthly Energy Review, November 2020,* Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0035(2020/11).

EIA (2020c). *Petroleum Supply Annual*, Energy Information Administration, U.S. Department of Energy, Washington, D.C., Volume I. DOE/EIA-0340.

EIA (2020d). *Still Gas,* Glossary. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at: <https://www.eia.gov/tools/glossary/index.php?id=still%20gas>.

EIA (2011). *Annual Energy Review,* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0384(2011).

EIA (1992). Coal and lignite production. *EIA State Energy Data Report 1992*, Energy Information Administration, U.S. Department of Energy, Washington, DC.

EPA (2010). Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Gunderson, J. (2019) Montana Coal Sample Database. Data received 28 February 2019 from Jay Gunderson, Montana Bureau of Mines & Geology.

ICF (2020) Potential Improvements to Energy Sector Hydrocarbon Gas Liquid Carbon Content Coefficients. Memorandum from ICF to Vincent Camobreco, U.S. Environmental Protection Agency. December 7, 2020.

Illinois State Geological Survey (ISGS) (2019) *Illinois Coal Quality Database*, Illinois State Geological Survey.

Indiana Geological Survey (IGS) (2019) *Indiana Coal Quality Database 2018*, Indiana Geological Survey.

IPCC (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds.). Published: IGES, Japan.

Pennsylvania State University (PSU) (2010) Coal Sample Bank and Database. Data received by SAIC 18 February 2010 from Gareth Mitchell, The Energy Institute, Pennsylvania State University.

USGS (1998). *CoalQual Database Version 2.0*, U.S. Geological Survey.

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[138] 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 and sinks, 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.

The anthropogenic source and sink category of greenhouse gas emissions described in this annex are not included in the U.S. national inventory estimates. The reasons for not including that source in the national greenhouse gas Inventory include one or more of the following:

- Emissions are not likely to occur within the United States.
- A methodology for estimating emissions from a source does not currently exist.
- Though an estimating method has been developed, adequate data are not currently available to estimate emissions.
- Emissions are determined to be insignificant in terms of overall national emissions, as defined per UNFCCC reporting guidelines, based on available data or a preliminary assessment of significance. Further, data collection to estimate emissions would require disproportionate amount of effort (e.g., dependent on additional resources and impacting improvements to key categories, etc.).

In general, data availability remains the primary constraint for estimating and including the emissions and removals from source and sink categories that do occur within the United States and are not estimated, as discussed further below. Methods to estimate emissions and removals from these categories are available in the *2006 IPCC Guidelines*. Many of these categories are insignificant in terms of overall national emissions based on available proxy information, qualitative information on activity levels per national circumstances, and/or expert judgment, and not including them introduces a very minor bias.

Reporting of inventories to the UNFCCC under Decision 24/CP.19 states that "Where methodological or data gaps in inventories exist, information on these gaps should be presented in a transparent manner." Furthermore, these reporting guidelines allow a country to indicate if 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.[139] Specifically, where the notation key "NE," meaning not estimated, is used in the Common Reporting Format (CRF)[140] tables that accompany this Inventory report submission to the UNFCCC, countries are required to further describe why such emissions or removals have not been estimated (UNFCCC 2013).

Based on the latest UNFCCC reporting guidance, the United States is providing more information on the significance of these excluded categories below and aims to update information on the significance to the extent feasible during each annual compilation cycle. Data availability may impact the feasibility of undertaking a quantitative significance assessment. The United States is continually working to improve the understanding of such sources or sinks and seeking to find the data required to estimate related emissions, prioritizing efforts and resources for significant categories. As such improvements are implemented, new emission and removal categories will be quantified and included in the Inventory to enhance completeness of the Inventory.

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[138] 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*).

[139] 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>.

[140] See <http://unfccc.int/national_reports/annex_i_ghg_inventories/reporting_requirements/items/2759.php>.

The full list of sources and sink categories not estimated, along with explanations for their exclusion, is provided in Table 9 of the CRF submission. Information on coverage of activities within the United States and its territories is provided within the sectoral chapters and category-specific estimate discussions and will be updated further in this Annex in the next Inventory and future submissions as part of ongoing improvement efforts.

Source and Sink Categories Not Estimated

This section provides additional information on the reasons each category was not estimated, arranged by sector and source or sink category. A summary of these exclusions, including the estimated level of emissions where feasible, is included in Table A-237. Per 37(b) of the UNFCCC Reporting Guidelines Decision 24/CP.19, considering overall level and trend of U.S. emissions, the threshold for significance for estimating emissions from a specific category is 500 kt CO_2 Eq. Collectively, per paragraph 37(b) of the UNFCCC Reporting Guidelines noted above, it is likely that these exclusions should not exceed 0.1 percent of gross emissions, or 6.5 MMT CO_2 Eq. (6,577 kt CO_2 Eq.).

1 **Table A-237: Summary of Sources and Sinks Not Included in the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019**

CRF Category Number	Source/Sink Category	Gas(es)	Reason for Exclusion	Estimated 2019 Emissions (kt CO_2 Eq.)
Energy				
1.A Fossil Fuel Combustion				
1.A.3 Transport				
1.A.3.a	Domestic Aviation-Biomass	N_2O	Prior to 2011, no biobased jet fuel was assumed to be used for domestic aviation. Between 2011 and 2015, 22 airlines performed over 2,500 commercial passenger flights with blends of up to 50 percent biojet fuel. Furthermore, several airlines have concluded long-term offtake agreements with biofuel suppliers.[141] An analysis was conducted based on the total annual volumes of fuels specified in the long-term agreements. Emissions of N_2O were estimated based on the factors for jet fuel combustion. As for jet fuel use in commercial aircraft, contributions of methane (CH_4) emissions are reported as zero.	16
1.A.3.b.iv	Motorcycles-Biomass	CH_4 and N_2O	Emissions from ethanol mixed with gasoline in low blends are included in the on-road gasoline emissions for motorcycles. If there is any use of high blend ethanol fuel in motorcycles, it is considered insignificant. The percent of VMT from high ethanol blends in light duty gas vehicles (flex fuel vehicles) is less than 1 percent. If the same percentage is applied to motorcycle VMT with assumed flex fuel CH_4 and N_2O emission factors, it results in estimated emissions of 0.0015 kt CO_2 Eq.	0.0015
1.A.3.c	Railways-Biomass	CH_4 and N_2O	There are no readily available data sources to estimate the use of biofuel in railways. Railways represent about 6 percent of all diesel fuel use. An assumption can be made that railways consume that same percentage of biofuels (6 percent of all biodiesel). Based on that assumption for biofuel use and applying fossil fuel CH_4 and N_2O factors results in estimated emissions of 12.9 kt CO_2 Eq. per year.	13
1.A.3.d	Domestic Navigation-Biomass	CH_4 and N_2O	There are no readily available data sources to estimate the use of biofuel in domestic navigation. Domestic navigation represents about 3 percent of all diesel fuel use and about 1 percent of all gasoline fuel use. An assumption can be made that domestic navigation consumes that same percentage of biofuels (3 percent of all biodiesel and 1 percent of all ethanol use). Based on that assumption for biofuel use and applying fossil fuel CH_4 and N_2O factors results in estimated emissions of 39.0 kt CO_2 Eq. per year.	39
1.A.3.d	Domestic Navigation—Gaseous Fuels	CO_2	Emissions from gaseous fuel use in domestic navigation are not currently estimated. Gaseous fuels are used in liquid natural gas (LNG) tankers and are being demonstrated in a small number of other ships. Data are not available to	NQ

[141] See <https://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-alternative-fuels.pdf>.

			characterize these uses currently.	
1.A.3.e Other Transportation				
1.A.3.e.i	Pipeline Transport—Liquid Fuels	CO_2, CH_4 and N_2O	Use of liquid fuels to power pipeline pumps is uncommon, but has occurred. Data for fuel used in various activities including pipelines are based on survey data conducted by the U.S. Energy Information Association (EIA). From January 1983 through December 2009, EIA Survey data included information on liquid fuel used to power pipelines reported in terms of crude oil product supplied. Reporting of crude oil used for this purpose was discontinued after December 2009. Beginning with data for January 2010, product supplied for pipeline fuel is assumed to equal zero. 1997 was the last year of data reported on pipeline fuel. Taking the data reported for 1997 of 797,000 barrels of crude oil and using conversion factors of 5.8 MMBtu/bbl and 20.21 MMT C/Qbtu results in estimated emissions of 342.6 kt CO_2.	343
1.A.3.e.i	Pipeline Transport—Gaseous Fuels	CO_2, CH_4 and N_2O	CO_2 emissions from gaseous fuels used as pipeline transport fuel are estimated in the Inventory, however CH_4 and N_2O emissions from gaseous pipeline fuel use have not been estimated. The CO_2 / non-CO_2 emissions split for other natural gas combustion can be used to estimate emissions. Based on that analysis, non-CO_2 emissions represent approximately 0.43 percent of CO_2 emissions from all natural gas combustion. If that percentage is applied to CO_2 emissions from natural gas use as pipeline fuel, it results in an emissions estimate of 179.6 kt CO_2 Eq. in 2017.	180
1.A.3.e.ii	Non-Transportation Mobile-Biomass	CH_4 and N_2O	There are no readily available data sources to estimate the use of biofuel in non-transportation mobile sources. These sources represent about 21 percent of all diesel fuel use and about 4 percent of all gasoline fuel use. An assumption can be made that these sources consume that same percentage of biofuels (21 percent of all biodiesel and 4 percent of all ethanol use). Based on that assumption for biofuel use and applying fossil fuel CH_4 and N_2O factors results in estimated emissions of 256.4 kt CO_2 Eq. per year.	256
1.A.5.a Other Stationary				
1.A.5.a	Incineration of Waste: Medical Waste Incineration	CO_2	The category 1.A.5.a Other Stationary sources not specified elsewhere includes emissions from waste incineration of the municipal waste stream and waste tires. The category also includes emissions from non-energy uses of fuels which includes 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 hazardous industrial waste, it does capture a subset. A portion of hazardous industrial waste not captured is from medical waste. However, a conservative analysis was conducted based on a study of hospital/medical/infectious waste incinerator (HMIWI) facilities in the United	333

			States[142] showing that medical waste incineration emissions could be considered insignificant. The analysis was based on assuming the total amount of annual waste throughput was of fossil origin and an assumption of 68.9 percent carbon composition of the waste. It was determined that annual greenhouse gas emissions for medical waste incineration are approximately 333 kt CO_2 Eq. per year.	
1.A.5.a	Stationary Fuel Combustion: Biomass in U.S. Territories	CH_4 and N_2O	Data are not available to estimate emissions from biomass in U.S. Territories. However, biomass consumption is likely small in comparison with other fuel types. An estimate of non-CO_2 emissions from biomass fuels used in Territories can be made based on assuming the same ratio of domestic biomass non-CO_2 emissions to fossil fuel CO_2 emissions. Non-Territories data indicate that biomass non-CO_2 emissions represents 0.2 percent of fossil fuel combustion CO_2 emissions. Applying this same percentage to proxy U.S. Territories fossil fuel combustion CO_2 emissions results in estimated emissions of 74.8 kt CO_2 Eq. from biomass in U.S. Territories.	75
1.B Fugitive Emissions from Fuels				
1.B.1 – Solid Fuels				
1.B.1.a.1.i, 1.B.1.a.1.ii	Fugitive Emissions from Underground Coal Mining Activities and Post-Mining Activities	CO_2	A preliminary analysis by EPA determined that CO_2 emissions for active underground coal mining activities are negligible. The analysis was based on gas composition data from three active underground mines in three different states.[143] An average ratio of CO_2 to CH_4 composition in mine gas was derived for active underground mines. This ratio was applied as a percentage (0.4 percent) to CH_4 emission estimates to derive an estimate of CO_2 emissions for active underground mines (including post-mining activities). Applying a CO_2 emission rate as a percentage of CH_4 emissions for active coal mines results in a national emission estimate of 177 kt CO_2 Eq. per year. Future inventories may quantify these emissions, if it is deemed it will not require a disproportionate amount of effort.	177
1.B.1.a.1.iii	Fugitive Emissions from Abandoned Underground Coal Mines	CO_2	A preliminary analysis by EPA determined that CO_2 emissions for abandoned underground coal mining activities are negligible. The analysis was based on gas composition data from two abandoned underground mines in two different states.[144] An average ratio of CO_2 to CH_4 composition in mine gas was derived for abandoned mines. This ratio was applied as a percentage (1.5 percent) to CH_4 emission estimates to derive an estimate of CO_2 emissions for abandoned mines. Applying a CO_2 emission rate as a percentage of CH_4 emissions for abandoned coal mines results in a national emission estimate below 93 kt CO_2 Eq. per year. Future inventories may quantify these emissions, if it is deemed it will not require a	94

[142] RTI 2009. Updated Hospital/Medical/Infectious Waste Incinerator (HMIWI) Inventory Database.
[143] Ruby Canyon Engineering 2008. "Accounting for Carbon Dioxide Emissions in the Coal Emissions Inventory". Memorandum from Ruby Canyon Engineering to EPA.
[144] Ibid.

			disproportionate amount of effort.	
1.B.1.a.2	Fugitive Emissions from Surface Coal Mining Activities and Post-Mining Activities	CO_2	A preliminary analysis by EPA determined that CO_2 emissions for active surface coal mining activities are negligible. The analysis was based on gas composition data from three active underground mines in three different states.[145] An average ratio of CO_2 to CH_4 composition in mine gas was derived for surface mines (including post-mining activities). This estimate for CO_2 is considered conservative, as surface mining fugitive emissions of CH_4 are significantly lower than those from underground coal mines. This ratio was applied as a percentage (0.4 percent) to CH_4 emission estimates to derive an estimate of CO_2 emissions for surface mines (including post-mining activities). Applying a CO_2 emission rate as a percentage of CH_4 emissions for surface coal mines results in a national emission estimate of 34 kt CO_2 Eq. per year. Future inventories may quantify these emissions, if it is deemed it will not require a disproportionate amount of effort.	34
1.B.2 – Oil and Natural Gas and Other Emissions from Energy Production				
1.B.2.a.5	Oil: Distribution of Oil Products	CO_2 and CH_4	Emissions from the distribution of oil products are not currently estimated due to lack of available emission factors.	NQ
Industrial Processes and Product Use				
2.A Mineral Industry				
2.A.4.a	Other Process Uses of Carbonates: Ceramics	CO_2	Data are not currently available to estimate emissions from this source. During the Expert Review process for compilation of the current Inventory, EPA sought expert solicitation on data for carbonate consumption in the ceramics industry but has yet to identify data sources to apply IPCC methods to proxy emissions and assess significance.	NQ
2.A.4.c	Other Process Uses of Carbonates: Non-metallurgical Magnesium Production	CO_2	Data are not currently available to estimate emissions from this source. During the Expert Review process for compilation of the current Inventory, EPA sought expert solicitation on data for non-metallurgical magnesium production but has yet to identify data sources to apply IPCC methods to proxy emissions and assess significance.	NQ
2.B. Chemical Industry				
2.B.4.b	Glyoxal Production	CO_2 and N_2O	Glyoxal production data are not readily available to apply Tier 1 methods and estimate emissions from this source. EPA continues to conduct basic outreach to relevant trade associations and review potential databases that can be purchased and contain the necessary data. Outreach this year did not identify potential data sources. Any further progress on outreach will be included in next (i.e., 1990 through 2020) Inventory report.	NQ

[145] Ibid.

2.B.4.c	Glyoxylic Acid Production	CO_2 and N_2O	Data on national glyoxylic acid production data are currently not available to estimate emissions from this source using IPCC methods and then assess significance. EPA is conducting basic outreach to relevant trade associations reviewing potential databases that can be purchased and contain the necessary data. Outreach this year did not identify potential data sources. Any further progress on outreach will be included in next (i.e., 1990 through 2020) Inventory report.	NQ
2.B.5.b	Calcium Carbide	CH_4	Data are not currently available to estimate CH_4 emissions from this source. It is difficult to obtain production data from trade associations and trade publications. This information is not collected by USGS, the agency that collects information on silicon carbide. EPA has initiated some research to obtain data from the limited production facilities in the United States (less than 5). In addition, during the Expert Review process for compilation of the current Inventory, EPA sought expert solicitation on production data for this source, but has yet to identify data sources to apply Tier 1 methods to proxy emissions and assess significance. Carbon dioxide emissions from calcium carbide are implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke in the Energy chapter.	NQ
2.B.8.d	Petrochemical and Carbon Black Production	CO_2 recovery	EPA's GHGRP has data starting in reporting year 2010 on the amount of CO_2 captured, including at petrochemical facilities and ethylene oxide processes. Due to schedule and resource constraints, data on CO_2 sequestration have not been compiled and need to be reviewed to better understand available data to estimate the fate of these captured emissions. Any CO_2 potentially captured from petrochemical facilities is currently assumed to be released.	NQ
2.C. Metal Industry				
2.C.1.c	Iron and Steel Production: Direct Reduced Iron (DRI) Production	CH_4	Data on fuel consumption used in the production of DRI are not readily available to apply the IPCC default Tier 1 CH_4 emission factor. However, an assumed emission factor can be developed based on the default energy consumption of 12.5 GJ natural gas per metric ton of DRI produced. Based on this assumption and annual DRI production in metric tons results in CH_4 emissions of 0.74 kt CO_2. Eq.	0.74
2.E Electronics Industry				
2.E.2	Fluorinated Gas Emissions from Electronics Industry: TFT Flat Panel Displays	HFCs, PFCs, SF_6, and NF_3	In addition to requiring reporting of emissions from semiconductor manufacturing, micro-electro-mechanical systems (MEMs), and photovoltaic cells, EPA's GHGRP requires the reporting of emissions from the manufacture of flat panel displays. However, no flat panel displays manufacturing facilities have ever reported to EPA's GHGRP, indicating that there are no facilities in the United States that have exceeded the GHGRP's applicability threshold for display manufacturers since 2010. The available information on this sector indicate these emissions are well	NQ

			below the significance threshold.[146] Per this published literature, the United States has never been significant display manufacturer aside from a small amount of manufacturing in the 1990s, but not mass production.	
2.G Other				
2.G.2	Other Product Manufacture and Use: SF_6 and PFCs from Other Product Use	SF_6	Emissions of SF_6 occur from particle accelerators and military applications, and emissions of PFCs and other F-GHGs occur from military applications such as use of fluorinated heat transfer fluids (HTFs). Emissions from some particle accelerators and from military applications are reported by the U.S. government to the Federal Energy Management Program along with emissions of other fluorinated greenhouse gases (e.g., HFCs from mobile and stationary air conditioning) under the categories "Fugitive Fluorinated Gases and Other Fugitive Emissions" and "Industrial Process Emissions." Analysis of the underlying data for 2018 indicated "fugitive" emissions of SF_6 of approximately 600 kt CO_2 Eq. from the U.S. government as a whole, and "process" emissions of SF_6 of approximately 100 kt CO_2 Eq. (Emissions of SF_6 that are known to be accounted for elsewhere, such as under Electrical Transmission and Distribution, have been excluded from these totals.) The sources of the "fugitive" emissions of SF_6 were not identified, but the source of the vast majority of "process" emissions of SF_6 was particle accelerators. Fugitive emissions of approximately 200 kt CO_2 Eq. of compounds that are commonly used as fluorinated HTFs (HFEs and fully fluorinated compounds) were also reported. EPA plans to contact reporting agencies to better understand the sources of the emissions and the estimation methods used by reporters, which may equate emissions to consumption and therefore over- or underestimate some emissions, depending on the circumstances. This step will help EPA improve its assessment of significance and prioritize incorporating estimates in future Inventory submissions.	900
Agriculture				
3.A Livestock				
3.A.4	Enteric Fermentation: Camels	CH_4	Enteric fermentation emissions from camels are not estimated because there is no significant population of camels in the United States. Due to limited data availability (no population data are available from the Agricultural Census), the estimates are based on use of IPCC defaults and population data from Baum, Doug (2010).[147] Based on this source, a Tier 1 estimate of enteric fermentation CH_4 emissions from camels results in a value of approximately 2.8 kt CO_2 Eq. per year from 1990 to 2019. Given the insignificance of these emissions in terms of the overall level and trend in national emissions, there are no immediate improvement	3

[146] The Display Industry: Fast to Grow, Slow to Change Article in Information Display 28(5):18-21 · May 2012 with 4. DOI: 10.1002/j.2637-496X.2012.tb00504.x The Display Industry: Fast to Grow, Slow to Change. Available online at: <http://archive.informationdisplay.org/id-archive/2012/may-june/display-marketplace-the-display-industry-fast-to>.
[147] *The status of the camel in the United States of America*. Available online at: <https://www.soas.ac.uk/camelconference2011/file84331.pdf>.

			plans to include this emissions category in the Inventory.	
3.A.4	Enteric Fermentation: Poultry	CH_4	No IPCC method has been developed for determining enteric fermentation CH_4 emissions from poultry. Based on expert input, developing of a country-specific method would require a disproportionate amount of resources given the small magnitude of this source category.	No method provided in IPCC Guidelines
3.B.1.4, 3.B.2	Manure Management: Camels	CH_4 and N_2O	Manure management emissions from camels are not estimated because there is no significant population of camels in the United States.[148] Due to limited data availability and disproportionate effort to collect time-series data (i.e., no population data is available from the Agricultural Census), this estimate is based on population data from Baum, Doug (2010).[149] Based on this source, a Tier 1 estimate of manure management CH_4 and N_2O emissions from camels results in a value of approximately 0.14 kt CO_2 Eq. per year from 1990 to 2019. Given the insignificance of these emissions in terms of the overall level and trend in national emissions, there are no immediate improvement plans to include this emissions category in the Inventory.	0.14
3.F Field Burning of Agricultural Residues				
3.F.1.4, 3.F.4	Sugarcane	CH_4 and N_2O	Remote sensing data were used in combination with a resource survey to estimate non-CO_2 emissions from agricultural residue burning. These data did not allow identification of burning of sugarcane. This potential gap in the activity data will be re-evaluated in a future inventory using other datasets.	NQ
Land Use, Land-Use Change, and Forestry				
4.A Forest Land				
4.A(II)	Emissions and Removals from Rewetting of Organic and Mineral Soils	CO_2 and CH_4	Emissions from this source may be estimated in future Inventories when data necessary for classifying the area of rewetted organic and mineral soils become available.	NQ
4.A.1 Forest Land Remaining Forest Land				
4.A.1	N mineralization/ immobilization	N_2O	Direct N_2O emissions from N mineralization/immobilization associated with loss or gain of soil organic matter resulting from change of land use or management of mineral soils will be estimated in a future Inventory. They are not estimated currently because resources have limited EPA's ability to use the available data on soil carbon stock changes on forest lands to estimate these emissions.	NQ
4.B Cropland				

[148] 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>.
[149] *The status of the camel in the United States of America*. Available online at: <https://www.soas.ac.uk/camelconference2011/file84331.pdf>.

4.B(II)	Emissions and Removals from Rewetting of Organic and Mineral Soils	CO_2 and CH_4	Emissions of CO_2 and CH_4 from rewetting on mineral or organic cropland soils are not currently estimated due to lack of activity data on rewetting, except for CH_4 emissions from drainage and rewetting for rice cultivation.	NQ
4.B.1 Cropland Remaining Cropland				
4.B.1	Carbon Stock Change in Living Biomass and Dead Organic Matter	CO_2	Carbon stock change in living biomass and dead organic matter are not estimated, other than for forest land converted to cropland, because data are currently not available. The impact of management on perennial biomass C is currently under investigation for agroforestry management and will be included in a future Inventory if stock changes are significant and activity data can be compiled for this source.	NQ
4.B.1(V)	Biomass Burning—Controlled Burning	CO_2	The CO_2 emissions from controlled burning of crop biomass are not estimated as they are part of the annual cycle of C and not considered net emissions. Methane and N_2O emissions are included under 3.F Field Burning of Agricultural Residues.	NQ
4.B.1(V)	Biomass Burning—Wildfires	CO_2, CH_4, and N_2O	Emissions from wildfires are not estimated because the activity data on fire area and fuel load, particularly for perennial vegetation, are not available to apply IPCC methods.	
4.B.2 Land Converted to Cropland				
4.B.2	Carbon Stock Change in Perennial Living Biomass and Dead Organic Matter	CO_2	Carbon stock change in living biomass and dead organic matter are not estimated, other than for forest land converted to cropland, because data are currently not available. The impact of management on perennial biomass C is currently under investigation for agroforestry management and will be included in a future Inventory if stock changes are significant and activity data can be compiled for this source.	NQ
4.B.2(V)	Biomass Burning—Wildfires and Controlled Burning	CO_2	Emissions from wildfires are not estimated because the activity data on fire area and fuel load, particularly for perennial vegetation, are not available.	NQ
4.C Grassland				
4.C(II)	Emissions and Removals from Rewetting of Organic and Mineral Soils	CO_2 and CH_4	Emissions of CH_4 from drainage and CO_2 and CH_4 from rewetting on mineral or organic Grassland soils are not currently estimated due to lack of activity data.	NQ
4.C.2 Land Converted to Grassland				
4.C.2	Carbon Stock Change in Living Biomass and Dead Organic Matter	CO_2	Carbon stock change in living biomass and dead organic matter are not estimated, other than for forest land converted to grassland, because data are currently not available. The impact of management on perennial biomass C is currently under investigation for agroforestry management and will be included in a future Inventory if stock changes are significant and activity data can be compiled for this source.	NQ
4.D Wetlands				

4.D(II)	Flooded Lands and Peat Extraction Lands: Emissions and Removals from Drainage and Rewetting and Other Management of Organic and Mineral Soils	CO_2, CH_4, and N_2O	Data are currently not available to apply IPCC methods and estimate emissions from rewetting of peat extraction lands and flooded lands.	NQ
4.D.1 Wetlands Remaining Wetlands				
4.D.1(V)	Biomass Burning: Controlled Burning, Wildfires	CO_2, CH_4, and N_2O	Data are not currently available to estimate emissions from biomass burning in Wetlands to apply IPCC methods.	NQ
4.D.1.2	Carbon Stock Change in *Flooded Land Remaining Flooded Land*	CO_2	Carbon stock changes in flooded land remaining flooded land are not estimated due to lack of activity data, other than for peatlands and coastal wetlands. See the Wetlands chapter in the Inventory report to apply IPCC methods.	NQ
4.D.2 Land Converted to Wetlands				
4.D.2(V)	Biomass Burning: Controlled Burning, Wildfires	CO_2, CH_4, and N_2O	Data are not currently available to estimate emissions from biomass burning in Wetlands to apply IPCC methods.	NQ
4.E Settlements				
4.E(V)	Biomass Burning in Settlements	CO_2, CH_4, and N_2O	Data are currently not available to estimate emissions from biomass burning in Settlements to apply IPCC methods.	NQ
4.E.1 Settlements Remaining Settlements				
4.E.1	Settlements Remaining Settlements	CH_4	Data are not currently available to apply IPCC methods and estimate CH_4 emissions in Settlements.	NQ
4.E.1	Direct N_2O Emissions from N Mineralization/Immobilization (Mineral Soils)	N_2O	Activity data are not available on N_2O emissions from nitrogen mineralization/immobilization in *Settlements Remaining Settlements* and *Land Converted to Settlements* as a result of soil organic carbon stock losses from land use conversion and management.	NQ
4.E.2 Land Converted to Settlements				
4.E.2	Direct N_2O Emissions from N Mineralization/Immobilization	N_2O	Activity data are not available on N_2O emissions from nitrogen mineralization/immobilization in *Settlements Remaining Settlements* and *Land Converted to Settlements* as a result of soil organic carbon stock losses from land use conversion and management.	NQ
4.F Other Land				
4.F(V)	Biomass Burning	CO_2, CH_4, and N_2O	Data are not currently available to estimate emissions from biomass burning in Other Lands.	NQ
Waste				
5.A.1 Solid Waste Disposal				

5.A.1.a	Managed Waste Disposal Sites-Anaerobic	CH_4 and N_2O	The amount of CH_4 flared and the amount of CH_4 for energy recovery is not estimated for the years 2005 through 2019 in the time series. The amount of CH_4 flared and recovered for 2005 and each subsequent Inventory year, i.e., through 2019, is included in the net CH_4 emissions estimates. A methodological change was made for 2005 to the current Inventory year to use the directly reported net CH_4 emissions from the EPA's GHGRP versus estimate CH_4 generation and recovery. See the Methodology explanation in Section 7.1.	No method provided in IPCC Guidelines
5.B Biological Treatment of Solid Waste				
5.B.1.a	Composting – Municipal Solid Waste	Recovered CH_4 and N_2O	CH_4 and N_2O emissions from combustion of the recovered gas at composting sites are very small "so good practice in the Waste Sector does not require their estimation." (IPCC 2006, Volume 5, Chapter 4, pp. 4.5). EPA will periodically assess trends and based on significance consider reflecting as over time as data become available and prioritize with other improvements to make best use of available resources.	NQ
5.B.2.a, 5.B.2.b	Anaerobic Digestion at Biogas Facilities—Municipal Solid Waste and Other Waste	N_2O	N_2O emissions from anaerobic digestion of municipal solid waste at biogas facilities are not estimated because N_2O emissions are assumed to be negligible (i.e., no methodology [Tier 1 nor associated default emission factors] are provided). See IPCC (2006) Volume 5, Chapter 4, p. 4.6, Table 4.1.	No method provided in IPCC Guidelines
5.D Wastewater Treatment				
5.D.2	Industrial Wastewater	CH_4	Emissions associated with sludge generated from the treatment of industrial wastewater is not included because the likely level of emissions is insignificant and because quantitative activity data on who operates anaerobic sludge digesters is unavailable. It would require a disproportionate amount of effort to collect this data, and more recent methodological work also suggests this is the case (i.e., Table 6.3 (Updated) in the *2019 IPCC Refinement* only identifies CH_4 emissions from anaerobic digestion of sludge as a source of emissions to be reported in the Wastewater sector (note that N_2O is noted as "not significant" in Table 6.8A). Methane emissions from the wastewater treatment category are not considered a key source category (see Annex 1, Table A-1). In addition, the United States continues to review the six industries included in the wastewater sector to determine if activity data are sufficient to include methane emissions from anaerobic digestion of sludge. The United States has worked first with the pulp and paper industry to confirm that virtually no pulp and paper mills operate anaerobic sludge digesters and will continue to identify stakeholders in the remaining five industries to confirm sludge management techniques. The United States notes that methane emissions associated with anaerobic digestion of ethanol waste (a combination of process wastewater and solids) is already included in the Inventory and is not considered sludge management. The United States believes the likely level of emissions associated with anaerobic digestion of industrial wastewater sludge is less than 5 kt CO_2 Eq., which is	5

		considered insignificant for the purposes of inventory reporting under the UNFCCC.

NQ (Quantified estimate not available due to insufficient data but method is available in IPCC Guidelines)

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 countries who are Parties to the United Nations Framework Convention on Climate Change (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-238). While this Inventory uses agreed-upon GWP values according to the specific reporting requirements of the UNFCCC, described below, unweighted gas emissions and sinks in kilotons (kt) are provided in the Trends chapter of this report (Table 2-2) and users of the Inventory can apply different metrics and different time horizons to compare the impacts of different greenhouse gases.

> *…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...*[150]

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, 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.

[150] 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)

Table A-238: 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[d]	25	72	7.6
Nitrous oxide (N_2O)	114[d]	298	289	153
HFC-23	270	14,800	12,000	12,200
HFC-32	4.9	675	2,330	205
HFC-41	3.7	150	490	45
HFC-125	29	3,500	6,350	1,100
HFC-134a	14	1,430	3,830	435
HFC-143a	52	4,470	5,890	1,590
HFC-152a	1.4	124	437	38
HFC-227ea	34.2	3,220	5,310	1,040
HFC-236fa	240	9,810	8,100	7,660
HFC-43-10mee	15.9	1,640	4,140	500
HFC-245fa	7.6	1,030	3,380	314
HFC-365mfc	8.6	794	2,520	241
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_6[e]	1.1	0.003	NA	NA
c-C_5F_8[e]	31	1.97	7.0	NA
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}	3,200	9,300	6,600	13,300
SF_6	3,200	22,800	16,300	32,600
NF_3	740	17,200	12,300	20,700

NA (Not Available)

[a] GWP values used in this report are calculated over 100-year time horizon.

[b] 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.

[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.

[d] Methane and N_2O 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), but only the perturbation time is listed here and not the atmospheric residence time.

[e] See Table A-1 of FR 40 CFR Part 98.

Source: IPCC (2007)

Table A-239 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; direct GWP values are shown, but AR4 does provide a range of net GWP values 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-239). The effects of these compounds on radiative forcing are not addressed in this report.

Table A-239: 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

Note: Because these compounds have been shown to deplete stratospheric ozone, they are typically referred to as 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, and HCFCs by 2030.
Source: IPCC (2007).

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 *Fourth Assessment Report* (AR4) (IPCC 2007). Although the AR4 GWP values are used throughout this Inventory report in line with UNFCCC inventory reporting guidelines, it is informative to review the changes to the 100-year 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 *Second Assessment Report* (SAR) and *Third Assessment Report* (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-240 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 AR5, including addressing inconsistencies with incorporating climate carbon feedbacks. 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 2019). As such, GWP comparisons throughout this chapter are presented relative to AR4 GWPs.

Table A-240: 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)[e]	**12±3**	**8.7/12[f]**	**12.4**	**21**	**25**	**28**	**34**	**(4)**	**-16%**	**3**	**12%**	**9**	**36%**
Nitrous oxide (N_2O)	**120**	**120/114[f]**	**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	950	1,030	858	1,032	(80)	-8%	(172)	-17%	2	+%
HFC-365mfc	NA	8.6	8.7	860	794	804	966	66	8%	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-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-C_5F_8	NA	NA	31	NA	NA	2.0	NA	NA	NA	NA	NA	NA	NA
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%

Note: Parentheses indicate negative values.
+ Does not exceed 0.5 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. See footnote e for more information on GWPs for methane of fossil origin.
[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.
[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. See footnote e for more information on GWPs for methane of fossil origin.
[d] No single lifetime can be determined for CO_2 (see IPCC 2007).

[e] The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. Additionally, the AR5 reported separate values for fossil versus biospheric methane in order to account for the CO_2 oxidation product. The GWP associated with methane of fossil origin is not shown in this table. Per AR5, the GWP for methane of fossil origin is 30 versus 28 using methodology most consistent with AR4. If using methodology to include climate carbon feedbacks, per the AR5 report, the value is higher by 2 for GWP for methane of fossil origin, so would be 36 versus 34.

[f] Methane and N_2O have chemical feedback systems that can alter the length of the atmospheric response, in these cases, global mean residence time is given first, followed by perturbation time.

Source: IPCC (2013), IPCC (2007), 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-241 shows the overall trend in U.S. greenhouse gas emissions, by gas, from 1990 through 2019 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 2019.

Table A-241: Effects on U.S. Greenhouse Gas Emissions Using SAR, AR4, and AR5 GWP values (MMT CO_2 Eq.)

Gas	Difference in Emissions Between 1990 and 2019 (Relative to 1990)				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			2019		
CO_2	157.9	157.9	157.9	157.9	NC	NC	NC	NC	NC	NC
CH_4	(98.8)	(117.6)	(131.7)	(159.9)	(124.4)	93.3	280.0	(105.6)	79.2	237.6
N_2O	4.9	4.7	4.1	4.7	18.2	(50.2)	NC	18.4	(50.7)	NC
HFCs, PFCs, SF_6, and NF_3	72.1	85.2	82.9	102.1	(12.7)	(9.8)	0.4	(25.8)	(12.1)	17.3
Total	**136.0**	**130.1**	**113.2**	**104.7**	**(118.9)**	**33.4**	**280.4**	**(112.9)**	**16.4**	**254.9**
Percent Change	**2.1%**	**2.0%**	**1.7%**	**1.6%**	**-1.8%**	**0.5%**	**4.3%**	**-1.7%**	**0.2%**	**3.9%**

Note: Totals may not sum due to independent rounding. Excludes sinks. Parentheses indicate negative values.
NC (No Change)
[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, for methane the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product and that is not shown on this table. See footnotes to Table A-242.

When the GWP values from the SAR are applied to the emission estimates presented in this report, total emissions for the year 2019 are 6,464.2 MMT CO_2 Eq., as compared to the official emission estimate of 6,577.2 MMT CO_2 Eq. using AR4 GWP values (i.e., the use of SAR GWPs results in a 1.7 percent decrease relative to emissions estimated using AR4 GWPs).

Further, Table A-242 and Table A-243 show the comparison of emission estimates using AR5 GWP values relative to AR4 GWP values without climate-carbon feedbacks for the non-CO_2 gases, on an emissions and percent change basis. Table A-244 and Table A-245 show the comparison of emission estimates using AR5 GWP values with climate-carbon feedbacks. The use of AR5 GWP values without climate-carbon feedbacks[151] 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 CH_4, SF_6, and NF_3 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 calculated U.S. emissions, resulting in an increase in emissions of less than 1 percent using AR5 GWP values, or approximately 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 Substitution of Ozone Depleting Substances.

[151] The IPCC AR5 report provides additional information on emission metrics. See <https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf>.

Table A-242: 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	2015	2016	2017	2018	2019
CO_2	NC	NC	NC	NC	NC	NC	NC
CH_4	93.3	82.6	78.3	77.2	77.9	78.7	79.2
N_2O	(50.2)	(50.5)	(51.9)	(50.0)	(49.5)	(50.9)	(50.7)
HFCs	(7.5)	(11.0)	(10.0)	(9.8)	(10.2)	(10.0)	(10.4)
PFCs	(3.2)	(1.6)	(1.9)	(1.8)	(1.8)	(2.0)	(1.9)
SF_6	0.9	0.4	0.2	0.2	0.2	0.2	0.2
NF_3	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Unspecified Mix of HFCs, PFCs, SF_6, and NF_3	NA	NA	NA	NA	NA	NA	NA
Total	**33.4**	**19.8**	**14.7**	**15.8**	**16.6**	**15.9**	**16.4**

Notes: Total emissions presented without LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values.
+ Absolute value does not exceed 0.05 MMT CO_2 Eq.
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. The AR5 report has also calculated GWP values (shown in Table A-244) 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, for methane the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product and that is not shown on this table. See footnotes to Table A-244.

Table A-243: Change in U.S. Greenhouse Gas Emissions Using AR5[a] without Climate-Carbon Feedbacks Relative to AR4 GWP Values (Percent)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
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%)**	**(11%)**	**(11%)**	**(11%)**	**(11%)**	**(11%)**	**(11%)**
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%)**
HFCs	**(16.1%)**	**(8.6%)**	**(5.9%)**	**(5.8%)**	**(6.0%)**	**(5.9%)**	**(6.0%)**
Substitution of Ozone Depleting Substances	11.3%	(7.1%)	(5.7%)	(5.6%)	(5.6%)	(5.7%)	(5.7%)
HCFC-22 Production[b]	(16.2%)	(16.2%)	(16.2%)	(16.2%)	(16.2%)	(16.2%)	(16.2%)
Electronics Industry[c]	(16.2%)	(16.4%)	(16.4%)	(16.8%)	(16.6%)	(16.7%)	(20.7%)
Magnesium Production and Processing[d]	0.0%	0.0%	(9.1%)	(9.1%)	(9.1%)	(9.1%)	(9.1%)
PFCs	**(13.1%)**	**(24.1%)**	**(35.7%)**	**(40.9%)**	**(44.8%)**	**(42.3%)**	**(41.3%)**
Electronics Industry[c]	(36.5%)	(38.9%)	(53.8%)	(56.3%)	(58.3%)	(60.5%)	(62.6%)
Aluminum Production[e]	(10.1%)	(10.1%)	(10.0%)	(9.9%)	(9.9%)	(10.0%)	(10.0%)
Substitution of Ozone Depleting Substances[d,f]	0.0%	(10.3%)	(10.3%)	(10.3%)	(10.3%)	(10.3%)	(10.3%)
Unspecified Mix of HFCs, PFCs, SF_6, and NF_3	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
Electronics Industry	NA	NA	NA	NA	NA	NA	NA
Total	**0.5%**	**0.3%**	**0.2%**	**0.2%**	**0.3%**	**0.2%**	**0.2%**

Note: Total emissions presented without LULUCF. Parentheses indicate negative values.
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. The AR5 report has also calculated GWP values (shown in Table A-245) 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, as well as other HFCs and PFCs used as heat transfer fluids.
[d] Zero change in beginning of time series since emissions were zero.
[e] PFC emissions from CF_4 and C_2F_6.
[f] PFC emissions from CF_4.

Table A-244: 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	2015	2016	2017	2018	2019
CO_2	NC	NC	NC	NC	NC	NC	NC
CH_4	280.0	247.7	234.8	231.7	233.7	236.1	237.6
N_2O	NC	NC	NC	NC	NC	NC	NC
HFCs	(2.9)	9.4	17.7	17.9	17.6	17.7	18.0
PFCs	(0.9)	(1.1)	(1.5)	(1.5)	(1.6)	(1.7)	(1.6)
SF_6	4.2	1.7	0.8	0.9	0.9	0.8	0.9
NF_3	+	+	+	+	+	+	+
Unspecified Mix of HFCs, PFCs, SF_6, and NF_3	NA	NA	NA	NA	NA	NA	NA
Total	**280.4**	**257.8**	**251.7**	**248.9**	**250.6**	**253.0**	**255.0**

Notes: Total emissions presented without LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values.
+ Absolute value does not exceed 0.05 MMT CO_2 Eq.
NC (No Change)
NA (Not Applicable)
[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, for methane the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product and that is not shown on this table. See footnotes to Table A-244.

Table A-245: Change in U.S. Greenhouse Gas Emissions Using AR5 with Climate-Carbon Feedbacks[a] Relative to AR4 GWP Values (Percent)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
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	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**
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%**
HFCs	**(6.2%)**	**7.4%**	**10.5%**	**10.6%**	**10.3%**	**10.5%**	**10.4%**
Substitution of Ozone Depleting Substances	34.6%	10.0%	11.0%	11.0%	10.9%	10.8%	10.8%
HCFC-22 Production[b]	(6.4%)	(6.4%)	(6.4%)	(6.4%)	(6.4%)	(6.4%)	(6.4%)
Electronics Industry[c]	(6.4%)	(6.6%)	(6.6%)	(7.0%)	(6.8%)	(6.9%)	(11.4%)
Magnesium Production and Processing[d]	0.0%	0.0%	8.3%	8.3%	8.3%	8.3%	8.3%
PFCs	**(3.6%)**	**(15.7%)**	**(28.6%)**	**(34.4%)**	**(38.7%)**	**(36.0%)**	**(34.9%)**
Electronics Industry[c]	(29.5%)	(32.1%)	(48.6%)	(51.4%)	(53.7%)	(56.1%)	(58.4%)
Aluminum Production[e]	(0.3%)	(0.3%)	(0.1%)	(0.0%)	0.0%	(0.1%)	(0.2%)
Substitution of Ozone Depleting Substances[d,f]	0.0%	(0.6%)	(0.6%)	(0.6%)	(0.6%)	(0.6%)	(0.6%)
Unspecified Mix of HFCs, PFCs, SF_6, and NF_3	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
Electronics Industry	NA	NA	NA	NA	NA	NA	NA
Total	**4.3%**	**3.5%**	**3.8%**	**3.8%**	**3.9%**	**3.8%**	**3.9%**

Notes: Total emissions presented without LULUCF. Parentheses indicate negative values. Excludes Sinks.
NC (No Change)
NA (Not Applicable)
+ Does not exceed 0.05 percent.

[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, for methane the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product and that is not shown on this table. See footnotes to Table A-244.

[b] HFC-23 emitted.

[c] Emissions from HFC-23, CF_4, C_2F_6, C_3F_8, C_4F_8, SF_6, as well as other HFCs and PFCs used as heat transfer fluids.

[d] Zero change in beginning of time series since emissions were zero.

[e] PFC emissions from CF_4 and C_2F_6.

[f] PFC emissions from CF_4.

6.2. Ozone Depleting Substance Emissions

Ozone is present in both the stratosphere,[152] where it shields the earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[153] 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.[154] 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,[155] 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 generally in 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 ODPs. 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 Montreal Protocol controls, however, the production for domestic use of all HCFCs in the United States must 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 direct 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 the inventory presents a more complete picture of climate impacts when we include these compounds. Emission estimates for several ozone depleting substances are provided in Table A-246.

[152] 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.

[153] 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.

[154] 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.

[155] Older refrigeration and air-conditioning equipment, fire extinguishing systems, and foam products blown with CFCs/HCFCs may still contain Class I ODS.

Table A-246: Emissions of Ozone Depleting Substances (kt)

Compound	1990	2005	2015	2016	2017	2018	2019
Class I							
CFC-11	31	12	11	11	12	11	9
CFC-12	136	23	4	3	2	1	1
CFC-113	59	17	0	0	0	0	0
CFC-114	4	1	0	0	0	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	2	1	1	1	1	1
Halon-1301	2	+	+	+	+	+	+
Class II							
HCFC-22	31	74	58	54	51	47	43
HCFC-123	0	1	1	1	1	1	1
HCFC-124	0	2	+	+	+	+	+
HCFC-141b	1	4	10	9	8	9	10
HCFC-142b	1	4	2	3	3	4	5
HCFC-225ca/cb	+	3	12	13	14	15	17

+ 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 Substitution of Ozone Depleting Substances 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-247.

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 46.9 percent of total SO_2 emissions in 2019 (see Table A-248); coal combustion accounted for approximately 92.0 percent of that total. The second largest source was industrial fuel combustion, which produced 17.4 percent of 2019 SO_2 emissions (see Table A-247). Overall, SO_2 emissions in the United States decreased by 90.6 percent from 1990 to 2019. 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,[156] (2) New Source Performance Standards,[157] (3) the New Source Review/Prevention of Significant Deterioration Program,[158] and (4) the Sulfur Dioxide Allowance Program.[159]

Table A-247: SO_2 Emissions (kt)

Sector/Source	1990	2005	2015	2016	2017	2018	2019
Energy	**19,628**	**12,364**	**3,096**	**2,439**	**1,803**	**1,724**	**1,457**
Stationary Sources	18,407	11,541	2,901	2,269	1,638	1,569	1,304
Oil and Gas Activities	390	180	92	89	86	86	86
Mobile Sources	793	619	78	57	58	47	45
Waste Combustion	38	25	26	24	22	22	22
Industrial Processes and Product Use	**1,307**	**831**	**482**	**466**	**509**	**509**	**509**
Miscellaneous[a]	11	114	137	139	198	198	198
Other Industrial Processes	362	327	145	139	132	132	132
Chemical and Allied Product Manufacturing	269	228	108	104	101	101	101
Metals Processing	659	158	89	83	77	77	77
Storage and Transport	6	2	2	2	1	1	1
Solvent Use	+	+	+	+	+	+	+
Degreasing	+	+	+	+	+	+	+
Graphic Arts	+	+	+	+	+	+	+
Dry Cleaning	NA	NA	+	+	+	+	+
Surface Coating	+	+	+	+	+	+	+
Other Industrial	+	+	+	+	+	+	+
Nonindustrial	NA	NA	NA	NA	NA	NA	NA

[156] [42 U.S.C § 7409, CAA § 109]
[157] [42 U.S.C § 7411, CAA § 111]
[158] [42 U.S.C § 7473, CAA § 163]
[159] [42 U.S.C § 7651, CAA § 401]

Agriculture	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA
Waste	**+**	**1**	**1**	**1**	**1**	**1**	**1**
Landfills	+	+	1	1	1	1	1
Wastewater Treatment	+	+	+	+	+	+	+
Miscellaneous[a]	+	1	+	+	+	+	+
Total	**20,935**	**13,196**	**3,578**	**2,906**	**2,313**	**2,233**	**1,966**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.5 kt
NA (Not Applicable)
[a] Miscellaneous includes other combustion and fugitive dust categories.
Source: Data taken from EPA (2019) and disaggregated based on EPA (2003).

Table A-248: SO_2 Emissions from Electricity Generation (kt)

Fuel Type	1990	2005	2015	2016	2017	2018	2019
Coal	13,808	8,680	2,189	1,673	1,156	1,092	849
Oil	580	458	115	88	61	58	45
Gas	1	174	44	33	23	22	17
Internal Combustion	45	57	14	11	8	7	6
Other	NA	71	18	14	9	9	7
Total	**14,433**	**9,439**	**2,381**	**1,819**	**1,257**	**1,188**	**923**

Note: Totals may not sum due to independent rounding.
NA (Not Applicable)
Source: Data taken from EPA (2019) and disaggregated based on EPA (2003).

6.4. Complete List of Source and Sink Categories

Chapter/Source/Sink	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	CO_2, CH_4, N_2O
Natural Gas Systems	CO_2, CH_4, N_2O
Abandoned Oil and Gas Wells	CO_2, CH_4
Incineration of Waste	CO_2, CH_4, N_2O, NO_x, CO, NMVOC
Industrial Processes and Product Use	
Cement Production	CO_2
Lime Production	CO_2
Glass Production	CO_2
Other Process Uses of Carbonates	CO_2
Ammonia Production	CO_2
Urea Consumption for Non-Agricultural Purposes	CO_2
Nitric Acid Production	N_2O
Adipic Acid Production	N_2O
Caprolactam, Glyoxal, and Glyoxylic Production	N_2O
Carbide Production and Consumption	CO_2, CH_4
Titanium Dioxide Production	CO_2
Soda Ash Production	CO_2
Petrochemical Production	CO_2, CH_4
HCFC-22 Production	HFC-23
Carbon Dioxide Consumption	CO_2
Phosphoric Acid Production	CO_2
Iron and Steel Production & Metallurgical Coke Production	CO_2, CH_4
Ferroalloy Production	CO_2, CH_4
Aluminum Production	CO_2, CF_4, C_2F_6
Magnesium Production and Processing	CO_2, HFCs, SF_6
Lead Production	CO_2
Zinc Production	CO_2
Electronics Industry	N_2O, HFCs, PFCs,[a] SF_6, NF_3
Substitution of Ozone Depleting Substances	HFCs, PFCs[b]
Electrical Transmission and Distributing	SF_6
N_2O from Product Uses	N_2O
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
Stand-Alone Anaerobic Digesters	CH_4

[a] Includes HFC-23, CF_4, C_2F_6, as well as a mix other HFCs and PFCs used as heat transfer fluids.
[b] 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.
[c] The LULUCF Sector includes CH_4 and N_2O emissions to the atmosphere and net carbon stock changes. 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-249 provides a guide for determining the magnitude of metric units.

Table A-249: 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	=	0.621 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[160]

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

[160] Reference: EIA (2007)

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-250 can be used as default factors, if local data are not available. See Appendix A of EIA's *Monthly Energy Review, November 2020* (EIA 2020) for more detailed information on the energy content of various fuels.

Table A-250: Conversion Factors to Energy Units (Heat Equivalents)

Fuel Type (Units)	Factor
Solid Fuels (Million Btu/Short ton)	
Anthracite coal	22.57
Bituminous coal	23.89
Sub-bituminous coal	17.14
Lignite	12.87
Coke	21.49
Natural Gas (Btu/Cubic foot)	**1,036**
Liquid Fuels (Million Btu/Barrel)	
Motor gasoline	5.052
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	6.287
Misc. products	5.796

Note: For petroleum and natural gas, *Monthly Energy Review, November 2020* (EIA 2020). For coal ranks, *State Energy Data Report 1992* (EIA 1993). All values are given in higher heating values (gross calorific values).

6.6. Abbreviations

ABS	Acrylonitrile butadiene styrene
AC	Air conditioner
ACC	American Chemistry Council
AEDT	FAA Aviation Environmental Design Tool
AEO	Annual Energy Outlook
AER	All-electric range
AF&PA	American Forest and Paper Association
AFEAS	Alternative Fluorocarbon Environmental Acceptability Study
AFOLU	Agriculture, Forestry, and Other Land Use
AFV	Alternative fuel vehicle
AGA	American Gas Association
AGR	Acid gas removal
AHEF	Atmospheric and Health Effect Framework
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AISI	American Iron and Steel Institute
ALU	Agriculture and Land Use
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
ARMA	Autoregressive moving-average
ARMS	Agricultural Resource Management Surveys
ASAE	American Society of Agricultural Engineers
ASLRRA	American Short-line and Regional Railroad Association
ASR	Annual Statistical Report
ASTM	American Society for Testing and Materials
AZR	American Zinc Recycling
BCEF	Biomass conversion and expansion factors
BEA	Bureau of Economic Analysis, U.S. Department of Commerce
BIER	Beverage Industry Environmental Roundtable
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
BSEE	Bureau of Safety and Environmental Enforcement
BTS	Bureau of Transportation Statistics, U.S. Department of Transportation
Btu	British thermal unit
C	Carbon
C&D	Construction and demolition waste
C&EN	Chemical and Engineering News
CAAA	Clean Air Act Amendments of 1990
CAFOS	Concentrated Animal Feeding Operations
CaO	Calcium oxide
CAPP	Canadian Association of Petroleum Producers
CARB	California Air Resources Board

CBI	Confidential business information
C-CAP	Coastal Change Analysis Program
CDAT	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
CHAPA	Calfornia Health and Productivity Audit
CHP	Combined heat and power
CI	Confidence interval
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
CONUS	Continental United States
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
DGGS	Division of Geological & Geophysical Surveys
DHS	Department of Homeland Security
DLA	DoD's Defense Logistics Agency
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
DOM	Dead organic matter
DOT	U.S. Department of Transportation
DRE	Destruction or removal efficiencies
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
EREF	Environment Research & Education Foundation
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
FAS	Fuels Automated System
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
FOD	First order decay
FOEN	Federal Office for the Environment
FQSV	First-quarter of silicon volume
FSA	Farm Service Agency
FTP	Federal Test Procedure
g	Gram
G&B	Gathering and boosting
GaAs	Gallium arsenide
GCV	Gross calorific value
GDP	Gross domestic product
GEI	Gulfwide Emissions Inventory
GHG	Greenhouse gas
GHGRP	EPA's Greenhouse Gas Reporting Program
GIS	Geographic Information Systems
GJ	Gigajoule
GOADS	Gulf Offshore Activity Data System
GOM	Gulf of Mexico
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
HCFO	Hydrochlorofluoroolefin
HDDV	Heavy duty diesel vehicle
HDGV	Heavy duty gas vehicle
HDPE	High density polyethylene
HF	Hydraulically fractured
HFC	Hydrofluorocarbon

HFO	Hydrofluoroolefin
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
ICBA	International Carbon Black Association
ICE	Internal combustion engine
ICR	Information Collection Request
IEA	International Energy Agency
IFO	Intermediate Fuel Oil
IGES	Institute of Global Environmental Strategies
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
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
M&R	Metering and regulating
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
MDP	Management and design practices
MECS	EIA Manufacturer's Energy Consumption Survey
MEMS	Micro-electromechanical systems
MER	Monthly Energy Review
MGO	Marine gas oil

MgO	Magnesium oxide
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 applicable; 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
NAS	National Academies of Sciences, Engineering, and Medicine
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
ND	No data
NE	Not estimated
NEH	National Engineering Handbook
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
NFI	National forest 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
NMOG	Non-methane organic gas

NO	Nitric oxide
NO	Not occurring
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
NOAA	National Oceanic and Atmospheric Administration
NOF	Not on feed
NPDES	National Pollutant Discharge Elimination System
NPP	Net primary productivity
NPRA	National Petroleum and Refiners Association
NRBP	Northeast Regional Biomass Program
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NREL	National Renewable Energy Laboratory
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
OGOR	Oil and Gas Operations Reports
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
OVS	Offset verification statement
PADUS	Protected Areas Database of the United States
PAH	Polycyclic aromatic hydrocarbons
PCA	Portland Cement Association
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
PHEV	Plug-in hybrid vehicles
PHMSA	Pipeline and Hazardous Materials Safety Administration
PI	Productivity index
PLS	Pregnant liquor solution
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
PRCI	Pipeline Research Council International
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
RFA	Renewable Fuels Association
RFS	Renewable Fuel Standard
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
SAIC	Science Applications International Corporation
SAN	Styrene Acrylonitrile
SAR	IPCC Second Assessment Report
SCR	Selective catalytic reduction
SCSE	South central and southeastern coastal
SDR	Steel dust recycling
SEC	Securities and Exchange Commission
SEMI	Semiconductor Equipment and Materials Industry
SF_6	Sulfur hexafluoride
SIA	Semiconductor Industry Association
SiC	Silicon carbide
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
SWICS	Solid Waste Industry for Climate Solutions
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
TOW	Total organics in wastewater
TPO	Timber Product Output
TRI	Toxic Release Inventory

TSDF	Hazardous waste treatment, storage, and disposal facility
TTB	Tax and Trade Bureau
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
USITC	U.S. International Trade Commission
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
WBJ	Waste Business Journal
WEF	Water Environment Federation
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
WRRF	Water resource recovery facilities
WTE	Waste-to-energy
WW	Wastewater
WWTP	Wastewater treatment plant
ZEVs	Zero emissions vehicles

6.7. Chemical Formulas

Table A-251: 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_4F_6	Hexafluoro-1,3-butadiene

$c\text{-}C_4F_8$	Perfluorocyclobutane
C_4F_{10}	Perfluorobutane
$c\text{-}C_5F_8$	Perfluorocyclopentene
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
CH_2CFCF_3	HFO-1234yf
$CHFCHCF_3$	HFO-1234ze(E)
$CF_3CHCHCF_3$	HFO-1336mzz(Z)
$C_3H_2ClF_3$	HCFO-1233zd(E)
$CHF_2OCF_2OC_2F_4OCHF_2$	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
GaAs	Gallium arsenide
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

NO_x	Nitrogen oxides
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.

References

EIA (2020) *Monthly Energy Review*, *November 2020*. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2019/11). November 2020.

EIA (2007) *Emissions of Greenhouse Gases in the United States 2006, Draft Report.* Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE-EIA-0573 (2006).

EPA (2003) E-mail correspondence. Air pollutant data. Office of Air Pollution to the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency (EPA). December 22, 2003.

EIA (1993) *State Energy Data Report 1992*, DOE/EIA-0214(93), Energy Information Administration, U.S. Department of Energy. Washington, DC. December.

EPA (2020) "1970-2019 Average annual emissions, all criteria pollutants in MS Excel." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards. Last Modified April 2020. Available online at: <https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data>.

EPA (2003) E-mail correspondence. Air pollutant data. Office of Air Pollution to the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency (EPA). December 22, 2003.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (1996) Climate Change 1995: The Science of Climate Change. Intergovernmental Panel on Climate Change, J.T.Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.). Cambridge University Press. Cambridge, United Kingdom.

ANNEX 7 Uncertainty – TO BE UPDATED FOR FINAL REPORT

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. An Addendum to Annex 7 is provided separately which includes additional information related to the characteristics of input variables used in the development of the uncertainty estimates reported in the Inventory.

7.1. Overview – TO BE UPDATED FOR FINAL REPORT

The primary purpose of the uncertainty analysis conducted in support of the U.S. Inventory is (1) 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 (2) to evaluate the relative importance of the input parameters in contributing to uncertainty in the associated source or sink 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 or sink 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 or sink category's discussion in the main body of the report.

For some of the current estimates, such as CO_2 emissions from energy-related combustion activities, the impact of uncertainties on overall emission estimates is believed to be relatively small. For some other limited categories of emissions, uncertainties could have a larger impact on the estimates presented (i.e., storage factors of non-energy uses of fossil fuels). As noted, for all source categories, the inventory emission estimates include "Uncertainty and Time-Series Consistency" sections that consider both quantitative and qualitative assessments of uncertainty, considering factors consistent with good practices noted in Volume 1, Chapter 3 of the *2006 IPCC Guidelines* (e.g., completeness of data, representativeness of data and models, sampling errors, measurement errors). 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 or sink 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 included in the U.S. Inventory totals, with the exception of a few very small emission source categories (i.e., CH_4 emissions from Incineration of Waste, and certain F-GHGs, photovoltaics (PV), micro-electro-mechanical systems (MEMS) devices, and Heat Transfer Fluids (HTFs) from the Electronics Industry). Given the very low emissions for these source categories, uncertainty estimates were not derived.

Uncertainty associated with three other source categories (International Bunker Fuels, Energy Sources of Indirect Greenhouse Gas Emissions, and CO_2 emissions from Wood Biomass and Biofuel Consumption) whose emissions are not included in the Inventory totals is discussed qualitatively in their respective sections in the main body of the report.

7.2. Methodology and Results – TO BE UPDATED FOR FINAL REPORT

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 2019 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, Wood Biomass and Biofuel Consumption, and Indirect Greenhouse Gas Emissions are not included in the total emissions estimated for the U.S. Inventory; therefore, no quantitative uncertainty estimates have been developed for these source categories.[161] CO_2 Emissions from Biomass and Biofuel 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 Biofuel 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 or sink category values. Inherent in employing the Approach 1 method are the assumptions that, for each source and sink 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 or sink 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

[161] However, because the input variables that determine the emissions from the Fossil Fuel Combustion and the International Bunker Fuels source categories are correlated, uncertainty associated with the activity variables in the International Bunker Fuels was taken into account in estimating the uncertainty associated with the Fossil Fuel Combustion.

source or sink 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 or sink 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 and Sink Category Inventory Uncertainty Estimates

Discussion surrounding the input parameters and sources of uncertainty for each source and sink category appears in the body of this report. Table A-252 summarizes results based on assessments of source and sink category-level uncertainty. The table presents base year (1990 or 1995) and current year (2019) emissions for each source and sink category. The combined uncertainty (at the 95 percent confidence interval) for each source and category is expressed as the percentage deviation above and below the total 2019 emissions estimated for that source and category. Source or sink category trend uncertainty is described subsequently in this Appendix.

Table A-252: Summary Results of Source and Sink Category Uncertainty Analyses – TO BE UPDATED FOR FINAL INVENTORY REPORT

Source or Sink Category	Base Year Emissions[a]	2018 Emissions[b]	2018 Uncertainty[b]	
	MMT CO_2 Eq.	MMT CO_2 Eq.	Low	High
CO_2	**5,128.3**	**5,424.9**	**-2%**	**4%**
Fossil Fuel Combustion	4,740.0	5,031.8	-2%	4%
Non-Energy Use of Fuels	119.5	134.6	-28%	40%
Iron and Steel Production & Metallurgical Coke	104.7	42.6	-17%	18%
Cement Production	33.5	40.3	-6%	6%
Petroleum Systems	9.6	36.8	-31%	34%
Natural Gas Systems	32.2	35.0	-15%	14%
Petrochemical Production	21.6	29.4	-6%	6%
Ammonia Production	13.0	13.5	-4%	5%
Lime Production	11.7	13.2	-2%	2%
Incineration of Waste	8.0	11.1	-26%	29%
Other Process Uses of Carbonates	6.3	10.0	-11%	14%
Urea Fertilization	2.0	4.6	-35%	16%
Carbon Dioxide Consumption	1.5	4.5	-5%	5%
Urea Consumption for Non-Agricultural Purposes	3.8	3.6	-16%	16%
Liming	4.7	3.1	-111%	88%
Ferroalloy Production	2.2	2.1	-12%	12%
Soda Ash Production	1.4	1.7	-9%	8%
Titanium Dioxide Production	1.2	1.5	-12%	13%
Aluminum Production	6.8	1.5	-2%	2%
Glass Production	1.5	1.3	-4%	5%
Zinc Production	0.6	1.0	-16%	16%
Phosphoric Acid Production	1.5	0.9	-18%	20%
Lead Production	0.5	0.5	-15%	15%
Carbide Production and Consumption	0.4	0.2	-10%	9%
Abandoned Oil and Gas Wells	+	+	-83%	219%
Magnesium Production and Processing	+	+	-3%	3%
Wood Biomass, Ethanol, and Biodiesel Consumption[c]	*219.4*	*328.9*	*NE*	*NE*
International Bunker Fuels[d]	*103.5*	*122.1*	*NE*	*NE*
CH_4	**774.4**	**634.5**	**-5%**	**14%**
Enteric Fermentation	164.2	177.6	-11%	18%
Natural Gas Systems	183.3	140.0	-15%	14%

Landfills	179.6	110.6	-23%	22%
Manure Management	37.1	61.7	-18%	20%
Coal Mining	96.5	52.7	-17%	12%
Petroleum Systems	46.1	36.2	-31%	34%
Wastewater Treatment	15.3	14.2	-28%	23%
Rice Cultivation	16.0	13.3	-31%	62%
Stationary Combustion	8.6	8.6	-35%	130%
Abandoned Oil and Gas Wells	6.6	7.0	-83%	219%
Abandoned Underground Coal Mines	7.2	6.2	-20%	15%
Mobile Combustion	12.9	3.1	-8%	26%
Composting	0.4	2.5	-50%	50%
Field Burning of Agricultural Residues	0.3	0.4	-16%	16%
Petrochemical Production	0.2	0.3	-57%	46%
Ferroalloy Production	+	+	-12%	12%
Carbide Production and Consumption	+	+	-9%	9%
Iron and Steel Production & Metallurgical Coke	+	+	-20%	20%
Incineration of Waste	+	+	NE	NE
International Bunker Fuels[d]	*0.2*	*0.1*	*NE*	*NE*
N_2O	**434.6**	**434.5**	**-23%**	**27%**
Agricultural Soil Management	315.9	338.2	-35%	-1%
Stationary Combustion	25.1	28.4	-27%	51%
Manure Management	14.0	19.4	-16%	24%
Mobile Combustion	42.0	15.2	-8%	14%
Adipic Acid Production	15.2	10.3	-5%	5%
Nitric Acid Production	12.1	9.3	-5%	5%
Wastewater Treatment	3.4	5.0	-74%	109%
N_2O from Product Uses	4.2	4.2	-24%	24%
Composting	0.3	2.2	-50%	50%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	1.4	-32%	32%
Incineration of Waste	0.5	0.3	-51%	328%
Electronics Industry	+	0.3	+%	+%
Field Burning of Agricultural Residues	0.2	0.2	-19%	13%
Petroleum Systems	+	0.1	-31%	34%
Natural Gas Systems	+	+	-15%	14%
International Bunker Fuels[d]	*0.9*	*1.1*	*NE*	*NE*
HFCs, PFCs, SF_6 and NF_3	**131.6**	**182.7**	**1%**	**10%**
Substitution of Ozone Depleting Substances	32.2	167.9	-1%	10%
Electronics Industry[e]	3.6	4.8	-6%	6%
Electrical Transmission and Distribution	23.2	4.1	-13%	15%
HCFC-22 Production	46.1	3.3	-7%	10%
Aluminum Production	21.5	1.6	-7%	7%
Magnesium Production and Processing	5.2	1.2	-7%	7%
Total Emissions[f]	**6,437.0**	**6,676.6**	**-2%**	**5%**
LULUCF Emissions[g]	7.4	26.1	-14%	25%
LULUCF Carbon Stock Change[h]	(860.7)	(799.6)	33%	-25%
LULUCF Sector Net Total[i]	**(853.4)**	**(773.5)**	**34%**	**-26%**
Net Emissions (Sources and Sinks)[f]	**5,583.6**	**5,903.1**	**-4%**	**6%**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF.

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.5 percent.

NE (Not Estimated)

[a] Base Year is 1990 for all sources except Substitution of Ozone Depleting Substances, for which the United States has chosen 1995.

[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] Emissions from Wood Biomass and Biofuel Consumption are not included in summing energy sector totals.

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

[e] This source category's estimate for 2018 excludes 0.033 MMT CO_2 Eq. of HTF emissions, as uncertainties associated with those sources were 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.

[f] Totals exclude emissions for which uncertainty was not quantified.

[g] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.
[h] LULUCF Carbon Stock Change 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*.
[i] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Overall (Aggregate) Inventory Level Uncertainty Estimates

The overall level uncertainty estimate for the U.S. Inventory was developed using the IPCC Approach 2 uncertainty estimation methodology for 1990 and 2019. 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 or sink 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 sources or sink category emission estimates based on the most detailed data available from the quantitative uncertainty analysis performed.

Approach 1 uncertainty results were used in the overall uncertainty analysis estimation for Composting, several LULUCF source categories, and parts of Agricultural Soil Management source categories. However, for all other emission sources (excluding international bunker fuels, CO_2 from biomass and biofuel combustion, CH_4 from incineration of waste, and certain F-GHGs, photovoltaics (PV), micro-electro-mechanical systems (MEMS) devices, and Heat Transfer Fluids (HTFs) from the Electronics Industry)), Approach 2 uncertainty results were used in the overall uncertainty estimation.

The overall uncertainty model results indicate that the 1990 U.S. greenhouse gas emissions are estimated to be within the range of approximately 6,334.2 to 6,743.5 MMT CO_2 Eq., reflecting a relative 95 percent confidence interval uncertainty range of -2 percent to 4 percent with respect to the total U.S. greenhouse gas emission estimate of approximately 6,468.9 MMT CO_2 Eq. The uncertainty interval associated with total CO_2 emissions, ranges from -2 percent to 4 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 -7 percent to 12 percent, uncertainty associated with the total inventory N_2O emission estimate ranges from -21 percent to 26 percent, and uncertainty associated with fluorinated greenhouse gas (F-GHG) emissions ranges from -4 percent to 7 percent. When the *LULUCF* sector is included in the analysis, the uncertainty is estimated to be -6 to +8 percent of Net Emissions (sources and sinks) in 1990.

Table A-253: Quantitative Uncertainty Assessment of Overall National Inventory Emissions for 1990 (MMT CO_2 Eq. and Percent) – TO BE UPDATED FOR FINAL INVENTORY REPORT

Gas	1990 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)		Mean[b] (MMT CO_2 Eq.)	Standard Deviation[b] (MMT CO_2 Eq.)
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO_2	5,128.3	5,017.9	5,339.6	-2%	4%	5,178.4	82.9
CH_4[d]	774.4	720.6	868.7	-7%	12%	793.2	37.6
N_2O[d]	434.6	344.3	549.3	-21%	26%	431.7	51.9
PFCs, HFCs, SF_6, and NF_3[d]	131.6	126.6	140.6	-4%	7%	133.4	3.6
Total Emissions	**6,468.9**	**6,334.2**	**6,743.5**	**-2%**	**4%**	**6,536.7**	**106.0**
LULUCF Emissions[e]	7.4	5.8	8.8	-22%	19%	7.2	0.8
LULUCF Carbon Stock Change Flux[f]	(860.7)	(1,178.4)	(527.7)	37%	-39%	(853.8)	164.4
LULUCF Sector Net Total[g]	**(853.4)**	**(1,171.5)**	**(520.7)**	**37%**	**-39%**	**(846.6)**	**164.4**
Net Emissions (Sources and Sinks)	**5,615.6**	**5,305.2**	**6,075.2**	**-6%**	**8%**	**5,690.1**	**197.0**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF.
+ Does not exceed 0.5 percent.
[a] 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.
[b] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.
[c] The 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.
[d] 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 1990. The base year for uncertainty is 1995 for Substitution of Ozone Depleting Substances.
[e] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.
[f] LULUCF Carbon Stock Change 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*.
[g] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

The overall uncertainty model results indicate that the 2018 U.S. greenhouse gas emissions are estimated to be within the range of approximately 6,550.7 to 6,985.0 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 6,676.6 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 2018, ranges from -2 percent to 4 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 -5 percent to 14 percent, uncertainty associated with the total inventory N_2O emission estimate ranges from -23 percent to 27 percent, and uncertainty associated with fluorinated greenhouse gas (F-GHG) emissions ranges from -1 percent to 10 percent. When the *LULUCF* sector is included in the analysis, the uncertainty is estimated to be -4 to +6 percent of Net Emissions (sources and sinks) in 2018.

A summary of the overall quantitative uncertainty estimates is shown below.

Table A-254: Quantitative Uncertainty Assessment of Overall National Inventory Emissions for 2018 (MMT CO_2 Eq. and Percent)

Gas	2018 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)		Mean[b] (MMT CO_2 Eq.)	Standard Deviation[b] (MMT CO_2 Eq.)
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO_2	5,424.9	5,303.2	5,661.3	-2%	4%	5,479.0	90.1
CH_4[d]	634.5	603.2	723.8	-5%	14%	662.1	30.9
N_2O[d]	434.5	335.0	552.1	-23%	27%	429.1	54.8
PFC, HFC, SF_6, and NF_3[d]	182.7	181.2	200.7	-1%	10%	190.7	5.1
Total Emissions	**6,676.6**	**6,550.7**	**6,985.0**	**-2%**	**5%**	**6,760.9**	**110.4**
LULUCF Emissions[e]	26.1	22.3	32.8	-14%	25%	27.5	2.7
LULUCF Carbon Stock Change Flux[f]	(799.6)	(1,061.7)	(597.1)	33%	-25%	(829.6)	118.3
LULUCF Sector Net Total[g]	**(773.5)**	**(1,034.5)**	**(569.3)**	**34%**	**-26%**	**(802.1)**	**118.3**
Net Emissions (Sources and Sinks)	**5,903.1**	**5,642.0**	**6,284.3**	**-4%**	**6%**	**5,958.8**	**163.1**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF.
+ Does not exceed 0.5 percent.

[a] 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.
[b] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.
[c] The 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.
[d] 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 2018.
[e] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.
[f] LULUCF Carbon Stock Change 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*.
[g] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

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., 2019) 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 and sink category is estimated using the sensitivity of the calculated difference between the base year and the current year (i.e., 2019) emissions to an incremental (i.e., 1 percent) increase in one or both of these values for that source and sink 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 or sink category emissions are assumed to exhibit the same uncertainty characteristics as the current year emissions (or removals). Source and sink category-specific PDFs for base year estimates were developed using current year (i.e., 2019) uncertainty output data. These were adjusted to account for differences in magnitude between the two years' inventory estimates. Then, for each source and sink category, a trend uncertainty estimate was developed using the Monte Carlo method. The overall inventory trend uncertainty estimate was developed by combining all source and sink category-specific trend uncertainty estimates. These trend uncertainty estimates present the range of likely change from base year to 2019 and are shown in Table A-255.

Table A-255: Quantitative Assessment of Trend Uncertainty (MMT CO_2 Eq. and Percent) – TO BE UPDATED FOR FINAL INVENTORY REPORT

Gas/Source	Base Year Emissions[a]	2018 Emissions	Emissions Trend	Trend Range[b]	
	(MMT CO_2 Eq.)		(%)	(%)	
				Lower Bound	Upper Bound
CO_2	**5,128.3**	**5,424.9**	**6%**	**1%**	**11%**
Fossil Fuel Combustion	4,740.0	5,031.8	6%	1%	11%
Non-Energy Use of Fuels	119.5	134.6	13%	-34%	89%

Iron and Steel Production & Metallurgical Coke Production	104.7	42.6	-59%	-69%	-48%
Cement Production	33.5	40.3	20%	10%	32%
Petroleum Systems	9.6	36.8	282%	82%	694%
Natural Gas Systems	32.2	35.0	9%	-21%	51%
Petrochemical Production	21.6	29.4	36%	26%	47%
Ammonia Production	13.0	13.5	4%	-2%	10%
Lime Production	11.7	13.2	13%	10%	16%
Incineration of Waste	8.0	11.1	40%	-7%	109%
Other Process Uses of Carbonates	6.3	10.0	58%	33%	87%
Urea Fertilization	2.0	4.6	129%	24%	322%
Carbon Dioxide Consumption	1.5	4.5	204%	183%	226%
Urea Consumption for Non-Agricultural Purposes	3.8	3.6	-4%	-24%	20%
Liming	4.7	3.1	-33%	-856%	633%
Ferroalloy Production	2.2	2.1	-4%	-19%	14%
Soda Ash Production	1.4	1.7	20%	6%	35%
Titanium Dioxide Production	1.2	1.5	29%	8%	55%
Aluminum Production	6.8	1.5	-79%	-79%	-78%
Glass Production	1.5	1.3	-18%	-23%	-12%
Zinc Production	0.6	1.0	60%	26%	101%
Phosphoric Acid Production	1.5	0.9	-39%	-53%	-19%
Lead Production	0.5	0.5	-1%	-20%	24%
Carbide Production and Consumption	0.4	0.2	-50%	-56%	-42%
Abandoned Oil and Gas Wells	+	+	13%	-1438%	1635%
Magnesium Production and Processing	+	+	5%	+%	10%
Wood Biomass and Biofuel Consumption[c]	*219.4*	*328.9*	*50%*	*NE*	*NE*
International Bunker Fuelc[d]	*103.5*	*122.1*	*18%*	*NE*	*NE*
CH_4	**774.4**	**634.5**	**-18%**	**-28%**	**-6%**
Enteric Fermentation	164.2	177.6	8%	-20%	47%
Natural Gas Systems	183.3	140.0	-24%	-39%	-4%
Landfills	179.6	110.6	-38%	-56%	-14%
Manure Management	37.1	61.7	66%	6%	158%
Coal Mining	96.5	52.7	-45%	-60%	-26%
Petroleum Systems	46.1	36.2	-21%	-63%	64%
Wastewater Treatment	15.3	14.2	-7%	-36%	34%
Rice Cultivation	16.0	13.3	-17%	-71%	140%
Stationary Combustion	8.6	8.6	+%	-62%	170%
Abandoned Oil and Gas Wells	6.6	7.0	7%	-87%	774%
Abandoned Underground Coal Mines	7.2	6.2	-14%	-43%	30%
Mobile Combustion	12.9	3.1	-76%	-80%	-70%
Composting	0.4	2.5	545%	174%	1384%
Field Burning of Agricultural Residues	0.3	0.4	16%	-19%	66%
Petrochemical Production	0.2	0.3	38%	-44%	243%
Ferroalloy Production	+	+	-15%	-28%	1%
Carbide Production and Consumption	+	+	-67%	-71%	-62%
Iron and Steel Production & Metallurgical Coke Production	+	+	-63%	-72%	-51%
Incineration of Waste	+	+	-32%	NE	NE
International Bunker Fuels[d]	*0.2*	*0.1*	*-37%*	*NE*	*NE*
N_2O	**434.6**	**434.5**	**+%**	**-29%**	**39%**
Agricultural Soil Management	315.9	338.2	7%	-33%	66%
Stationary Combustion	25.1	28.4	13%	-35%	99%
Manure Management	14.0	19.4	39%	-9%	113%
Mobile Combustion	42.0	15.2	-64%	-69%	-58%
Adipic Acid Production	15.2	10.3	-32%	-36%	-27%
Nitric Acid Production	12.1	9.3	-23%	-28%	-17%
Wastewater Treatment	3.4	5.0	48%	-69%	563%
N_2O from Product Uses	4.2	4.2	+%	-30%	41%

Composting	0.3	2.2	545%	196%	1335%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	1.4	-15%	-48%	37%
Incineration of Waste	0.5	0.3	-32%	-86%	223%
Electronics Industry	+	0.3	613%	611%	615%
Field Burning of Agricultural Residues	0.2	0.2	15%	-19%	64%
Petroleum Systems	+	0.1	323%	162%	573%
Natural Gas Systems	+	+	116%	75%	167%
International Bunker Fuels[d]	*0.9*	*1.1*	*27%*	*NE*	*NE*
HFCs, PFCs, SF_6, and NF_3	**131.6**	**182.7**	**39%**	**33%**	**54%**
Substitution of Ozone Depleting Substances	32.2	167.9	422%	382%	465%
Electronics Industry	3.6	4.8	33%	23%	45%
Electrical Transmission and Distribution	23.2	4.1	-82%	-85%	-79%
HCFC-22 Production	46.1	3.3	-93%	-94%	-91%
Aluminum Production	21.5	1.6	-93%	-93%	-92%
Magnesium Production and Processing	5.2	1.2	-77%	-81%	-76%
Total Emissions[f]	**6,468.9**	**6,676.6**	**3%**	**-1%**	**8%**
LULUCF Emissions[g]	7.4	26.1	254%	185%	367%
LULUCF Carbon Stock Change[h]	(860.7)	(799.6)	-7%	-48%	65%
LULUCF Sector Net Total[i]	**(853.4)**	**(773.5)**	**-9%**	**-50%**	**63%**
Net Emissions (Sources and Sinks)[f]	**5,615.6**	**5,903.1**	**5%**	**-4%**	**15%**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF.
+ Does not exceed 0.05 MMT CO_2 Eq. or 0.5 percent.
NE (Not Estimated)
[a] Base Year is 1990 for all sources except Substitution of Ozone Depleting Substances, for which the United States has chosen 1995.
[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] Emissions from Wood Biomass and Biofuel Consumption are not included specifically in summing energy sector totals.
[d] Emissions from International Bunker Fuels are not included in the totals.
[e] This source category's estimate for 2018 excludes 0.033 MMT CO_2 Eq. of HTF emissions, as uncertainties associated with those sources were 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.
[f] Totals exclude emissions for which uncertainty was not quantified.
[g] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.
[h] LULUCF Carbon Stock Change 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*.
[i] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

7.3. Reducing Uncertainty – TO BE UPDATED FOR FINAL REPORT

There have been many improvements in reducing uncertainties across source and sink categories over the last several years. These improvements are result of new data sources that provide more accurate data or more coverage, as well as methodological improvements. Several source categories now use the U.S. EPA's GHGRP reported data, which is an improvement over prior methods using default emission factors and provides more country-specific data for Inventory calculations. EPA's GHGRP relies on facility-level data which undergoes a multi-step verification process, including automated data checks to ensure consistency, comparison against expected ranges for similar facilities and industries, and statistical analysis.

For example, the use of EPA's GHGRP reported data to estimate CH_4 emissions from Coal Mining resulted in the uncertainty bounds of -17 to 12 percent in the 1990 to 2018 Inventory, which was an improvement over the uncertainty bounds in the 1990 to 2011 Inventory of -15 to 18 percent. Prior to 2012, Coal Mining emissions were estimated using an array of emission factor estimations with higher assumed uncertainty. Estimates of CH_4 emissions from MSW landfills were also revised with the availability of GHGRP reported data resulting in methodological and data quality

improvements that reduced uncertainty. Previously, MSW landfill emissions estimates were calculated using a model and default factors with higher assumed uncertainty.

Due to the availability of GHGRP reported data, Electronics Industry emissions methodology as well as the uncertainty model was revised for the 1990 to 2012 Inventory. The revised model to estimate uncertainty relies on analysis conducted during the development of the EPA's GHGRP Subpart I rulemaking to estimate uncertainty associated with facility-reported emissions. These results were applied to the GHGRP-reported data as well as to the non-reported emissions. An improved methodology to estimate non-reported emissions along with improved methodology to estimate uncertainty of these non-reported emissions led to a reduced overall uncertainty of -6 to 6 percent in the 1990 to 2018 Inventory compared against a range of -8 to 9 percent in the 1990 to 2011 Inventory for the emissions of F-GHGs from the Semiconductor Manufacturing source category.

7.4. Planned Improvements – TO BE UPDATED FOR FINAL REPORT

Identifying the sources of uncertainty in the emission and removal 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 or sink 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, CO_2 from Wood Biomass and Biofuel Consumption, and Indirect Greenhouse Gas Emissions source categories, which are not included in the energy sector totals. CO_2 Emissions from Wood Biofuel 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 include an estimate of CO_2 emissions from Wood Biomass and Biofuel Consumption in total emissions estimates, but rather it is provided as a memo item for informational purposes.

Specific areas that require further research to reduce uncertainties and improve the quality of uncertainty estimates include:

- *Improving conceptualization*. Improving the inclusiveness of the structural assumptions chosen can reduce uncertainties. An example is better treatment of seasonality effects that leads to more accurate annual estimates of emissions or removals for the Agriculture, Forestry and Other Land Use (AFOLU) Sector.
- *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, consistent with IPCC good practice principles, efforts will focus on estimating emissions and sinks from excluded emission and removal sources occurring in U.S. and developing uncertainty estimates for all source and sink categories for which emissions and removals 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 manure management are uncertain, and research is underway to improve these emission factors per planned improvements noted in Section 5.2 on Manure Management.
- *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.
- *Improving models.* Improving model structure and parameterization can lead to better understanding and characterization of the systematic and random errors, as well as reductions in these causes of uncertainty.
- *Collecting more measured data and using more precise measurement methods.* Uncertainty associated with bias and random sampling error can be reducing by increasing the sample size and filling in data gaps.

Measurement error can be reduced by using more precise measurement methods, avoiding simplifying assumption, and ensuring that measurement technologies are appropriately used and calibrated.

- *Refine source and sink 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. For example, activity data provided by EPA's GHGRP are used to develop estimates for several source categories—including but not limited to Magnesium Production and Processing, Semiconductor Manufacturing, and Electrical Transmission and Distribution. Additionally, GHGRP data could potentially be implemented for other source categories to improve uncertainty results, where appropriate.
- *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, especially for earlier parts of the time series.
- *Improving state of knowledge and eliminating known risk of bias.* Use expert judgment to improve the understanding of categories and processes leading to emissions and removals. Ensure methodologies, models, and estimation procedures are used appropriately and consistent with *2006 IPCC Guidelines*.

7.5. Summary Information on Uncertainty Analyses by Source and Sink Category – TO BE UPDATED FOR FINAL REPORT

The quantitative uncertainty estimates associated with each emission and removal category are reported within sectoral chapters of this Inventory following the discussions of inventory estimates and their estimation methodology. To better understand the uncertainty analysis details, refer to the respective chapters and Uncertainty and Time-series Consistency sections in the body of this report, as needed. EPA provides additional documentation on uncertainty information consistent with the guidance presented in Table 3.3 in Vol. 1, Chapter 3 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) in an Uncertainty Addendum. Due to the number of detailed tables it is not published with the Inventory but is available upon request. All uncertainty estimates are reported relative to the current Inventory estimates for the 95 percent confidence interval, unless otherwise specified.

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 U.S. Greenhouse Gas 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-21. 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 QA good practice and the *2006 IPCC Guidelines* (IPCC 2006).
- *Quality Control*: application of *General (Tier 1) and Category-specific (Tier 2)* quality controls and checks, as recommended by *2006 IPCC Guidelines* (IPCC 2006), along with consideration of secondary data and category-specific checks (additional 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.
- *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, focusing on key categories.
- *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 and sink-specific QA/QC plans have been developed for a number of sources and sinks. 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, minimum general QA/QC analysis consistent with Vol. 1, Chapter 6 of the *2006 IPCC Guidelines* has been undertaken. Where QA/QC activities for a particular source go beyond the general level, and include 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 or sink category text. For transparency, responses to public and expert review comments are also posted on the EPA website with the final report.

Figure A-21: U.S. QA/QC Plan Summary

	Data Gathering	Data Documentation	Calculating Emissions	Cross-Cutting Coordination

Inventory Analyst	• Obtain data in electronic format (if possible)
	• Review spreadsheet construction
	  ○ Avoid hardwiring
	  ○ Use data validation
	  ○ Protect cells
	• Develop automatic checkers for:
	  ○ Outliers, negative values, or missing data
	  ○ Variable types match values
	  ○ Time series consistency
	• Maintain tracking tab for status of gathering efforts
		• Contact reports for non-electronic communications
		• Provide cell references for primary data elements
		• Obtain copies of all data sources
		• List and location of any working/external spreadsheets
		• Document assumptions
		• Complete QA/QC checklists
		• CRF and summary tab links
			• Clearly label parameters, units, and conversion factors
			• Review spreadsheet integrity
			  ○ Equations
			  ○ Units
			  ○ Inputs and outputs
			• Develop automated checkers for:
			  ○ Input ranges
			  ○ Calculations
			  ○ Emission aggregation
			  ○ Trend and IEF checks
				• Common starting versions for each inventory year
				• Utilize unalterable summary and CRF tab for each source spreadsheet for linking to a master summary spreadsheet
				• Follow strict version control procedures
				• Document QA/QC procedures

QA/QC Analyst	• Check input data for transcription errors • Inspect automatic checkers • Identify spreadsheet modifications that could provide additional QA/QC checks	• Check citations in spreadsheet and text for accuracy and style • Check reference docket for new citations • Review documentation for any data / methodology changes • Complete QA/QC checklists • CRF and summary tab links	• Reproduce calculations • Review time series consistency • Review changes in data/consistency with IPCC methodology	

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* [162] and *A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information*. [163] 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-256 defines each factor and explains how it was considered during the process of creating the current Inventory.

Table A-256: 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 analyzes	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

[162] 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>.
[163] 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>.

	employed to generate the information are documented.	implement the *2006 IPCC Guidelines* approaches. Any changes made to calculations, due to updated data and methods, are explained and 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 most source and/or category emissions data to produce a 95 percent confidence interval for the annual greenhouse gas emissions for that source. The error propagation approach is used to quantify uncertainties for some categories that are not significant contributors to emissions across the time series. 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 category of emissions and sinks and have an extended opportunity to provide feedback on the methodologies used, calculations, data sources, and presentation of information.

8.4. Responses to Review Processes – TO BE UPDATED FOR FINAL REPORT

EPA is continually working to improve transparency, accuracy, completeness, comparability, and consistency of emission estimates in the Inventory in response to the feedback received during the Expert, Public, and UNFCCC Review periods, as well as stakeholder outreach. For instance, as mentioned in the Planned Improvements section of the Petroleum and Natural Gas Systems source categories (Section 3.6 and 3.7), EPA has engaged in stakeholder outreach to increase the transparency in the Inventory methodology and to identify supplemental data sources that can lead to methodological improvements. During the annual preparation of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, In considering and prioritizing improvements, EPA reviews the significance of the source and sink category (i.e., key categories), along with QC, QA, and uncertainty assessments. Identified planned improvements to methods (including data, emissions factors, and other key parameters), along with QA/QC and uncertainty assessments are documented within each source and sink category to complement the Recalculations and Improvements chapter. Additionally, the Executive Summary, also highlights key changes in methodologies from previous Inventory reports.

As noted in the previous section, for transparency, responses to comments received while developing the annual estimates from Public Review and Expert Review are posted on the EPA website with the final Inventory.[164]

As noted above in section 8.2 the expert technical review conducted by the UNFCCC supplements these QA processes. This review by an international expert review team (ERT) occurs after submission of the final report to the UNFCCC and assesses consistency with UNFCCC reporting guidelines. More information on the UNFCCC reporting guidelines and the review process can be found here:

- UNFCCC Reporting Guidelines for annual national greenhouse gas inventories[165]
- UNFCCC Review Process and Guidelines for annual national greenhouse gas inventories[166]
- Inventory Review reports of annual submissions (latest reviews).[167]

The draft review report with findings from the UNFCCC expert review of the April 2019 Inventory submission completed October 7-12, 2019 was only received by EPA on March 17, 2020. EPA was unable to provide accurate responses on how ERT recommendations have been reflected in this Inventory (i.e., to be submitted to UNFCCC in April 2020). Following receipt of the final review report from the UNFCCC ERT, this Annex was updated to include update of Table A-257 to summarize areas of improvement identified through UN review and the response column provides a status of the findings. The table includes responses to the latest recommendations to facilitate future reviews.

[164] See <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>.
[165] Available online at: <https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>.
[166] Available online at: <https://unfccc.int/resource/docs/2014/cop20/eng/10a03.pdf#page=3>.
[167]Available online at: <https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/inventory-review-reports-2016>.

Table A-257: Response to UN Review of the 2019 Inventory Submission

ID#	*Issue classification*	*Recommendation made in previous review report including ERT assessment and rationale*	*Response on status of issue*
General			
G.1	Completeness (G.1, 2018) (G.1, 2016) (G.1, 2015) (9, 2013) (8, 2012)	Improve the completeness of the inventory, in particular for those categories for which there are methodologies in the 2006 IPCC Guidelines. Addressing. The United States improved the completeness of the inventory. The Party still reports "NE" for a number of categories (see annex II for a list of the completeness issues identified by the ERT). The ERT noted that the Party's planned improvements include incorporating some of these categories into future submissions and/or providing additional information on the likely level of emissions and removals in annex 5 to the NIR (see also ID# G.2 below).	Still addressing. The United States reiterates that planned improvements include incorporating these categories into future submissions and/or providing additional information on the likely level of emissions and removals in annex 5 to the NIR. These improvements will be made over time as data becomes available and prioritized with other improvements to make best use of available resources.
G.2	Annual submission Completeness	The United States reported in the NIR (annex 5, table A-247, p.A-416) a summary of sources and sinks not included in the inventory. This table covers both sources and sinks for which methodologies are provided in the 2006 IPCC Guidelines and those without methodologies. The ERT commends the Party for the transparency provided by the table but notes that a numerical value was not provided in the "Estimated 2017 emissions" column for all sources and sinks that occur in the United States and for which there are methodologies in the 2006 IPCC Guidelines. During the review, the Party stated that, in some cases, approximated AD are currently unavailable to derive a likely level of emissions or removals. Further, the effort to develop a proxy estimate is better invested in developing estimates to include in the inventory itself as part of ongoing planned improvements. The ERT acknowledges the point made by the Party but notes that in accordance with paragraph 37(b) of the UNFCCC Annex I inventory reporting guidelines, Parties should provide justifications for exclusions in terms of the likely level of emissions for all mandatory sources and sinks considered insignificant and the total national aggregate of estimated emissions for all gases and categories considered insignificant shall remain below 0.1 per cent of national total GHG emissions. The ERT recommends that the United States provide a justification in the NIR, based on the likely level of emissions as per paragraph 37(b) of the UNFCCC Annex I inventory reporting guidelines, for all sources and sinks that occur but are considered insignificant and excluded from the inventory and for which there are methodologies provided in the 2006 IPCC	Still addressing. The Unites States reiterates that planned improvements include incorporating these categories into future submissions and/or providing additional information on the likely level of emissions and removals in annex 5 to the NIR. These improvements will be made over time as data becomes available and prioritized with other improvements to make best use of available resources. Annex 5 of the 2020 submission does include updates to both quantitative and qualitative assessments of significance for some categories.

		Guidelines. The ERT recommends that the Party provide in its next NIR evidence that the total national aggregate of estimated emissions for all mandatory gases and categories considered insignificant remains below 0.1 per cent of national total GHG emissions.	
G.4	Uncertainty Analysis. Convention reporting adherence	The ERT noted that the uncertainty analyses provided in table A-265 (NIR annex 7, p.A-451) show the results for the latest inventory year (2017) but do not show the results for the base year (1990). According to paragraph 15 of the UNFCCC Annex I inventory reporting guidelines, the quantitative uncertainty analysis should be reported for at least the base year and the latest inventory year. During the review, the Party clarified that it performed an uncertainty analysis for the base year (1990), but was unable to incorporate the results in the final version of section 1 of and annex 7 to the NIR because the issue was identified late, and the Party decided to postpone their inclusion until the following submission year. The ERT recommends that the United States include the results of the uncertainty analysis for 1990 in the relevant tables of section 1 and annex 7 in its next submission.	See pp. 1-25 of 2020 NIR submission.
Energy			
E.2	1. General (energy sector) – gaseous fuels – CO_2 and CH_4 (E.18, 2018) Convention reporting adherence	Addressing. Examine if the uncertainty analysis needs to be updated to reflect the findings of the research on the natural gas combustion and document the findings in future submissions. The United States examined but did not include an explanation in the NIR to clarify whether the uncertainty analysis for natural gas needs to be updated owing to the update in the CO_2 EF and CH_4 content (see ID# E.1 above). In NIR table 3-17 reported uncertainty continues to range between –3 and 7 per cent for residential, commercial, industrial and transportation, –3 to 5 per cent for electric power and –13 to 17 per cent for United States territories. During the review, the Party explained that the uncertainty associated with the updated EFs (as discussed in ID# E.1 above) did not have an impact on the overall uncertainty, as the general findings regarding the carbon content of fuels still apply, meaning that the amount of carbon contained in the fuel per unit of useful energy can vary. The United States documented in broad terms (NIR p.3-33) that the impact of these uncertainties on the overall CO2 emission estimates is considered to be minor. However, the information provided is not specific to the updates made to the natural gas CO2 EF.	This issue was addressed in the latest submission. See 2020 NIR Report Section 3.1 pp. 3-35. "For the United States, however, the impact of these uncertainties on overall CO2 emission estimates is believed to be relatively small. See, for example, Marland and Pippin (1990). See also Annex 2.2 for a discussion of uncertainties associated with fuel carbon contents. Even with recent updates to carbon factors for natural gas and coal, the uncertainty estimates are not impacted."

E.3	1. General (energy sector) – gaseous fuels – CO_2 and CH_4 (E.18, 2018) Transparency	Addressing..Research CO_2 EF data for fuel gas used by upstream oil and gas producers, and natural gas that has been processed and injected into downstream distribution networks, in order to determine whether a different CO_2 EF for fuel gas used in offshore oil and gas production than the CO_2 EF for the processed gas that enters the transmission, storage and distribution networks used in power and industrial plants and by other users is warranted and whether it can be determined; and document the findings of the research on the CO_2 EFs in the NIR. During the review, the Party noted that, as reported in the NIR (section 3, p.3-36 and annex 2.2), the annual natural gas carbon content was updated across the time series to reflect annual heat content data for natural gas obtained from EIA. The CO_2 EF was based on the heat content of natural gas. EIA also reports the heat content of natural gas produced as the same value as natural gas consumed, meaning that the same EF would be used in both upstream and downstream operations. However, the Party did not document the findings of this research on CO_2 EFs in the NIR.	This issue was addressed in the latest submission. See 2020 NIR Annex Section 2.2 pp. A-106. "Furthermore, as natural gas carbon content is based on the heating value of the gas, EIA also reports that the heat content of dry natural gas produced is the same value as natural gas consumed (EIA 2019). Therefore, the same carbon factor is used for all natural gas consumption including upstream operations."
E.4	Fuel combustion – reference approach – all fuels – CO_2 (E.3, 2018) (E.5, 2016) (E.5, 2015) (32, 2013) (41, 2012) Transparency	Addressing. Provide a more transparent clarification of how the difference in emissions between the reference and the sectoral approach is determined and which fuels are subtracted as NEU and feedstocks. The comparison between the reference approach and the sectoral approach is provided in annex 4 to the NIR. The energy data presented in the NIR (table A-244) for the reference approach fuel consumption of gaseous and petroleum fuels match the data presented in CRF table 1.A(c). The ERT noted, however, that values for the apparent energy consumption and apparent energy consumption excluding NEU are still the same in CRF table 1.A(c). During the review, the Party explained that the total amount of carbon stored in products produced from NEU of fossil fuels is subtracted from the emissions in both the sectoral and reference approaches (NIR table A-243). Emissions from carbon that was not stored during NEU of fuels are subtracted from the sectoral approach and reported under the NEU of fossil fuels source category (NIR section 3.2). These emissions, however, are not subtracted in the reference approach and are reported as their own line item in CRF table 1.A(b) (lubricants and petrochemical feedstocks). As a result, the reference approach emission estimates are comparable to those of the sectoral approach, with the exception that the NEU source category emissions are included in the reference approach. The ERT noted that this explanation was not provided in the NIR.	The United States refers the ERT to the 2020 NIR (annex 4, starting on pp. A-481) describing the different treatments of NEU under the reference and sectoral approaches. Further clarification is in the 2020 NIR chap. 3 (pp. 3-38) and additional language was added to the 2020 submission to address this issue, see annex 4 pp. A-482 under Step 3 of the Reference Approach description: "As a result, the Reference Approach emission estimates are comparable to those of the Sectoral Approach, with the exception that the NEU source category emissions are included in the Reference Approach and reported separately in the Sectoral Approach."

E.5	Feedstocks, reductants and other NEU of fuels – all fuels – CO_2 (E.4, 2018) (E.7, 2016) (E.7, 2015) (38, 2013) (47, 2012) Comparability	Not resolved. Report only emissions from fuels combusted for the use of energy under fuel combustion, and reallocate the relevant emissions currently reported under the subcategory NEU (other) and part of the fuel used under the subcategory United States territories (other). The Party explained during the review that it does not currently collect or hold data to be able to disaggregate overall NEU emissions into categories that can be reported under IPPU (such as emissions from calcium carbide, lubricants and paraffin waxes). The ERT acknowledges that reallocating the emissions to IPPU may not improve the overall accuracy of the Party's inventory, but it would improve the comparability against other reporting Parties. The ERT notes that if emissions cannot be reported under NEU owing to national circumstances, this should be clarified in the NIR.	The United States reiterates that it uses a country specific methodology for non-energy use of fuels in line with para. 10, Decision 24/CP.19 to most accurately portray U.S. emissions from NEU. The United States has improved the explanation of its country specific approach to the allocation of NEU of fuels in the introduction of the IPPU chapter 4 and Annex 2 of the NIR. The United States continues to evaluate ways to update this approach and provides more clarification as applicable in the current Inventory (i.e., 2020 submission).
E.6	Feedstocks, reductants and other NEU of fuels – CO_2 (E.19, 2018) Accuracy	Not resolved. Continue to research the data for the emissions from NEU of fuels reported under the energy and IPPU sectors mass-balance method used across petrochemical production to estimate CO_2 emissions from NEU of fuels and the method based on process emissions reported under facility-level reporting used to estimate emissions from feedstock consumption under IPPU, and further clarify the country-specific approach used in the NIR consistently with paragraph 10 of the UNFCCC Annex I inventory reporting guidelines. The Party continues to use a mass-balance method across petrochemical production to estimate CO_2 emissions from NEU of fuels, in conjunction with reporting separate emissions from feedstock consumption under IPPU, which may lead to double counting of emissions. See ID# E.5 above.	This issue was addressed in the latest submission. See 2020 NIR Report Section 4.13 pp. 4-64 for the following discussion: "Some degree of double counting may occur between CO_2 estimates of non-energy use of fuels in the energy sector and CO_2 process emissions from petrochemical production in this sector. This is not considered to be a significant issue since the non-energy use industrial release data includes different categories of sources than those included in this sector and the non-energy use estimates are roughly 20 percent of the emissions captured here. As noted previously in the methodology section, data integration is not feasible at this time as feedstock data from the EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries."
E.7	International aviation – liquid fuels – CO_2, CH_4 and N_2O (E.5, 2018) (E.6, 2016) (E.6, 2015) (35, 2013) Transparency	Not resolved. Harmonize and reconcile the data between the reference and the sectoral approach for the reporting of jet kerosene consumption between CRF tables 1.A(b) and 1.D or furnish an adequate explanation of inconsistencies, where appropriate. There are still inconsistencies in the reporting of jet kerosene consumption between CRF tables 1.A(b) (–1,158,833.17 TJ) and 1.D (1,163,988.07 TJ) for 2017. During the review, the Party explained that this is due to different data sources used for the values reported in the tables: its country-specific values for the consumption of fuels under the reference approach (CRF table 1.A(b)) come from EIA, which is responsible for gathering the official fuel production and consumption statistics for the country, and are the most appropriate AD for the energy	This issue was addressed in the latest submission. See 2020 NIR Annex 4, Footnote 6 to Table A-244 on pp. 4-487 for the following discussion: "Jet fuel used in bunkers has a different heating value based on data specific to that source. When physical values are converted based on a combined heating value across all sources of jet fuel (as shown in Table 1.A(b) of CRF) it will not necessarily match jet fuel bunker data (as shown in Table 1.D of CRF)."

		sector of the Party's inventory. The Party also clarified that the inventory relies on data on individual flights to determine the split between domestic and international fuel use in the sectoral approach and further explanation of the calculation used is included in the NIR (annex 3.3, p.A-189). According to the Party, the approach used could be leading to differences in the consumption of jet kerosene in international aviation (CRF table 1.D). The Party further clarified that the above information will be included in the next NIR.	
E.9	1.A Fuel combustion – sectoral approach – biomass – CH_4 and N_2O (E.20, 2018) Completeness	Not resolved. Advance the research on CH_4 and N_2O emissions from the combustion of landfill gas, sewage gas and other biogas in order to review data sources for biogas, review the reporting of non-CO_2 emissions in the waste sector and assess the need to add new estimates. The United States did not review the data sources for biogas to determine the completeness of non-CO_2 emissions reported in the waste sector. The planned improvements described in the NIR (p.3-109) continue to indicate that the Party intends to research data on biogas for future inclusion in the inventory.	The United States is investigating sources of data on biogas use and combustion for energy and confirming whether these emissions are not reported elsewhere. Updates will be implemented as needed and described in future submissions.
E.12	1.A.2.g Other (manufacturing industries and construction) – liquid fuels – CO_2, CH_4 and N_2O (E.22, 2018) Transparency	Addressing. Document the impacts of the new model and the validity of the outputs and transparently document the recalculations in the NIR when the latest version of the model (MOVES2014b) is incorporated in the inventory. The Party applied the MOVES2014b model in the 2019 submission. The NIR (section 3.1, p.3-43) describes the recalculations and the impact on CH4 and N2O emissions. <u>The Party made no reference to CO2 emissions</u> but the ERT noted that they increased across the time series following the recalculation. Documentation on the validity of the model was not included in the NIR.	The use of the MOVES model in the development of the Inventory is limited primarily to the estimation of CH4 and N2O emissions from non-transportation mobile sources. The model is also used to generate vehicle age distributions that are used to estimate CH4 and N2O emissions from Transportation sources. The model is not used to derive CO2 emissions from Transportation sources. The United States plans to incrementally improve the discussion of the validity of the MOVES model in future submissions.
E.13	1.A.2.g Other (manufacturing industries and construction) – liquid fuels – CO_2, CH_4 and N_2O (E.23, 2018) Comparability	Not resolved. Research whether data are available to accurately reallocate emissions from fuel use by agricultural mobile machinery from subcategory 1.A.2.g to 1.A.4.c.ii and fuel use for fishing vessels to 1.A.4.c.iii in order to improve the comparability of the submission and ensure that emissions of all gases from a given source are reported under the same IPCC category. If data are not available to accurately reallocate emissions to the different categories, clarify, in the NIR, the country-specific approach taken consistently with paragraph 10 of the UNFCCC Annex I inventory reporting guidelines. The NIR did not state that such data are not available or clarify the use of the country-specific approach. The Party stated during the review that it is researching and comparing various AD sources, in addition to updating the MOVES model inputs (see	The United States is researching and comparing various AD sources, in addition to updating the MOVES model inputs (see ID# E.12 above). This will include researching the availability of data for addressing the allocation of emissions from fuel use by agricultural mobile machinery from subcategory 1.A.2.g (other) to 1.A.4.c.ii (off-road vehicles and other machinery) and fuel use for fishing vessels to 1.A.4.c.iii (fishing).

		ID# E.12 above). This will include researching the availability of data for addressing the allocation of emissions from fuel use by agricultural mobile machinery from subcategory 1.A.2.g (other) to 1.A.4.c.ii (off-road vehicles and other machinery) and fuel use for fishing vessels to 1.A.4.c.iii (fishing).	
E.14	1.A.2.g Other (manufacturing industries and construction) – liquid fuels – CO_2, CH_4 and N_2O (E.24, 2018) Accuracy	Not resolved. Research data by non-road mobile machinery vehicle type across the different data sets, including the Federal Highway Administration and MOVES model outputs, to determine the optimum AD estimate for each subsource under non-road mobile machinery, and improve inventory accuracy, as necessary, including for CO_2, CH_4 and N_2O emissions from industrial, commercial, agricultural machinery and fishing vessels. The United States did not provide information on the optimum AD estimate for each subsource under non-road mobile machinery for improving the accuracy of the inventory. The Party continued to estimate emissions for this category using AD from different sources (NIR p.3-30).	See pp. 3-40 of the April 2020 NIR where it states "EPA also tested an alternative approach that uses MOVES on-road fuel consumption output to define the percentage of the FHWA consumption totals (from MF-21) that are attributable to on-highway transportation sources, and applying this percentage to the EIA total, thereby defining gasoline consumption from on-highway transportation sources (such that the remainder would be defined as consumption by the industrial and commercial sectors). Results from this testing revealed differences between fuel consumption calculated by MOVES and fuel consumption data from FHWA. Given this inconsistency, no changes have been made to the methodology for estimating motor gasoline consumption for non-road mobile sources." The United States. is researching and comparing various AD sources, in addition to planning to update the MOVES model inputs to address this issue (see also responses to AR ID#s E.12 and E.13 above). Updating the MOVES model inputs is a longer-term effort.
E.15	1.A.3 Transport – liquid fuels – CO_2, CH_4 and N_2O (E.25, 2018) Accuracy	Not resolved. Advance the research in order to implement as soon as practicable the following improvements indicated during the review: (a) Updating on-road diesel CH_4 and N_2O EFs; (b) Developing improved methodology and data sources to estimate emissions from class II and III (short-line and regional) rail locomotives; (c) Applying a consistent methodology over time to estimate vehicle miles travelled for on-road vehicles by vehicle type, defined by wheel base; Including ongoing research and documentation of minor emissions sources currently not included in the inventory, such as urea use in trucks, bio jet fuel, and compressed natural gas or liquefied petroleum gas use in shipping.	Items (a) and (b) were addressed in the 2020 submission (see the Recalculations section of Chapter 3 of NIR). Onroad diesel CH_4 and N_2O EFs were updated using manufacturer certification data compiled and made publicly available by EPA. This update underwent Expert Review during the 2020 compilation cycle. The methodology for estimating fuel consumption and emissions from Class II and II rail sources was updated to use surrogate carload data reported by RailInc. (2014 onwards).

			Additional improvements will be undertaken in stages over the 2021 and 2022 submissions, pending data availability.
E.16	1.A.3.b Road transportation – liquid fuels – CO_2 (E.26, 2018) Accuracy	Not resolved. Review and update the time series of diesel and gasoline CO_2 EFs, including, where necessary, the data on fuel densities and carbon share by fuel grade, and report on progress, or document in the NIR that the EFs applied are accurate and representative of emissions across the time series, and update the uncertainty analysis as needed to reflect the findings of the research. The United States did not recalculate CO_2 emissions from diesel and gasoline for the 2019 submission and continues to use constant EFs for gasoline (67.62 t CO_2/TJ) for 2008–2017 and for diesel (70.10 t CO_2/TJ) for the entire time series.	The update of the time series of diesel and gasoline is under way. EPA sought expert input during the 2020 compilation cycle which identified additional considerations that extended development of this update. The U.S. anticipates addressing the gasoline and diesel EF in the 2021 submission.
E.17	1.A.3.b Road transportation – liquid fuels – CO_2 (E.27, 2018) Completeness	Either present information in the NIR to justify the omission of any fossil carbon component in the CO_2 EF for biofuel use (e.g. fatty acid methyl ester use) or update the inventory estimates to account for emissions from the fossil carbon component of biofuels and explain the estimations in the NIR. The Party added a footnote in the NIR (p.3-21) clarifying that biofuel estimates are presented in the energy sector and that carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for LULUCF. However, this does not fully justify the omission of emissions from the combustion of the fossil fraction of the biodiesel. According to the 2006 IPCC Guidelines (vol. 2, chap. 3, p.3.17), biodiesel produced using methanol as a feedstock will contain fossil carbon if the methanol is produced from a fossil fuel (such as natural gas). In addition, the tier 1 method used for estimating emissions for the production of methanol (in CRF table 2(I).A-Hs1) does not account for the carbon stored in products (in this case, methanol that is later combusted in the transport sector). Moreover, the Party did not clarify whether imports of methanol are used in the production of biodiesel or whether there are imports of pre-blended liquid fuels. During the review, the Party clarified that the NIR (section 4.13, p.4-51) explains that, owing to national circumstances, natural gas for non-fuel purposes in the production of petrochemicals (such as methanol) is accounted for in the NEU calculations. While the NIR does not explicitly mention methanol as part of the NEU calculations for carbon storage from petrochemical feedstocks, it is implied that it is part of those calculations. The Party also explained that it has recently become a net exporter of methanol and that the import-export analysis conducted for NEU provides an adjustment for methanol imports and exports. The ERT considers that the Party should explain clearly in the NIR how the fossil fraction of the biodiesel in road transportation is estimated and allocated. The ERT believes that future ERTs should consider this issue further to ensure that emissions from	This issue was addressed in the latest submission. See the 2020 NIR Report, Chapter 3, footnote 97 on pp. 3-114. "CO_2 emissions from biodiesel do not include emissions associated with the C in the fuel that is from the methanol used in the process. Emissions from methanol use and combustion are assumed to be accounted for under Non-Energy Use of Fuels. See Annex 2.3 – Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels." See also the 2020 NIR Annex 2.3, footnote 26 on pp. A-134. "Natural gas used as a petrochemical feedstock includes use in production of methanol. The storage factor developed for petrochemical feedstocks includes emissions from the use of products. Therefore, it is assumed that emissions from the combustion of methanol used in biodiesel are captured here and not reported as part of biodiesel combustion emissions."

		this category are not underestimated.	
E.18	1.A.3.b Road transportation – liquid fuels – CH4 and N2O (E.28, 2018) Convention reporting adherence	Not resolved. Include descriptions of the MOVES model used to estimate CH_4 and N_2O emissions from road transportation and the 2016 GREET model used to generate EF inputs for alternative fuel vehicles, and information to verify that the models have been tested and calibrated to be representative of the United States fleet, fuels, driving conditions, road types and vehicle types. The Party did not include a description of the MOVES model in the NIR indicating the process used to evaluate and improve the model in order to ensure adherence to the UNFCCC Annex I inventory reporting guidelines for tier 3 model verification. The ERT noted that the time series of CH4 EFs for biofuel use in alternative fuel vehicles, derived from the 2016 GREET model, was updated and no longer shows a large increase beginning in 2011 (NIR annex 3.2, table A-113). During the review, the Party explained that it plans to improve the discussion incrementally in future submissions, including by adding more descriptive text to annex 3 (section 3.2) and providing cross-references to the annex throughout section 3 (energy) of the NIR.	The United States plans to incrementally improve the discussion of the validity of the MOVES model in future submissions.
E.21	1.A.5.b Mobile – solid and gaseous fuels, and biomass use – CO2, CH4 and N2O (E.31, 2018) Transparency	Not resolved. The Party reported CO_2, CH_4 and N_2O emissions from solid and gaseous fuel and biomass use in 1.A.5.b (other mobile (military)) as “NA”. During the review, the Party indicated that these activities do not occur. Report AD and emissions of activities not occurring as “NO” instead of “NA”. The Party explained during the review that this change will be made in the 2020 submission.	See CRF Table1.A(a)s4 in 2020 Inventory Submission, the CO2, CH4 and N2O emissions from solid and gaseous fuel and biomass use in 1.A.5.b (other mobile (military)) are reported as NO.

E.22	1.B.2 Oil, natural gas and other emissions from energy production – all fuels – CO_2, CH_4 and N_2O (E.32, 2018) Accuracy	Addressing. Implement the planned improvements for this category discussed during the review, including the following: (a) Estimating emissions from natural gas gathering systems using component-level annual data instead of whole-facility study data; (b) Estimating emissions from hydraulically fractured oil well completions using annually reported facility emission data instead of production-based estimates; (c) Estimating fugitive emissions releases from liquefied natural gas storage and transfer using GHGRP data rather than data from an older reference; Estimating emissions from natural gas transmission pipeline blowdowns using GHGRP data rather than data from an older reference, ensuring that the recalculations are described transparently and that a consistent time series of estimates is maintained. For item (a) the United States did not estimate emissions from natural gas gathering systems using component-level annual data instead of whole-facility study data. During the review, the Party explained that a new data source has been identified for item (a) and is expected to be used for the 2020 submission. For items (b), (c) and (d), the United States implemented the planned improvements and explained the recalculations undertaken in the NIR (section 3.7, pp.3-88–3-98).	This update was implemented in the 2020 submission. See more information on updates and recalculation related to emissions from gathering systems in Section 3.7 on pp. 3-91. For additional information, please see https://www.epa.gov/sites/production/files/2020-04/documents/2020_ghgi_update_-_gb_stations_final.pdf.
E.23	1.B.2.c Venting and flaring – CO_2 and CH_4 (E.16, 2018) (E.20, 2016) (E.20, 2015) Transparency	Addressing. Enhance transparency in reporting CH_4 emissions from petroleum systems from venting and flaring, in accordance with the UNFCCC Annex I inventory reporting guidelines. The Party provided new estimates for venting and flaring (NIR section 3.7, pp.3- 88–3-98) (see ID# E.22 above). The ERT noted that the descriptions of additional recalculations, using improved data and methods including several data tables, indicate that increasing levels of detail in the data are available on emissions from several venting and flaring sources in the oil and gas sector across the time series, even though the Party still reports "IE" for venting and flaring in CRF table 1.B.2. During the review, the Party clarified that providing an estimate of disaggregated flaring emissions would involve the application of many assumptions and would result in inconsistent reporting and potentially decreased transparency. The Party stated that there are inconsistencies in data availability across subcategories (such as gathering) within oil and gas, and noted that EF data available for activities that include flaring (such as heavy fuel oil well completions with flaring) include emissions from multiple sources (flaring, venting and leaks).	The United States reiterates previous clarification and response provided during previous reviews.

E.25	1.C CO2 transport and storage – CO2 Yes. Transparency	The ERT noted in the NIR (box 3-7, p.3-79) that emissions of CO2 from EOR are treated differently depending on the source of CO2. When CO2 from naturally occurring CO2 reservoirs is used in EOR, the subsequent leakage of injected CO2 from the EOR site is not reported separately for injection and storage under category 1.C.2 (injection and storage) and, as described in the NIR (box 3-7), is assumed to be fully sequestered. When the CO2 is sourced from anthropogenic sources (such as gas processing or post-combustion capture at a coal-fired power station), it is assumed that complete loss of the CO2 occurs at the point of capture. While dedicated CCS sites are subject to GHGRP methods for estimating emissions from the geological storage formation, it is not clear whether the permanence of CO2 sequestration at EOR sites is assessed. When naturally occurring CO2 is sourced and injected into a geological formation as part of EOR operations, there is the potential for subsequent long-term leakage and loss of CO2 through pathways, as described in the 2006 IPCC Guidelines (vol. 2, table 5.3, p.5.12), and therefore the ERT could not identify whether this emission category is being accounted for in the inventory. During the review, the Party explained that it continues to review new data from the GHGRP and other sources for consideration in updating emission estimates for categories 1.C.1 (transport of CO2), 1.C.2.a (injection) and 1.C.2.b (storage). The ERT recommends that the United States report on the progress on the research to enable estimation of emissions for category 1.C.2, and provide a description of emission pathways associated with EOR and CCS processes for all relevant categories, including how leakage from CO2 geological storage formations is assessed for both EOR and CCS projects. The ERT recognizes that there is no method in the 2006 IPCC Guidelines and encourages the Party to report emissions under category 1.C.2, including emissions from naturally occurring CO_2.	The United States continues to review new data from GHGRP and other sources for consideration in updating emissions estimates from transport of CO2 (category 1.C.1), injection (category 1.C.2.a), and storage (category 1.C.2.b). The Party will provide an update as appropriate in future submissions in recalculations and, where feasible in planned improvements. This improvement will be made over time as data becomes available and prioritized with other improvements to make best use of available resources.
E.26	1.C CO_2 transport and storage – CO_2 Comparability	In addition to ID# E.25 above, the ERT noted that the notation keys in CRF table 1.C are not used consistently. For example, the total amount of CO2 injected at storage sites and the total leakage from transport, injection and storage are reported as “NA”, while category 1.C.1 (transport of CO2) and category 1.C.2 (injection and storage) are reported as “IE”. The ERT recommends that the United States change the total amount of CO2 captured for storage to “IE” in line with the Party’s existing approach of reporting EOR and CCS emissions in the sectors where the emissions are captured for use in EOR. The ERT also recommends that the Party report the total amounts of CO2 injected at storage sites and the total leakage from transport, injection and storage as “IE”.	The United States will review notation keys and correct as appropriate in a future submission.

I.1	2. General (IPPU) – CO_2 (I.26, 2018) Accuracy	Not resolved. Review the basis of EFs applied and, where appropriate, apply consistent carbon content factors to ensure consistency across the energy and IPPU sectors, reflecting any annual variations in the factors. The Party did not update the EFs in order to improve consistency across the energy and IPPU sectors. The Party explained during the review that it is reviewing the basis of EFs and will report on any applicable updates as part of recalculations in the 2020 submission. The Party clarified that it does not expect updates to have a discernible impact on emissions	This issue was addressed in the latest submission. See the 2020 NIR Report, Chapter 4, Section 4.5 on pp. 4-31. "the carbon factors used to determine the amount of natural gas used for ammonia feedstock were updated to be consistent with the factors used in the fossil fuel combustion estimates. This update did not have an impact on process-related ammonia emissions presented here but did impact the amount of natural gas subtracted from energy use as part of the CO2 Emissions from Fossil Fuel Combustion calculations." See also the 2020 NIR Report, Chapter 4, Section 4.17 on pp. 4-85. The C content of coking coal was updated to be more consistent with factors used in the Energy calculations of the Inventory. Other updates are pending ongoing review and are anticipated to be included as appropriate in future submissions.
I.2	2.A.1 Cement production – CO_2 (I.28, 2018) Transparency	Not resolved. Justify the applicability of the 2 per cent value of the cement kiln dust factor to national circumstances or investigate further the availability of the data required to derive a country- specific cement kiln dust factor for cement production and report on the outcome of this investigation. The 2006 IPCC Guidelines (vol. 3, chap. 2.2.1.2, pp.2.11–2.13) allow the use of the default cement kiln dust factor for the tier 2 approach if data are unavailable. However, the ERT noted that the Party did not justify the applicability of the 2 per cent cement kiln dust factor for this key category in the NIR. During the review, the United States confirmed that it will explain the use of the default cement kiln dust factor in the next submission.	This was addressed in 2020 NIR submission, see p. 4-10 (footnote 10).
I.3	2.A.4 Other process uses of carbonates – CO_2 (I.5, 2018) (I.17, 2016) (I.17, 2015) Completeness	Addressing. Conduct further research and consultation with industry, state-level regulators and/or statistical agencies to access additional AD and EFs and/or to seek verification of the current method and assumptions for estimating emissions from ceramics, non- metallurgical magnesium production and from other limestone and dolomite use; and report on progress in the NIR. The Party continues to report "NE" for categories 2.A.4.a (ceramics) and 2.A.4.c (non-metallurgical magnesium production) in CRF table 2(I).A-Hs1. The Party partially addressed this recommendation in its 2018 NIR by providing information on how unspecified uses are accounted for within the estimates (NIR section 4.4, p.4-20). During the review, the Party explained that further outreach work continues with trade associations, including consultation with current data providers. At this	See Annex 5 of 2020 NIR, pp. A-495. No reportable progress in identifying data to estimate emissions based on further outreach. Efforts continue under current cycle.

		time, the research has not yielded any alternative data on national levels of carbonates to verify United States Geological Survey data or provide information on carbonates consumed in these industries. The Party further explained that ceramics and non-metallurgical magnesia are currently not included in the United States Geological Survey. The Survey currently allows respondents to enter magnesia (dolomite) data but no data were reported.	
I.4	2.B.1 Ammonia production – CO_2 (I.7, 2018) (I.19, 2016) (I.19, 2015) Comparability	Addressing. Allocate emissions from all fossil fuel uses (i.e. fuel and feedstock use) for ammonia production under subcategory 2.B.1 of the IPPU sector in accordance with the 2006 IPCC Guidelines. The Party included in the NIR (section 4.5) an explanation of the use of the country-specific methodology to estimate emissions from ammonia production consistently with paragraphs 10–11 of the UNFCCC Annex I inventory reporting guidelines. The Party indicated in the NIR (p.4- 28, under planned improvements) that it has been obtaining data (since 2018) on feedstock quantities from ammonia production facilities via GHGRP and it is verifying these data to use in future inventories. During the review, the Party clarified that it was not able to addressthis issue in the 2019 submission and that it continues to work on collecting data to improve the inventory.	The United States reiterates that it currently uses a country specific methodology for ammonia production emissions consistent with para. 10, Decision 24/CP.19 to most accurately portray U.S. emissions from ammonia production. CO_2 emissions from production of synthetic ammonia from natural gas feedstock are estimated using a country-specific approach modified from the 2006 IPCC Guidelines (IPCC 2006) Tier 1 and 2 methods. In the country-specific approach, to avoid double counting, emissions are not based on total fuel requirement per the 2006 IPCC Guidelines due to data disaggregation limitations of energy statistics provided by the EIA. A country-specific emission factor is developed and applied to national ammonia production to estimate emissions from feedstock consumption, excluding consumption of fuel for energy purposes to avoid double counting and compatibility with methods in 2006 IPCC GL. The United States will continue to review the use of GHGRP data to better understand energy use for ammonia production and any information will be included as appropriate in future submissions.
I.6	2.B.3 Adipic acid production – CO_2, CH_4, N_2O and PFCs (I.30, 2018) Transparency	Not resolved. Include a trend analysis of the IEF in order to explain observed inter- annual changes and irregularities in these trends for adipic acid production (2.B.3). The Party did not include a trend analysis to explain the IEF variations in the NIR. During the review, the Party explained that inter-annual changes or trends in emissions are associated with the use of abatement equipment at the largest production facility. The Party indicated that the requested information will be included in the next submission as part of QA/QC and verification activities.	See Section 4.8 of the 2020 NIR Submission, p. 4-40 for information on trends.

I.7	2.B.4 Caprolactam, glyoxal and glyoxylic acid production – N_2O (I.31, 2018) Completeness	Not resolved. Gather the necessary data and report N_2O emissions from glyoxal and glyoxylic acid production. The Party still reports AD and N_2O emissions from glyoxal and glyoxylic acid production as "NE" in CRF table2(I).A-Hs1. During the review, the Party clarified that it has been researching available data sources but has not yet obtained any usable information for addressing this issue (either for estimating and reporting these emissions or for continuing to report "NE" and providing justification for exclusion in terms of the likely level of emissions in accordance with paragraph 37(b) of the UNFCCC Annex I inventory reporting guidelines). The Party also stated that it was not able to invest resources in this review in 2019 and that it hopes to update planned improvements and the annex listing the emissions not estimated for the 2020 submission.	See Annex 5 of 2020 NIR, pp. A-495. We have identified potential data sources for glyoxal, and glyoxylic acid based on ongoing research efforts. We hope to report more progress in the April 2021 submission, but anticipate the earliest reflection of this data, if useful, would be the April 2022 submission as it may not provide time series data.
I.8	2.B.5 Carbide production – CO_2 (I.32, 2018) Comparability	Not resolved. Allocate CO_2 emissions from production of calcium carbide to the IPPU sector in line with the 2006 IPCC Guidelines or provide clarity in the NIR as to the country-specific approach taken. The Party did not allocate the CO_2 emissions from the production of calcium carbide (category 2.B.5.b) to the IPPU sector. The NIR (p.4-42) stated that CO_2 from calcium carbide is accounted for within the NEUs of petroleum coke in the energy chapter. During the review, the Party stated that, overall, it is continuing to look for data enabling it to disaggregate and reallocate CO_2 emissions from calcium carbide.	The United States reiterates that a country-specific approach was taken for CO_2 emissions from production of calcium carbide. Footnote 16 in the 2020 NIR Report pp. 4-16 indicates calcium carbide is produced from quicklime and petroleum coke. Any emissions from quicklime production are included in lime production emissions (Section 4.2). Furthermore, Section 4.10 pp. 4-48 in the 2020 NIR Report, indicates that carbon dioxide (from petroleum coke used in calcium carbide production) is implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke in the Energy chapter. Table A-65 on pp. A-133 of the 2020 NIR Annexes indicates a storage factor of 30% for petroleum coke used in non-energy uses. This indicates effectively that 70% of any CO_2 emissions associated with petroleum coke used in calcium carbide production is released and accounted for under NEU emissions in the Inventory. There is no way to disaggregate and report emissions specifically associated with petroleum coke used in calcium carbide production (like is done for silicon carbide) since production data is not available for calcium carbide to estimate emissions directly.

I.9	2.B.8 Petrochemical and carbon black production – CH_4 and N_2O (I.10, 2018) (I.22, 2016) (I.22, 2015) Completeness	Addressing. Progress with plans to analyse new data reported by facilities (i.e. GHGRP data) and include emissions from combustion and flaring from installations not currently included in the inventory. The United States reported in the NIR (p.4-53) that a preliminary analysis of aggregated annual reports shows that flared CH_4 and N_2O emissions are less than 500 kt CO_2 eq/year. The Party also reported that the GHGRP is still reviewing these data across reported years to facilitate an update of category-specific QC documentation and EPA plans to address this more fully in future submissions.	The United States also points to pp. 4-57 of 2019 NIR Report on QA/QC and Verification, that "The CH4 emissions from ethylene production under the GHGRP have not been included in this chapter because this approach double counts carbon (i.e., all of the carbon in the CH4 emissions is also included in the CO2 emissions from the ethylene process units). So, it is not just an issue that the flaring emissions are small but that the C at least is already included in CO2 emission estimates. The US continues to assess the GHGRP data for ways to better disaggregate the data and incorporate it into the inventory and any information will be included as appropriate in future submissions.
I.10	2.B.8 Petrochemical and carbon black production – CO_2 and CH_4 (I.12, 2018) (I.25, 2016) (I.25, 2015) Comparability	Not resolved. Develop a methodology that is consistent with the 2006 IPCC Guidelines as soon as is practicable, allocating relevant fuel and feedstock emissions within the IPPU sector. The United States did not update the methodology for allocating the relevant fuel and feedstock emissions within the IPPU sector. During the review, the Party stated that it is reassessing data with EIA and the GHGRP to assess possible options. The Party also stated that, given how data are reported under the GHGRP and how data for the energy sector were received from EIA, this would require a longer-term effort. The Party further highlighted that the NIR (section 4.13) explains the use of the country-specific methodology for estimating emissions from petrochemical and carbon black production consistently with paragraphs 10–11 of the UNFCCC Annex I inventory reporting guidelines.	The United States reiterates that it uses an approach for calculating emissions associated with petrochemical and carbon black production that is consistent with the 2006 IPCC guidelines. Also, as per question E.6 the issue of potential double counting was addressed in the latest submission. See 2020 NIR Report Section 4.13 pp. 4-64 for the following discussion: "Some degree of double counting may occur between CO2 estimates of non-energy use of fuels in the energy sector and CO2 process emissions from petrochemical production in this sector. This is not considered to be a significant issue since the non-energy use industrial release data includes different categories of sources than those included in this sector and the non-energy use estimates are roughly 20 percent of the emissions captured here. As noted previously in the methodology section, data integration is not feasible at this time as feedstock data from the EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries."

I.11	2.B.8 Petrochemical and carbon black production – CO_2 (I.33, 2018) Accuracy	Addressing. Review the backcasting methods to estimate the CO2 EF for the period 1990–2009 for subcategories 2.B.8.b (ethylene), 2.B.8.c (ethylene dichloride and vinyl chloride monomer), 2.B.8.d (ethylene oxide) and 2.B.8.f (carbon black) with improved accuracy; and report transparently on the backcasting methodology for the CO2 EF that it chooses to apply. The United States explained in the NIR (p.4-57) that the CO2 EF for 1990–2009 for category 2.B.8.d (ethylene oxide) was updated using data for 2010–2013, rather than data for 2010–2016. As the EF decreased after 2013, the ERT considers this to be a good approach to characterizing the emissions for 1990–2009. During the review, the Party explained that this approach was not extended to other petrochemical production subcategories (2.B.8.b (ethylene), 2.B.8.c (ethylene dichloride and vinyl chloride monomer) and 2.B.8.f (carbon black)) because GHGRP data for 2017 were not available to the inventory staff until after the 2019 submission had been compiled.	This issue was addressed in the latest submission. See 2020 NIR Report Section 4.13 Recalculations Discussion pp. 4-63 – 4-64. The use of GHGRP data for 2010-2013 to develop EFs was applied for all petrochemical types.
I.12	2.B.8.b Ethylene – CO_2 (I.13, 2018) (I.26, 2016) (I.26, 2015) Transparency	Addressing. Provide an explanation for the country-specific approaches using the EFs for ethylene production derived from GHGRP data, including the outcome of consultation with industry experts, and the results of the quality checks between GHGRP production estimates and data from trade association membership surveys. The United States reported in the NIR (pp.4-53–4-55) that a country-specific approach was taken to estimate emissions from ethylene production. The description in the NIR addresses the data sources and methods used over the reporting period and the Party added further information on quality checks, taking into account data from production facilities (pp.4-56–4-57). However, the Party did not refer specifically to the outcome of other quality checks comparing country-specific GHGRP data with other data (e.g. data from trade association surveys).	This issue was addressed in the latest submission. See 2020 NIR Report Section 4.13 QA/QC and Verification section pp. 4-62 – 4-63. Additional text was added describing the verification procedures for use of the GHGRP data. Further checks relying on data from outside groups is not a necessarily part of the UNFCCC reporting guidelines.
I.13	2.C.1 Iron and steel production – CO_2 (I.16, 2018) (I.27, 2016) (I.27, 2015) Completeness	Not resolved. Conduct further research and consultation with industry, regulators and statistical agencies as necessary in order to access complete AD on natural gas consumption and coke oven gas production at merchant coke plants, and obtain EFs and/or emission estimates. The United States reported in its NIR (p.4-72) that data on natural gas use and coke oven gas production at merchant coke production plants were not included in the emission estimates owing to data being unavailable. The Party indicated during the review that it has begun an analysis, the first step being to assess and gather relevant data related to iron and steel merchant coke plants. The Party indicated that this planned improvement is unlikely to occur before the 2021 submission.	The United States reiterates that the carbon associated with all coking coal used in merchant and integrated coking facilities is accounted for in the Inventory in the Energy Sector emissions, see for example Table A-65 in the 2020 NIR Report Annex 2.3 pp. A-133. Furthermore, all natural gas used in merchant coke facilities would be captured under the Energy Sector natural gas Industrial category. The United States will continue to gather relevant data to better understand the mass and energy balance around all coking facilities and any information will be included as appropriate in future submissions.

I.14	2.C.1 Iron and steel production – CO_2 (I.17, 2018) (I.28, 2016) (I.28, 2015) Transparency	Addressing. Explain the allocation of the emissions from coke production and iron and steel production across both the energy and IPPU sectors, including the amount of carbon stored in the products of iron and steel production (this could be done, for example, through the provision of a quantitative summary of the carbon balance that the Party uses to compile and quality check the inventory estimates). The United States did not report a carbon balance supporting the allocation of emissions from coke production or iron and steel production across both the energy and IPPU sectors. However, the Party reported transparently in its NIR (pp.4-68–4-77) on the allocation of emissions and carbon stored from iron and steel production. The ERT noted that, to enhance the transparency of the NIR, the Party still needs to include all the conversion factors to allow the reported CO_2 emission estimate to be reproduced. During the review, the Party explained that it is reviewing ways to improve the presentation of information, but it currently seems unlikely that a full update will be included in the 2020 submission.	The United States reiterates that the Party has transparently reported in its NIR, see for example the 2020 NIR Annex 2.1 pp. A-56 – A-57, how emissions and carbon stored from iron and steel production have been allocated between the energy and IPPU sectors. The Party has also documented emission factors used in the Iron and Steel and coke production emissions estimates. See for example Table 4-66 on pp. 4-80, Table 4-69 on pp. 4-81 and Tables 4-70 and 4-71 on pp. 4-82 of the 2020 NIR Report. The United States will continue to review ways to improve the presentation of data and any updates will be included as appropriate in future submissions.
I.15	2.C.4 Magnesium production – SF_6 (I.35, 2018) Consistency	Addressing. Investigate the reasons for the SF_6 IEF increase between 2009 and 2011 and report in the NIR on the outcome of the investigation and on any recalculations of AD, IEF or emissions resulting from those investigations. The United States recalculated SF_6 emissions from die casting for 2009–2017 in CRF table 2(I).A-Hs2. In the NIR (p.4-90) the Party explained that the emissions were updated on the basis of revised AD. However, the Party did not report on the outcomes of the investigation explaining the reasons for the SF_6 IEF increase between 2009 and 2011 and how the new AD used in the recalculations improved the trend in the SF_6 IEF between 2009 and 2011. The ERT notes that the AD and EF are reported as confidential in the CRF table and that SF_6 emissions in 2011 are still considered as an outlier (an increase of 41 per cent between 2010 and 2011).	Adjustments to the activity data are discussed in the recalculation sections of the 2019 and 2020 NIRs in Section 4.20. The 2021 NIR will include a discussion on the trends in the SF6 IEF. The revised activity data more accurately reflects the change in production that occurred during the recession. The large increase in SF6 emissions from 2010 to 2011 is due in part to 1 facility reporting anomalously high emissions in 2011 and also partially due to increased production.

I.16	2.D Non-energy products from fuels and solvent use – CO_2 (I.36, 2018) Comparability	Not resolved. Estimate separately CO_2 emissions from lubricants and paraffin wax use and report them under category 2.D. The United States continues to report CO_2 emissions from lubricants and paraffin wax use under the energy sector and to report "IE" under category 2.D (non-energy products from fuels and solvent use). During the review, the Party explained that it uses a country-specific methodology to portray as accurately as possible the emissions from this category and stated that reallocating emissions will not necessarily produce a more accurate or comparable result. However, the ERT is of the view that reporting these emissions under category 2.D will improve comparability across Parties.	As per ID # above E.5, The United States reiterates that it uses a country specific methodology for non-energy use of fuels in line with para. 10, Decision 24/CP.19 to most accurately portray U.S. emissions from NEU. The United States has improved the explanation of its country specific approach to the allocation of NEU of fuels in the introduction of the IPPU chapter 4 and Annex 2 of the NIR.
I.17	2.F Product uses as substitutes for ozone- depleting substances – HFCs and PFCs (I.19, 2018) (I.29, 2016) (I.29, 2015) Transparency	Addressing. Improve the documentation of the refrigeration and air-conditioning model by including the clarifications on model assumptions, data sources and calculation methodologies provided to the ERT during the 2016 review, including (a) the assumed linear substitution trend between "start" and "full penetration" dates for substitution gases; (b) additional information on the annual growth rates cited in the NIR; (c) the model calculation approach for overlapping equipment technology substitutions; (d) details of country-specific circumstances and key references for the annual emission rates for servicing and leaks applied; and (e) information on assumed recovery, reuse and recycling of fluids at end of life (e.g. for fire extinguishers). The United States improved the documentation and described in the NIR (annex 3.9, pp.A-227–A-237) (a) the assumed linear substitution trend between "start" and "full penetration" dates for substitution gases; (b) the average annual growth rates for individual market sectors; and (c) the calculation approach relevant to overlapping equipment. Related to (d) the Party also provided information on country-specific circumstances and key references in the NIR (p.4-120). Related to (e), in annex 3.9 (pp.A-238–A-247), the Party provided information on assumed recovery, reuse and recycling in various subcategories. However, specific information on recovery and reuse of agents at end of life in fire extinguishers is not provided. During the review, the Party explained that all remaining fire protection agent from equipment reaching disposal (i.e. the full amount less the assumed annual emission rate) is recovered and reused, and indicated that it will provide this information in annex 3.9 to its 2020 submission.	The U.S. has included in the 2020 NIR the sentence "At end-of-life, remaining agent is recovered from equipment being disposed and is reused." In the 2020 NIR, see pp. A-285
I.19	2.F.5 Solvents – HFCs and PFCs (I.22, 2018) (I.32, 2016) (I.32, 2015) Transparency	Addressing. Either review and update the assumptions regarding solvent emissions, or provide country- specific information to justify the assumption that only 90 per cent of solvents are emitted. The United States added a reference to a report (EPA, 2004) to justify the sentence in the NIR (annex 3.9, p.A-239) that 10 per cent of solvents are not emitted. The Party stated	We appreciate sharing of the study. We consider this issue addressed as we have reported the basis for the assumption. At this time, U.S. EPA does not have the authority to commence a study at U.S. solvent industry facilities and therefore has relied

		in the NIR that, since the previous submission, the remainder of the consumed solvent is assumed to be entrained in sludge or waste and disposed of by incineration or other destruction technologies without being released into the atmosphere. However, the ERT checked the information in the EPA report (2004) and found that, in addition to the information provided in the NIR, the annual release rate is assumed to be 90 per cent on the basis of expert opinion (EPA, 2001), which assumes that, during the cleaning process, the solvent is recycled or is continuously reused through a distilling and cleaning process until it is eventually almost entirely emitted. However, no further detail or documentation was provided to clarify the expert judgment assumptions, for example by means of a mass balance assessment or details of common practice in the industry or demonstration of how the 90 per cent assumption was calculated (see the document found by the ERT at https://www.epa.ie/pubs/advice/air/emissions/air %20advise%20no%201.pdf).	on the expert opinion from those in the U.S. solvent industry. As conveyed to prior ERTs, this has been an area for review, with effort into further studies, etc. to inform consideration of updates. This effort has, to date, not identified new or additional documentation to supplement the expert judgement. Given the significance of 2.F.5 with respect to other 2.F subcategories and other IPPU emissions, consistent with continuous improvement principles, updates will be made over time as data becomes available and prioritized with other improvements to make best use of available resources.
I.20	2.F.5 Solvents (I.23, 2018) (I.32, 2016) (I.32, 2015) Comparability	Not resolved. Revise the reporting of emissions from solvents in the CRF tables (reported as "NA"). Emissions from solvents are still reported as "NA" in CRF tables 2(I)s2 and 2(II). During the review, the Party explained that, for the 2020 submission, fluorinated gas emissions from solvents will be reported as "IE" in CRF table 2(II)B-Hs2, because solvents only consist of confidential gases and therefore will be reported within the unspecified mix of HFCs and PFCs.	See 2030 CRF Submission, CRF tables 2(I)s2 and 2(II) and see revision of notation key to IE.
I.21	2.F.6 Other applications (product uses as substitutes for ozone-depleting substances) –	Not resolved. Provide in the NIR detailed information including the quality checks for all gases and sources included in the unspecified mix of HFCs and PFCs in the subcategory other applications under the category product uses as substitutes for ozone-depleting substances. The United States did not provide in the NIR detailed information including the quality checks for the unspecified mix of HFCs and PFCs. During the review, the Party explained that it will add a section on QA/QC and verification procedures discussing QA/QC efforts for all gases and sources under the category product uses as substitutes for ozone- depleting substances and, in particular, for the unspecified mix of HFCs and PFCs in the subcategory other applications.	Addressed in 2020 NIR submission on pp. 4-130. The QA/QC and verification process for individual gases and sources in the Vintaging Model includes regular review against up-to-date market information, including equipment stock estimates, leak rates, and sector transitions. In addition, comparisons against published emission and consumption sources by gas and by source are performed when available, including atmospheric measurements of HFC emissions for the United States and EPA's GHGRP, described further below. Independent peer reviews of the Vintaging Model are periodically performed, including one conducted in 2017 (EPA 2018), to confirm Vintaging Model estimates and identify updates. The HFCs and PFCs within the unspecified mix of HFCs and PFCs are modelled and verified individually in the same process as all other gases and sources in the Vintaging Model. The HFCs and PFCs are grouped in the unspecified mix of HFCs and PFCs category only

			for the purposes of reporting emissions to protect Confidential Business Information (CBI).
I.22	2.G.2 SF_6 and PFCs from other product use – SF_6 (I.37, 2018) Completeness	Addressing. Investigate possible SF6 emissions from airborne warning and control systems, particle accelerators and radars and include them in the next submission, providing a description of the identified sources, the SF6 emissions from them for the entire time series, a methodology description and an uncertainty analysis, in accordance with the 2006 IPCC Guidelines (vol. 2, chap. 8, pp.8.23–8.25 and 8.26–8.30). The United States stated in the NIR (annex 5, p.A-411) that the Government reported 1.8 Mt CO2 eq (or 1,800 kt CO2 eq) of fugitive fluorinated gases and other fugitive emissions, including SF6 and HFC emissions, for 2017 to the Federal Energy Management Program. EPA is still reviewing the reported emissions and methods used by reporters to ensure consistency with the 2006 IPCC Guidelines. The Party also stated that EPA is planning to investigate these emissions further to determine the fraction that actually consists of SF6. The ERT believes that future ERTs should consider this issue further to ensure that emissions from this category are not underestimated.	See Annex 5 of the NIR on pp. A-496. EPA's analysis was updated per ongoing review of reported data and EPA is continuing to review the available reported data and the methods used to estimate emissions.
I.23	2.H Other (IPPU) – N_2O (I.38, 2018) Transparency	Not resolved. Increase the transparency of the reporting of N_2O emissions from semiconductor manufacturing by including in both the NIR and the CRF tables a clear indication of where the emissions are reported and explaining that this is because CRF table 2(I).A-H does not allow for reporting N_2O emissions under category 2.E.1. The ERT noted that there is no footnote added to table 2(I)A-Hs2 or additional text included in the NIR regarding the reporting of N2O emissions from semiconductor manufacturing.	This has been addressed in the 2020 NIR submission. See note in both the CRF tables and the NIR. See documentation box in Table2(I)s2 and NIR Section 4.23.

I.24	2.B.1 Ammonia production – CO2 Transparency	The ERT identified significant changes in the CO2 IEF for category 2.B.1 (ammonia production) between 2000 (1.20 t/t) and 2001 (1.24 t/t), and between 2015 (1.27 t/t) and 2016 (1.32 t/t). The ERT noted that these outliers represent an increase in the CO2 IEF across the time series. For example, from 1990 to 2000, the CO2 IEF was constant (1.20 t/t), and increased by 3.4 per cent (1.24 t/t) in 2001. Between 2001 and 2015, the values of the CO2 IEF were in a similar range and increased again between 2015 and 2016 by 4.0 per cent (to 1.32 t/t). During the review, the United States explained that this might be because the CO2 IEF values in CRF table 2(I).A-Hs1 are based on the combined total of CO2 emissions and recovery emissions compared with production values and the change in annual recovery levels alters the CO2 IEF value in CRF table 2(I).A-Hs1. The ERT commends the Party for the information but notes that between 2000 and 2001 the AD, CO_2 emissions and recovery values decreased while the CO_2 IEF increased, and between 2015 and 2016, the AD, CO_2 emissions, recovery values and CO_2 IEF values increased. The ERT recommends that the United States further investigate the reasons behind the trends in the CO_2 IEF and underlying AD and emission and removal trends and report on the matter in its next submission.	This issue was addressed in the latest submission. See 2020 NIR Report Section 4.5 pp. 4-29. The Party has identified the differences in IEFs as coming from changes in production of ammonia from the different feedstocks used. The following text was included in the 2020 NIR: "The implied CO_2 emission factor for total ammonia production is therefore a combination of the emissions factor for ammonia production from natural gas and from petroleum coke. Changes in the relative production of ammonia from natural gas and petroleum coke will impact overall emissions and emissions per ton of total ammonia produced. For example, between 2000 and 2001 and 2015 and 2016 there were increases in the amount of ammonia produced from petroleum coke which caused increases in the implied emission factor across those years."
I.25	2.B.2 Nitric Acid production – N2O Transparency	The ERT noted that the AD for nitric acid production decreased by 6 per cent, from 7.7 to 7.2 Mt, between 2014 and 2015 but increased by 8 per cent to 7.8 Mt between 2015 and 2016. The ERT noted that N2O emissions follow the opposite trend and increased in 2015 by 6 per cent, from 36.7 to 38.8 kt. During the review, the United States explained that the changes are driven by the use of abatement technologies and that it will include information on the trends in the 2020 submission. The ERT recommends that the United States include in the NIR an explanation of the trends observed for N2O emissions and AD for nitric acid production.	This will be addressed in the 2021 submission.
I.27	2.B.5 Carbide production – CO2 Comparability	The ERT noted that the United States reported AD, CO_2 and CH4 emissions from category 2.B.5.b (calcium carbide production) as "NE" in CRF table 2(I).A-Hs1. However, as noted in ID# I.8 (in table 3), emissions from calcium carbide are allocated in the energy sector (NEU of petroleum coke) and therefore "IE" should be reported for AD and CO2 emissions in CRF table 2(I).A-Hs1. For CH4 emissions, "NE" should continue to be reported, as there is no method for its calculation under the tier 1 method applied by the Party for this non-key category. The ERT acknowledges the recommendation in ID# I.8 in table 3 for the United States to allocate CO_2 emissions from category 2.B.5.b to the IPPU sector. However, until this is possible, the ERT recommends that the Party report the correct notation key "IE" for AD and CO2 emissions in CRF table 2(I).A-Hs1 and provide the necessary explanation in CRF table 9.	See update in CRF tables 2(I).A-Hs1 and IE explanation in CRF Table 9.

Agriculture			
A.2	3.A Enteric fermentation – CH_4 (A.16, 2018) Convention reporting adherence	Not resolved. Undertake a quantitative uncertainty assessment in conjunction with future planned methodological updates. During the review, the Party indicated that a quantitative uncertainty assessment for CH_4 emissions from enteric fermentation will be undertaken as soon as methodological improvements are completed in the inventory in order to prioritize the use of resources. During the review, the Party acknowledged that this assessment should be updated (consistently with good practice) but, owing to resource constraints, the current focus is to improve AD. The ERT noted that the last quantitative uncertainty analysis for CH_4 emissions for the category was undertaken for the 2003 GHG inventory submission.	The United States reiterates previous response that updates will be considered with methodological refinements planned and underway in future submissions.
A.4	3.A.1 Cattle – CH_4 (A.18, 2018) Accuracy	Not resolved. Improve the accuracy of the milk fat percentage, for example by investigating the possibility of using additional data sources for information on milk fat percentage values, such as creameries and agricultural extension services. The Party continues to use the default value of 4 per cent for milk fat percentage for dairy cattle (NIR p.A-263). During the review, the Party explained that it has identified one potential data source and plans to update the calculation of emission estimates for future submissions. However, it is unlikely that the improvement will be made before the 2021 submission.	As noted in the comment, the US had obtained a source of milk fat percentages and expects to include these new values in the 2022 submission.
A.5	3.A.1 Cattle – CH_4 (A.19, 2018) Accuracy	Not resolved. Investigate the possibility of using additional data sources (e.g. farm extension services) to derive country-specific information on calf births from dairy cows throughout the year and report on the results of this investigation in the NIR. The Party continues to assume an even distribution of dairy calf births throughout the year (NIR p.A-253). During the review, the Party indicated that it is considering potential sources of information on the distribution of dairy calf births throughout the year and plans to use any available data in the calculation of emission estimates for future submissions. However, it is unlikely that the improvement will be made before the 2021 submission.	Work is underway to investigate sources of data. So far, the primary data source identified did not provide monthly data on calf births. This is a longer-term improvement and the earliest this could be incorporated would be the 2023 submission.
A.6	3.A.1 Cattle – CH_4 (A.20, 2018) Accuracy	Not resolved. Regional diet data are reported in the NIR (p.5-5) and in more detail in annex 3.10. The Party lists in its planned improvements section (NIR p.5-8) that it is investigating the availability of annual data for the digestible energy, Ym and crude protein values of specific diet and feed components for grazing and feedlot animals and dairy cattle but there is no clarity in the NIR on the progress made to date. The Party explained during the review that it is working to update regional diet data for future inventories. In response to the draft report, the Party explained that it continuously assesses available diet data and is working to incorporate these data into the inventory. The Party	Work is underway to address this in future submissions, earliest will be 2022 submission.

		also indicated that it will be unable to obtain state- and/or farm-specific data because many of the diets are likely to be proprietary; in addition, farm surveys are not conducted on an annual basis, but periodically. The ERT commends the Party for this additional information but considers that the issue remains unresolved as the diet characteristics have not been updated as recommended. Update regional diet characterization data used in the estimation of CH4 emissions from cattle in order to more accurately reflect the differences in diets across farms and states.	
A.7	3.A.2 Sheep- CH_4 (A.21, 2018) Accuracy	Not resolved Update the sheep population distribution as data availability allows, focusing resources as appropriate, in line with the 2006 IPCC Guidelines. The ERT noted that the AD for sheep were not recalculated. During the review, the United States clarified that it is assessing the availability of data and anticipates reporting estimates on the basis of available updated sheep population distribution data in the 2021 submission.	The United States expects to update sheep populations, as well as sheep EF from the 2019 IPCC refinements, in the 2022 submission.
A.11	3.B Manure management – CH4 (A.25, 2018) Convention reporting adherence	Not resolved. Update the quantitative uncertainty assessment. During the review, the Party indicated that a quantitative uncertainty assessment for CH4 emissions from manure management will be undertaken as soon as methodological improvements are completed in the inventory in order to prioritize the use of resources. During the review, the Party acknowledged that this assessment should be updated (consistently with good practice) but, owing to resource constraints, the current focus is to improve AD. The ERT noted that the last quantitative uncertainty analysis for CH4 emissions for the category was undertaken in the 2003 GHG inventory submission.	The United States reiterates previous response that updates will be considered with methodological refinements planned and underway in future submissions.
A.12	3.B Manure management – CH4 and N2O (A.5, 2018) (A.14, 2016) (A.14, 2015) Accuracy	Addressing. The ERT noted that in the 2016 NIR (p.5-11) and its annex 3.11 (pp.A.286–A.288), the amount of MMS usage has not been updated for several years (e.g. the most recent data for cattle are from a publication dated 2000, and those for swine are dated 2007). In the NIR 2015 (p.5-15) the Party stated that the 2012 Agricultural Census data will be incorporated into the inventory and will be used to update county-level animal population and MMS estimates. Obtain updated MMS data and estimate emissions using the updated MMS usage data; if this is not possible, report on progress in the effort to update the MMS data. The Party reported in the [2019] NIR (annex 3.11) updated MMS data for cattle (p. A- 291) and swine (p.A-293) but other livestock types, such as sheep, have not been updated since 2001. During the review, the Party informed the ERT that it aims to include further updated information in future submissions as it becomes available. In addition, the Party reported in its planned improvements (NIR p.5- 16) its aim of continuing to obtain and incorporate existing data sources (such as the 2016 Department of Agriculture agricultural resource management survey dairy data) to update MMS distributions.	The ERT notes that U.S. utilized updated WMS data for swine and dairy cattle in previous submissions. The U.S. also plans to update WMS data for poultry and beef cattle in the 2022 submission. The 2020 submission provides information on the progress of data implementation, including the 2012 and 2017 Ag Census. Other progress will be reported in the 2021 submission.

A.14	3.B Manure management – N_2O (A.26, 2018) Accuracy	Addressing. Investigate other potential data sources of animal MMS data, such as extension services (i.e. agricultural advisory services). During the review, the Party informed the ERT that it held an internal workshop where aspects of the United States manure management method and AD sources were discussed. No new data sources were identified at this workshop. The Party also informed the ERT that the Department of Agriculture is working to collect additional MMS data through its surveys (see ID# A.12 above).	Please see response to A.12, work is currently underway to obtain and incorporate updated data.
A.16	3.B.1 Cattle – CH_4 (A.7, 2018) (A.15, 2016) (A.15, 2015) Transparency	Addressing. If not using a more disaggregated livestock categorization in estimating emissions, use option A in reporting data and emissions for cattle in the CRF tables; if applying option C, report the values for population size, allocation by climate region to cool and temperate regions, typical animal mass, volatile solid daily excretion and CH_4 producing potential for all other cattle subcategories of option C in CRF tables 3.B(a)s1 and 3.B(a)s2. The United States applied option C in CRF table 3.B(a)s1. Between the 2017 and 2018 submissions, the Party increased the disaggregation of the cattle characterization in CRF table 3.B(a)s1 for livestock population, typical animal mass, volatile solid daily excretion and CH_4 producing potential, but has not yet reported disaggregated information on allocations to climate regions in CRF table 3.B(a)s2. Information in CRF table 3.B(a)s2 is still reported according to dairy and non-dairy cattle only. During the review, the Party informed the ERT that it is assessing the possibility of reporting climate parameters for certain individual non-dairy subcategories currently reported as "IE" and plans to update the CRF table in a future submission.	The United States reiterates previous response that updates will be considered with methodological refinements planned and underway in future submissions. We are still investigating the possibility of reporting disaggregated climate parameters in the CRF.
A.17	3.B.1 Cattle – CH_4 (A.27, 2018) Comparability	Not resolved. Report MMS that are not used as "NO" instead of "NE" in CRF table 3.B(a)s2 or, if they occur but are not estimated, replace "NE" with the appropriate estimate. The Party indicated that it is considering the most appropriate notation key for the MMS data reported in CRF table 3.B(a)s2 and will update the table accordingly in the 2020 submission.	See CRF table 3.B.(a)s2 in 2020 CRF submission. The notation keys applied reflect the U.S. national circumstances. For those WMS types listed as "NE" for sheep and swine, there is a possibility that those WMS types exist for those two livestock categories but there is currently no data to confirm "NE" or "NO" or to provide an estimate.
A.19	3.D Direct and indirect N_2O emissions from agricultural soils – N_2O (A.30, 2018) Completeness	Not resolved. Include all N_2O emissions from the States of Alaska and Hawaii in the emissions reported under this category or clearly outline in the improvement plan steps for including those emissions in the inventory. The Party did not report N_2O emissions from N inputs from manure, sewage sludge and biosolids, crop residue, N mineralization or the cultivation of organic soils for Alaska or Hawaii. During the review, the Party informed the ERT that it will include these estimates in the future as resources allow, but not before the 2020 submission. This issue is identified in the Party's planned improvements in its NIR (p.5-42). During the previous review, the Party had explained that the impact of N inputs on N_2O emissions had not been estimated for either Alaska or Hawaii, and that those emissions were likely to be less than 0.05 per cent of the total GHG emissions for the	Work is underway to assemble this data for inclusion in the Agricultural Soils N2O estimates. This will be provided either in the 2021 or 2022 submission.

		country, but may exceed the 500 kt CO_2 eq threshold defined in paragraph 37(b) of the UNFCCC Annex I inventory reporting guidelines (see ID# A.11 in this table).	
A.20	3.D Direct and indirect N_2O emissions from agricultural soils – N_2O (A.32, 2018) Transparency	Not resolved. Provide additional information in the NIR on the quantities and N content of commercial organic amendments (e.g. biosolids, dried blood and compost) applied to agricultural soils. There is no additional disaggregated information on the commercial organic amendments included in the NIR (section 5.4). The ERT notes that a footnote to NIR table 5-17 explained that organic amendment inputs include managed manure, daily spread manure and commercial organic fertilizers (i.e. dried blood, dried manure, tankage, compost and other). The Party explained during the review that it will include further information on commercial organic amendments in future inventories provided that the unique N content of each of the commercial organic amendments can be determined.	As noted in the previous review we will include this information in a future inventory if unique N contents of each of the non-commercial organic amendments can be found.
A.24	3.D.b Indirect N_2O emissions from managed soils – N_2O (A.12, 2018) (A.18, 2016) (A.18, 2015) Transparency	Addressing. Provide an explanation of how the methodology and the DAYCENT model used to estimate N volatilized and N loss are both compatible with the 2006 IPCC Guidelines and based on science. The United States included in the 2018 NIR a detailed explanation of how the DAYCENT model is used. During the review, the Party explained that methods are described in the publications that are referenced in the NIR and that the DAYCENT model volatilization (~1 per cent) and leaching (~1 per cent) factors are within the confidence intervals of the respective IPCC default tier 1 factors. However, the ERT was unable to identify any additional explanation in the NIR on how the methodology and the DAYCENT model used to estimate N volatilized and N loss are both compatible with the 2006 IPCC Guidelines and based on science. The Party could include the above information provided during the review along with clear references to the documents (e.g. relevant chapters) to explain the methodology of the DAYCENT model for estimating N volatilized and N loss.	Additional information will be added to the NIR in either the 2021 or 2022 submission.
A.25	3. General (agriculture) – CH4 and N2O Completeness	The ERT noted that the United States reported in the annex 5 to the NIR (p. 5-40) on the uncertainty associated with an incomplete estimation of N2O emissions for Alaska and Hawaii. During the review, the Party clarified that N2O emissions from inorganic mineral fertilizer, N additions for pasture, range and paddock in Alaska and Hawaii, and drained organic soils in Hawaii are reported in the inventory and that other sources are small and the emissions are likely to be insignificant. However, the ERT could not clearly deduce from the information in the NIR which other N sources are not estimated in the inventory for Alaska and Hawaii or whether they are insignificant. The ERT further noted that CH4 and N2O emissions for category 3.F (field burning of agricultural residues) for Alaska and Hawaii are also not estimated in the inventory (NIR p.5-50). The ERT recommends that the United States include in the NIR (e.g. in annex 5) an indication of the	Work is underway to assemble this data for Alaska and Hawaii for inclusion in the NIR. This will be provided either in the 2021 or 2022 submission.

		sources and categories not estimated for Hawaii and Alaska. If the emissions are insignificant, the ERT recommends that the Party justify their exclusion on the basis of the likely level of emissions in accordance with paragraph 37(b) of the UNFCCC Annex I inventory reporting guidelines.	
A.26	3. General (agriculture) – CH4 and N2O Consistency	In response to a previous review recommendation (see ID# A.1 in table 3) the United States reported in CRF tables AD for category 3.C.1 (rice cultivation, irrigated) and for all subcategories under categories 3.D.a and 3.D.b (direct and indirect N2O emissions from managed soils) and 3.F (field burning of agricultural residues) for all years of the time series (2013–2017) for which emissions were estimated using surrogate data, trend analysis and statistical approaches. The Party included in the NIR (pp.5-21 and 5-34) information on the approaches used for reporting AD for those categories for 2013–2017: it used a surrogate data method for categories 3.C, 3.D.a and 3.D.b, and linear regression for category 3.F. However, the ERT noted that the AD reported in CRF tables 3.C, 3.D and 3.F for 2013– 2017 are simply the figures for the most recent years for which NRI data are available (2012 for the current submission) held constant for the remainder of the time series (2013–2017). During the review, the Party informed the ERT that it may be possible to use alternative data sources such as the United States agricultural resource management survey, Landsat-based products or other data sets to inform the derivation of AD where NRI data are not available. The ERT recommends that the United States explore the use of alternative data sources to derive AD for the years of the time series where no DAYCENT data are available (2013–2017). If alternative data sets are not available, the ERT recommends that the Party use proxy data or extrapolation methods to derive AD.	We will continue to seek out alternative data sources to drive the inventory estimates for the portion of the time series not covered by the NRI. This is a medium to long-term update.
A.27	3.A Enteric fermentation - CH4. Convention reporting adherence	The ERT noted that the average GE for heifer feedlot cattle in CRF table 3.As1 is incorrectly reported for 2000 (161.01 MJ/head/day). For the other years of the time series, the reported GE value is 0.17 MJ/head/day. The ERT noted that the CH4 emissions and IEF are not affected by the reporting of 161.01 MJ/head/day in CRF table 3.As1. The ERT recommends that the United States correct the value of the GE reported in CRF table 3.As1 for 2000 for heifer feedlot cattle.	This transcription error was resolved with the 2020 submission. See CRF table 3.As1
A.28	3.A Enteric fermentation - CH4 Convention reporting adherence	In the NIR (annex 3.10, table A-160, p.A-253), the United States reported the monthly average population from the calf transition matrix. The ERT noted that the populations in the table for each cohort remain constant, for example the population for calves aged 0 years old in January was the same as for calves aged 1 year old in February (2,431 units). However, populations should be declining each month, on the basis of losses due to mortality and slaughter, rather than remaining constant. During the review, the Party clarified that the values in table A-160 were reported incorrectly and provided a new table with the correct values to the ERT, where, for example, there are 2,562 calves aged 0 years old in January and 2,560 calves aged 1	This was resolved with the 2020 NIR submission, please see NIR Annex Table A-160

		year old in February. The ERT recommends that the United States correct the values reported in table A-160 of the NIR to reflect the correct values of the monthly average calf population by including losses due to mortality and slaughter.	
A.29	3.B.1 Cattle – N2O Transparency	The ERT noted discrepancies in the values of the Nex rate in CRF table 3.B(b) for beef calves, dairy calves and beef replacements. When multiplying the population by the Nex rates reported in the CRF table, the result does not match the value of the total Nex reported in CRF table 3.B(b). For example, if the beef calf population (15,970,718) is multiplied by the Nex rate (20.07 kg N/head/year), the result is 320,510,941 kg N. However, the value reported in CRF table 3.B(b) (cell N31) is 309,748,493 kg N. During the review, the Party explained that it calculates Nex for each state using a state-specific Nex rate factor and then adds together the totals for all states to calculate and report the total national Nex value shown in CRF table 3.B(b). Therefore, the values will not be the same as if the average rate reported for each animal class were used to calculate the total Nex. The ERT recommends that the United States report the correct Nex values for beef calves, dairy calves and beef replacements in CRF table 3.B(b) so that they reflect the true average Nex rate.	We are currently investigating the possibility of providing the Nex values for these disaggregated cattle types in either the 2021 or 2022 submission.
A.30	3.B.1 Cattle – N2O Transparency	The ERT noted that the United States used “IE” to report the Nex rate for heifer stockers and beef replacements in CRF table 3.B(b) without providing an explanation as to where the Nex rates were included. During the review, the Party clarified that the Nex rate for non-dairy cattle was used for heifer stockers and beef replacements. However, the ERT noted that although the Nex rate was reported in CRF table 3.B(b) for non-dairy cattle (52.81 kg N/head in 2017), the population and total Nex were reported as “IE”. This is also the case for dairy cattle, where the Nex rate is 100.09 kg N/head in 2017 and the population and total Nex is reported as “IE”. The Party explained that the total Nex for dairy and non-dairy cattle is reported against individual cattle subcategories. The ERT recommends that the United States replace “IE” for the Nex rate for heifer stockers and beef replacements with the actual Nex rates applied for those individual animals in CRF table 3.B(b). The ERT further recommends that the Party replace the Nex rates for dairy cattle and non-dairy cattle with “IE” and explain in the documentation box of CRF table 3.B(b) that the Nex rates are reported against individual livestock classes.	We are currently investigating the possibility of updating the Nex values for these disaggregated cattle types in either the2021 or 2022 submission.
A.31	3.B.1 Sheep–CH4 and N2O Transparency	The United States provided information on MMS distribution among waste management systems by operation in annex 3.11 to the NIR (tables A-188–A-189, pp. A-291 and A-293). However, the ERT noted that table A-189 does not include information on manure management allocations for sheep. During the review, the Party informed the ERT that this was due to the small level of emissions from manure management for sheep. The ERT considers	We are currently working on including these values for the 2022 submission.

		that this information would enhance the transparency of the NIR and recommends that the United States include information on MMS distribution for sheep in NIR table A-189.	
A.32	3.D Direct and indirect N2O emissions from agricultural soils – N2O Convention reporting adherence	The United States reported in box 5-3 of its NIR that the DAYCENT model (tier 3 method) is used to estimate N2O emissions from tobacco crops while in a following sentence it is reported that the DAYCENT model is not applied to estimate N2O emissions and a tier 1 method is used for other crops including tobacco (p.5-34). During the review, the Party clarified that tobacco crops are included in the DAYCENT model (tier 3 method) and stated that it would correct the information in the next submission. The ERT recommends that the United States correct the text in its NIR to reflect the actual method applied, namely that N2O emissions from tobacco crops are estimated using the DAYCENT model (tier 3 method).	Clarification will be addressed in the 2021 submission.
A.33	3.D.a Direct N2O emissions from managed soils – N2O. Convention reporting adherence	The ERT noted that recalculations were performed for N2O emissions for categories 3.D.a.1 (inorganic fertilizers), 3.D.a.4 (crop residues), 3.D.a.5 (mineralization/immobilization associated with loss/gain of soil organic matter) and 3.D.a.6 (cultivation of organic soils). However, these recalculations were not described in the recalculations section of the NIR (p.5-41) in accordance with paragraphs 43–45 of the UNFCCC Annex I inventory reporting guidelines. During the review, the United States explained that it will investigate the reasons why the data for these categories were not updated. The ERT checked the CRF tables and found that the values reported for those categories in the 2019 submission are different from those reported in the 2018 submission. In CRF table 8s2, the recalculation for category 3.D reduced emissions by 5.63 per cent. The ERT was not able to check the changes that occurred in the AD, methods or EFs used and if these changes were made in response to the review process. The ERT recommends that the United States include in the NIR an explanation of the AD, methods and EFs used to estimate emissions under categories 3.D.a.1, 3.D.a.5 and 3.D.a.6 and explain why the new N2O emission values are more accurate than the previous ones. The ERT also recommends that the United States report on the recalculations in accordance with paragraphs 43–45 of the UNFCCC Annex I inventory reporting guidelines, if the Party performs recalculations for those categories in the next submission.	Future recalculations will be further explained in the recalculation section.
A.34	3.D.a.3 Urine and dung deposited by grazing animals – N2O Transparency	In response to a question raised by the ERT relating to ID# A.23 in table 3, the United States explained the approach to allocating N deposited in urine and dung to each county. The Party clarified during the review that N deposited on pasture, range and paddock MMS is provided at the county level but, owing to QC issues, the data are aggregated to the state level. The data are then applied to NRI survey locations at the same rate for a state (dividing the total N deposited in pasture, range and paddock by the total area of grassland in the state). The total input of N deposited for individual	The United States plans to include additional explanation on the approach used to allocate N deposited in the 2021 submission.

		survey locations in the NRI was determined by multiplying the rate by the weight. The ERT considers that this information should be included in the NIR to increase transparency and that the Party should explain that emission estimates are performed using the DAYCENT model by using data of N deposited by soil types. The ERT recommends that the United States include in the NIR the information provided to the ERT explaining the approach used to allocate N deposited in urine and dung to each county and how the DAYCENT model uses these data in the estimation of N2O emissions.	
LULUCF			
L.1	4. General (LULUCF)	Addressing. Conclude the technical work under way to be able to provide estimates for the carbon stock changes in the living biomass and DOM pools for each conversion category from forest land to any other land use for each year based on a reliable land-use change matrix, and report on the achievements made. The United States reported carbon losses in the living biomass and DOM pools for categories 4.B.2.1 (forest land converted to cropland), 4.C.2.1 (forest land converted to grassland), 4.D.2.3.1 (forest land converted to other wetlands) and 4.E.2.1 (forest land converted to settlements). Categories 4.D.2.2.1 (forest land converted to flooded land) and 4.F.2.1 (forest land converted to other land) are still reported as "NE".	The Unites States does not currently include estimates for the categories of forest land converted to other land. These categories will be included in a future inventory submission and will contain the estimates of carbon stock loss as a result of converting forest to these lands
L.2	4. General (LULUCF) – CO_2, CH_4 and N_2O (L.3, 2018) (L.3, 2016) (L.3, 2015) (82, 2013) (97, 2012) Completeness	Addressing. Include all managed United States lands in the inventory; improve the consistency of the time series of national areas; and report on the achievements made. The land-use matrix of CRF table 4.1 and the land representation tables in the NIR (tables 6-6–6-7, pp.6-9–6-10) include all areas of managed and unmanaged land in the United States, except for United States territories (see ID# L.41 in table 5). In addition, the "Total area" columns of CRF background tables 4.A, 4.B, 4.C, 4.D, 4.E and 4.F do not include managed land areas where emissions or removals do not occur. Instead, this information is provided in a documentation box for each CRF background table. During the review, the Party explained that the result of initial testing including all managed land in the CRF tables caused issues with the calculated IEFs. Therefore, the Party plans to improve transparency in the 2020 submission to indicate more clearly the areas of managed land that are not estimated in order to clarify why there is a difference between the areas reported in CRF table 4.1 and the CRF background land-use tables.	See the following tables included in 2020 NIR: Table 6-33: Area of Managed Land in Cropland Remaining Cropland that is not included in the current Inventory (Thousand Hectares) Table 6-37: Area of Managed Land in Land Converted to Cropland that is not included in the current Inventory (Thousand Hectares) Table 6-41: Area of Managed Land in Grassland Remaining Grassland in Alaska that is not included in the current Inventory (Thousand Hectares) Table 6-49: Area of Managed Land in Land Converted to Grassland in Alaska that is not included in the current Inventory (Thousand Hectares) Annex Table A-231: Forest Land Area Estimates and Differences Between Estimates in 6.1 Representation of the U.S. Land Base (CRF Category 4.1) and 6.2 Forest Land Remaining Forest Land

			(CRF Category 4A1) (kha) Annex Table A-233: Forest Land Area Estimates and Differences Between Estimates in 6.1 Representation of the U.S. Land Base and 6.3 Land Converted to Forest Land (kha) Area (Thousand)
L.3	4. General (LULUCF) – CO_2, CH_4 and N_2O (L.36, 2018) Convention reporting adherence	Not resolved. Until the Party is able to report anthropogenic emissions and removals from the entire national managed land area, report non- estimated managed land as a subdivision in the relevant CRF tables (i.e. tables 4.A, 4.B, 4.C, 4.D and 4.E), so that the managed land area for each land category reported in CRF table 4.1 corresponds with that reported for the same category in CRF tables 4.A, 4.B, 4.C, 4.D and 4.E. The Party did not report non- estimated managed land as a subdivision in CRF tables 4.A, 4.B, 4.C, 4.D and 4.E. See ID# L.2 above for the Party's action regarding this issue. During the review, the Party explained that the addition of the subdivision will have an impact on the IEF and introduce inconsistencies within the CRF tables. However, the ERT considers that adding a subdivision for reporting non-estimated managed land and applying the correct use of notation keys will not introduce inconsistencies within the CRF tables and will be important in improving the understanding of the Party's GHG inventory. The ERT also notes that, if emissions are insignificant, the Party can report "NE" and justify their exclusion in accordance with paragraph 37(b) of the UNFCCC Annex I inventory reporting guidelines.	The United States will consider this suggestion for the 2021 NIR and CRF submission (i.e. use of notation key, NE).
L.4	Land representation – CO_2, CH_4 and N_2O (L.7, 2018) (L.21, 2016) Consistency	Not resolved. Resolve the inconsistencies in land-use areas in the time series reported in the CRF tables. The discrepancy between land-use areas in the time series reported in CRF table 4.1, where the final area at the end of a given year is not the same as the initial area of the subsequent year, remains unresolved. For example, the final area reported in CRF table 4.1 for 2016 is 278,948.81 kha, while the total initial area reported in CRF table 4.1 for 2017 is 281,666.66 kha. During the review, the Party explained that the land-use areas in CRF table 4.1 were entered according to the definitions of remaining land (land that remains in the same land use over 20 years) and converted land (the cumulative area of conversion over the past 20 years) and also explained that the heading of CRF table 4.1 can be understood to allow it to be compiled according to the IPCC definition (namely, using the 20-year conversion). The ERT notes that the UNFCCC Annex I inventory reporting guidelines do not clearly mention whether annual area changes or 20 years of cumulative area change should be used in CRF table 4.1, as indicated by the Party; however, the consistency of areas in CRF table 4.1 between the final area in a land matrix of a given year and the initial area in a land matrix of the subsequent year is only achieved when the matrices are prepared using annual area changes rather than 20 years of cumulative area change. The	See explanation included in NIR on p. 6-10 and documentation box in CRF Table 4.A.

		Party further clarified during the review that preparing the annual change area requires land representation to be reanalysed and so the Party will note in the documentation boxes what it is reporting in the interim.	
L.6	Land representation – CO_2, CH_4 and N_2O (L.9, 2018) (L.23,2016) (L.22, 2015) Transparency	Addressing. When providing detailed information in the NIR on how the different data sources were harmonized, provide explicit information on how the model ensures consistent integration of the three data sources, for example by including a visual flow chart of data processing during the harmonization process. Three sets of land-use data are used: NRI, FIA and NLCD (see also ID# L.8 below). The Party updated land representation by including new FIA data in the 2019 submission and explained in the NIR (pp.6-17– 6-22) how the different land data sources are used and harmonized to classify their national land data into IPCC land-use categories. The Party further explained during the review that a figure showing the process of harmonizing the different data sources will be included in the submission for 2021 or 2022.	See section "Approach for Combining Data Sources" starting on p. 6-20 of 2020 NIR submission. In addition, the United States will be modifying its approach for developing the land representation over the next several years and will update the NIR text throughout this process.
L.8	Land representation – CO_2, CH_4 and N_2O (L.37, 2018) Accuracy	Addressing. Update the land representation with the latest available data from NRI, and proceed with plans to improve the coordination and timing of sharing data between federal agencies if necessary. The land-use data from NRI and NLCD were not updated in the 2019 submission and the land-use areas of cropland, grassland and settlements for 2013 onward were based on the land representation data from the previous submission. The ERT notes that the reporting of almost identical net emissions and removals from these land uses for 2013–2017 was affected by this land representation method. During the review, the Party explained that it will include new NRI data up to and including 2015, and updated land representation is planned for the 2020 submission. The Party further explained that data from NRI/NLCD currently used in its land representation are updated every two to four years, and that as part of the current compilation process and arrangements, it incorporates new NRI/NLCD data as soon they become available. There is currently no annual alternative to NRI for obtaining land-use/conversion and management data on croplands, grasslands or settlements, so the Party must continue to rely on these data until new annual data become available.	In 2020 NIR submission, see "Recalculations Discussion" in section 6.1 Representation of the U.S. Land Base (see p. 6-23). The land-use data from NRI and NLCD were updated for the 2020 NIR submitted in April. The United States will continue to update these datasets as new versions are released.
L.10	4.A Forest land – CO_2 (L.39, 2018) Convention reporting adherence	Addressing. Report up-to-date information on the verification of the outputs of the model used to estimate SOC changes in mineral soils, for example, at the level of annual fluxes in single specific sites representative of the variability of the population or, as done for the DAYCENT model for agricultural soils (NIR figure A-12), at the level of the total cumulated (across the time series and the entire territory modelled) net flux. The ERT notes that the explanation of forest soil in the annexes to the NIR (A-361– A-366) has	Additional detail will be included in the forest annex e.g., tables by broad forest types and average C stock per unit area, and stock changes. The discussion on uncertainty will also be expanded to discuss issue of consistency in soil depth across land use categories. We will also provide data on plot level soil carbon. We

		been updated but that the verification information on forest soil estimation by model is not provided in the NIR, despite a background research paper on the soil estimation approach being cited in the annexes to the NIR (p.A-361). During the review, the Party explained that it is currently analysing remeasurements of soil attributes from national forest inventory plots, which will be used to test and verify model results for SOC changes in mineral soils.	anticipate reporting this information in the April 2021 or 2022 submission.
L.11	4.A Forest land – CO2 (L.40, 2018) Accuracy	Addressing. Apply as the carbon conversion factor for forest biomass either a country-specific value or the default value provided in the 2006 IPCC Guidelines (vol. 4, chap. 4, table 4.3), and, for mangrove forests, either a country-specific value or the default value provided in the Wetlands Supplement. In the estimation of living biomass for forest land, the Party applies the same carbon conversion factor (0.50 t C/t dead matter) as that used in the previous submission for all forest types. During the review, the Party explained that the carbon conversion factor of 0.50 was used as a country-specific value for living biomass, although this was not clearly explained in the NIR. As the use of 0.50 for the estimation of living biomass in forest land is not consistent with the 2006 IPCC Guidelines or the Wetlands Supplement (for mangrove forests), a further explanation is needed for the ERT to evaluate the use of 0.50 t C/t dead matter as a country-specific value. During the review, the Party explained that it will improve the relevant documentation in the NIR for the 2020 submission.	This has been addressed in the 2020 submission, see Annex 3, p. A-422.
L.13	4.A Forest land – CO2 and N2O (L.42, 2018) Transparency	Addressing. Calculate the carbon stock change in each carbon pool at the level of each single plot and then aggregate the results at the state and national level, and explain any recalculations in the NIR. The methodology applied in the stock-difference method for forest land has not changed since the previous submission. However, during the review, the Party provided additional information on the methodology in response to the concern about double counting of carbon raised during the previous review. The Party explained that plot-level national forest inventory information is used for land-use classification relating to forest land, and confirmed that the stock-difference method is applied at each land-use category level (e.g. forest land remaining forest land) instead of for the entire forest land area. The Party also explained that applying the stock changes at the plot versus population level will not change the result, given how the estimators and expansion factors are used in the national forest inventory and incorporated into the current compilation approach. Additionally, the Party explained that it is moving towards a more spatially and temporally resolved system for compiling emission and removal estimates for the forest land category and has already started testing the new system. The system will include tracking individual trees through remeasurements at plot level along with all other	The United States plans to include the supplemental information provided to the previous ERT in the Annex to the 2021 NIR.

		carbon pools. The transition will be noted in the planned improvements section in future submissions. The ERT noted that current methodology for calculating carbon stock change in forest land is considered appropriately applied taking into account the information provided by the Party. However, the ERT also noted that this understanding was not clear from the information provided in the NIR and considers that the Party should include information in the NIR to demonstrate that the stock-difference method for forest land is applied at each land-use category level.	
L.14	4.A.1 Forest land remaining forest land – CO_2 (L.13, 2018) (L.26, 2016) Transparency	Not resolved. Provide in an annex to the NIR detailed tables on average carbon fluxes by region and type (e.g. the region and forest type classifications described in Smith et al. (2006) and used for estimating downed deadwood and understory, which might better reflect the diversity of forest types and age classes). The United States did not provide tables with carbon stock changes disaggregated by region, state or forest type. During the review, the Party explained that this information will be included in future submissions.	We anticipate reporting this information in the April 2021 or 2022 submission.
L.16	4.B Cropland – CO_2 (L.18, 2018) (L.14, 2016) (L.14, 2015) (93, 2013) (107, 2012) Completeness	Not resolved. Estimate the carbon stock changes in living biomass in perennial crops for all years in the time series. The United States did not report the biomass carbon stock changes in perennial cropland for either cropland remaining cropland or land converted to cropland. The Party explained that data are currently not available for estimation.	Work is planned to report this information April 2021 submission, but due to some administrative delays it may only be included in the April 2022 submission.
L.17	4.B Cropland – CO_2 (L.45, 2018) Accuracy	Check the quality of the data from which the land representation is derived, investigate the reasons for the sudden and temporary decrease in the area of organic soils by about 80 kha between 1999 and 2000 for cropland remaining cropland reported in CRF table 4.B, explain the result of this investigation in the NIR, correct any identified inconsistencies and explain any recalculations in the NIR. During the review, the Party explained that an investigation is under way and further information will be provided in the 2020 submission.	The area of organic soils for croplands remaining croplands was recalculated for the 2020 submission and this error has been corrected. See Recalculations Discussion on page 6-23 of the LULUCF chapter.
L.18	4.B.2.2 Grassland converted to cropland – CO_2 (L.46, 2018) Completeness	Not resolved. Estimate biomass carbon stock changes using the IPCC default method and factors or, where available, country-specific methods and factors, and report the estimations in the NIR. The Party did not provide estimates and "NE" was reported for carbon stock changes in biomass in grassland converted to cropland in CRF table 4.B. During the review, the Party explained that it is working to address completeness over time as improved data become available and to prioritize the work in line with other improvements to make best use of available resources.	Work is planned to report this information April 2021 submission, but due to some administrative delays it may only be included in the April 2022 submission.

L.19	4.B Cropland 4.C Grassland – CO_2 and N_2O (L.47, 2018) Convention reporting adherence	Not resolved. The Party reported in the NIR the same verification information comparing SOC changes with lower tiers (Figure A-13) as in the previous submission. Therefore, the concern of the previous ERT remains regarding coverage of land categories (i.e. that verification of the DAYCENT model was implemented for carbon stock change in cropland remaining cropland, but not implemented for other land-use categories and gases). Regarding the issue of time series covered by the verification flagged in the previous review, the ERT believes that the Party would not be required to provide that information under verification, considering the exchange of views with the Party during the review and noting that covering the entire time series is not specifically mentioned in the 2006 IPCC Guidelines as a verification step. The ERT notes that, in terms of accuracy of the time series estimated by the model, the Party provided in the NIR (annex 3, p.A-342–A-345) detailed information on the calibration step as part of QA/QC of the model development. The ERT understands that recalibration of the model or modifications to the structure (i.e. algorithms) may be necessary if the model does not capture general trends or there are large systematic biases.	As noted to prior ERT, the United States plans to improve the documentation and calibration are ongoing as well as implementation of additional verification, in step with ongoing methodological refinements for estimating soil carbon, soil nitrous oxide and soil methane. This will be address in 2021 and 2022 submissions.
L.20	4.B Cropland 4.C Grassland – CO_2 and N_2O (L.48, 2018) Comparability	Not resolved. Report SOC changes and associated CO_2 and N_2O emissions from cropland and grassland mineral soils using a depth increment of at least 30 cm in line with the 2006 IPCC Guidelines (vol. 4, chap. 2). The Party did not estimate SOC changes using a depth increment of at least 30 cm. Instead, the estimate was made using a depth of 20 cm. During the review, the Party explained that it will implement this recommendation in the 2020 submission.	CO_2 and N_2O emissions from cropland and grassland mineral soils are estimated to 30 cm. See Recalculations section of Cropland Remaining Cropland of 2020 NIR
L.21	4.C Grassland – CO_2 (L.49, 2018) Transparency	Not resolved. Report woody grassland as a subdivision of the grassland category, estimate accordingly the area and carbon stock change for all carbon pools of woody grassland within the category grassland remaining grassland and within all land-use categories of conversion from and to grassland, and report the estimations in the NIR. The Party did not estimate carbon stock changes in woody grassland. The Party provided information on its progress in the NIR (box 6-6, p.6-71) and explained during the review that further work will be done to estimate the carbon stock changes in biomass and DOM in woody grassland. The Party clarified that it plans to provide the information in its 2021 submission.	Work is planned to report this information April 2021 submission, but due to some administrative delays it may only be included in the April 2022 submission.
L.23	4.C.2 Land converted to grassland – CO_2 (L.23, 2018) (L.33, 2016) (L.26, 2015) Accuracy	Not resolved. Revise the estimates of carbon stock change in mineral soils under forest land converted to grassland using the updated data for mineral soils and report the results in the NIR. No updates were made in the estimation of mineral soils since the previous submission. During the review, the Party explained that the improvement of SOC estimation associated with land-use conversions is a planned improvement.	Work is planned to report this information April 2021 submission, but due to some administrative delays it may only be included in the April 2022 or 2023 submission.

L.24	4.C.2.2 Cropland converted to grassland – CO_2 (L.51, 2018) Completeness	Not resolved. Estimate biomass carbon stock change using the IPCC default method and factors or, where available, country-specific methods or factors, and explain the estimations in the NIR. The Party did not provide estimates and "NE" was reported for carbon stock changes in biomass in cropland converted to grassland. During the review, the Party explained that it will work to address completeness over time as improved data become available and to prioritize this work in line with other improvements to make best use of available resources.	Work is planned to report this information April 2021 submission, but due to some administrative delays it may only be included in the April 2022 submission.
L.25	4.D.1 Wetlands remaining wetlands – CO_2, CH_4 and N_2O (L.25, 2018) (L.34, 2016) (L.27, 2015) Transparency	Addressing. Noting the need to determine the quantity of peat harvested per ha and the total area undergoing peat extraction, provide the respective AD and IEFs for the on-site CH_4 and N_2O emission estimates in CRF table 4(II) for organic soils under peat extraction. The quantity of peat harvested per ha used for determining the peat extraction area (100 t/ha) is noted in the NIR (p.6-83) and has not changed since the previous submission. The Party added to the NIR (p.6-84) an explanation that the AD for on-site CH_4 emissions are the total peat extraction area and the AD for on-site N_2O emissions are the nutrient-rich peat production area. However, these AD were not included in CRF table 4(II). During the review, the Party explained that the omission will be addressed in the 2020 submission.	We started working on this issue during the 2020 submission cycle but are continuing progress. Documentation on our approach was provided in the documentation box in CRF Table 4(II) of the 2020 submission.
L.26	4.D.2.2 Land converted to flooded land – CO_2 (L.53, 2018) Completeness	Not resolved. Estimate carbon stock change in flooded land using the 2006 IPCC Guidelines (vol. 4, chap. 7) default method and factors or, where available, country-specific methods or factors, and explain the estimations in the NIR. Carbon stock changes in all carbon pools for land converted to flooded land are reported as "NE". During the review, the Party explained that improvements are planned for future inventory submissions. See ID# L.1 above for the case of forest land converted to flooded land.	The United States reiterates that improvements are underway to report these emissions in the April 2022 submission.
L.27	4.D.2.3 Land converted to wetlands – CO_2 (L.54, 2018) Completeness	Not resolved. Estimate biomass and DOM carbon stock changes for forest land converted to other wetlands as planned for the 2020 submission, and explain the estimations in the NIR. Carbon stock changes in DOM for land (forest land) converted to other wetlands (vegetated coastal wetlands) were not estimated. During the review, the Party explained that improvements are planned for future inventory submissions.	Work is planned to report on this information in a future submission.
L.28	4.D.2.3 Land converted to wetlands – CO_2 (L.54, 2018) Completeness	Not resolved. Estimate carbon stock changes in biomass for the conversion of cropland and grassland to other wetlands using IPCC default methods and factors (2006 IPCC Guidelines, vol. 4, chap. 7) or, where available, country-specific methods or factors, and explain the estimations in the NIR. Carbon stock changes in biomass for land (cropland and grassland) converted to other wetlands (vegetated coastal wetlands) are estimated for one year of removals after conversion. During the review, the Party explained that improvement by including biomass losses due to land conversion to other	Work is planned to report on this information in a future submission.

		wetlands is planned for future inventory submissions.	
L.29	4.E Settlements – CO_2 (L.27, 2018) (L.15, 2016) (L.15, 2015) (94, 2013) Accuracy	Addressing. Eliminate the overlap between the urban forest inventory and the forest inventory. The tree cover area in settlements (urban forest area) has been updated in the 2019 submission, even though the Party indicated its plan to address the overlap between forest and urban forest in the NIR (planned improvements in settlements, p.6-112). During the review, the Party indicated that there may be a minor overlap with forest and urban forest and this will be considered when new NLCD data become available.	This overlap is still being investigated with new NLCD data. We anticipate reporting an update status of this consideration in the 2021 or 2022 submission.
L.30	4.E.1 Settlements remaining settlements – CO_2 (L.55, 2018) Comparability	Not resolved. Remove the reporting of the carbon stock change associated with yard trimmings and food scraps from under the settlements category and allocate it to the category other under the relevant sector. The Party continues to report carbon stock changes associated with yard trimmings and food scraps under the settlements category instead of 4.H (other). During the review, the Party indicated that this reallocation will be addressed in the 2020 submission.	We will plan on reporting these carbon stock changes under CRF category 4.H (other) in the 2021 submission.
L.31	4.E.1 Settlements remaining settlements – CO_2 (L.55, 2018) Comparability	Not resolved. Report information on the long- term stored carbon stock of yard trimmings and food scraps, as well as on its annual changes, in the memo item in CRF table 5. The Party did not report on the memo items on the long-term storage of carbon in waste disposal sites or on the annual change in total long-term carbon storage in CRF table 5. During the review, the Party indicated that this will be addressed in the 2020 submission.	We will plan on reporting these carbon stock changes under CRF category 4.H (other) in the 2021 submission.
L.32	4.E.2.2 Cropland converted to settlements 4.E.2.3 Grassland converted to settlements – CO_2 (L.56, 2018) Completeness	Not resolved. Estimate biomass carbon stock change for cropland converted to settlements (category 4.E.2.2) and grassland converted to settlements (category 4.E.2.3) using the IPCC default method and factors (2006 IPCC Guidelines, vol. 4, chap. 8) or, where available, country- specific methods or factors, and explain the estimations in the NIR. Carbon stock changes in biomass for cropland converted to settlements and grassland converted to settlements were not estimated. During the review, the Party explained that it will work to address completeness over time as improved data become available and to prioritize the work in line with other improvements to make best use of available resources.	Work is planned to report on this information in a future submission.
L.33	4.F.2 Land converted to other land – CO_2 (L.57, 2018) Completeness	Not resolved. Report estimates of carbon stock change for land converted to other land using the IPCC default method and factors (2006 IPCC Guidelines, vol. 4, chap. 9) or, where available, country-specific methods or factors, and explain the estimations in the NIR. The Party reported all carbon stock changes in all carbon pools as "NE". During the review, the Party explained that this will be improved in future submissions. See ID# L.1 above for the	Work is planned to report on this information in a future submission.

		issue of forest land converted to other land.	
L.34	4.G HWP – CO_2 (L.58, 2018) Transparency	Not resolved. Complete CRF table 4.Gs2 with aggregated values in t carbon for each of the three HWP subcategories (solid wood, paper and paperboard, and other) and report in the NIR a table with all subcategories used by the model to calculate the HWP contribution as well as the conversion factors to carbon weight applied for each subcategory. The United States did not complete CRF table 4.Gs2 and only reported the values of paper and paperboard for 1990–2017 and changed the notation key from "NA" to "IE" for sawnwood and wood panels. During the review, the Party explained that the relevant information for HWP will be provided in its 2020 submission.	Work is planned to improve reporting of HWP in the CRF for the 2021 submission.
L.35	4.H Other (LULUCF) – CO_2 (L.31, 2018) (L.17, 2016) (L.17, 2015) (96, 2013) (112, 2012) Accuracy	Not resolved. Reflect the intersectoral linkages and document the differences in the decay values for yard trimmings and food scraps to ensure the consistent use of decay values across the whole inventory. The CH_4 emissions from yard trimmings and food scraps are reported in the waste sector as part of total CH_4 emissions from MSW. As disaggregated CH_4 emissions from yard trimmings and food scraps are not reported in the waste sector (NIR p.6-120), it is not possible to check the relationship or consistency between the carbon storage and the CH_4 emissions from yard trimmings and food scraps. During the review, the Party explained that the relevant information will be provided in future submissions. See also ID# L.36 below for information on documentation.	This issue was resolved with the 2020 NIR, see explanation starting on page 6-132.
L.36	4.H Other (LULUCF) – CH_4 (L.60, 2018) Transparency	Not resolved. Report the complete calculation of the decay rates applied to yard trimmings and food scraps as well as information on the impact that the calculation has on the CH_4 emission rates applied to other MSW. The Party did not provide in the NIR a complete description of the calculation of decay rates (including an explanation as to how the decay rates were derived), or information on the impact of these decay rates on the CH_4 emission rates applied to other MSW. During the review, the Party clarified that it will address this recommendation in the 2021 submission.	This issue is resolved with 2020 submission. Discussion of decay rates begins at the end of page 6-131 in NIR (2020 submission).
L.37	4(III) Direct N_2O emissions from N mineralization/ immobilization – N_2O (L.61, 2018) Completeness	Not resolved. Estimate N_2O emissions associated with the mineralization of the N content of SOC losses in mineral soils for forest land, wetlands, settlements and other land, as well as for their conversion to and from cropland and grassland, using the IPCC default method and factors (2006 IPCC Guidelines, vol. 4, chap. 11) or, where available, country-specific methods or factors, and report the estimations in CRF table 4(III) and the NIR. Direct N_2O emissions associated with the mineralization of the N content of SOC losses in mineral soils were not estimated. The Party continued to report "NE" in CRF table 4(III) for forest land remaining forest land and settlements (both remaining and converted) and "NA" for land converted to forest land, land converted to cropland, grassland (both	Work is underway to report these emissions for all land categories in future submissions.

		remaining and converted), wetlands (both remaining and converted) and other land. During the review, the Party acknowledged that the correct notation keys should be "IE" for land converted to cropland and grassland, and "NE" for land converted to forest land and other land. The Party also clarified that land converted to wetlands leads to a gain in soil carbon and so "NA" is the appropriate notation key to use.	
L.38	4(IV) Indirect N_2O emissions from managed soils – N_2O (L.62, 2018) Completeness	Not resolved. Estimate indirect N_2O emissions associated with the mineralization of the N content of SOC losses in mineral soils for forest land, wetlands, settlements and other land and report them in CRF table 4(IV), and explain the estimations in the NIR. Both direct and indirect N_2O emissions associated with the mineralization of the N content of SOC losses in mineral soils were explained as not estimated in the NIR for forest land (p.6-50) and settlements (p.6-112) and therefore not included in the reported indirect N_2O emissions in CRF table 4(IV) (the ERT notes that this is relevant to N fertilization only). During the review, the Party clarified that indirect N_2O emissions associated with the mineralization of the N content of SOC losses in mineral soils for wetlands and other land are not estimated either. The Party explained that estimating indirect N_2O from N mineralization for all land-use categories is a planned improvement that will be implemented for either the 2020 or 2021 inventory submission.	Work is underway to report these emissions for all land categories in future submissions.
L.39	4(V) Biomass burning – CO_2, CH_4 and N_2O (L.35, 2018) (L.42, 2016) (L.33, 2015) Completeness	Not resolved. Noting that CH_4 and N_2O emissions from forest fires are key categories, estimate CH_4 and N_2O emissions from biomass burning for land converted to forest land, land converted to wetlands, cropland, grassland and settlements; and populate CRF table 4(V). CH_4 and N_2O emissions from biomass burning from forest land and grassland are estimated but all burning is reported under forest land remaining forest land and grassland remaining grassland. The Party explained that it is currently unable to report separately the emissions from land converted to forest land and land converted to grassland. Biomass burning from wildfires on cropland and biomass burning on wetlands and settlements were not estimated owing to a lack of data.	As noted in our original response, we are unable to report on these emissions at the level of land use conversion, but we will continue to explore approaches for doing this.
L.38	4(IV) Indirect N_2O emissions from managed soils – N_2O (L.62, 2018) Completeness	Not resolved. Estimate indirect N_2O emissions associated with the mineralization of the N content of SOC losses in mineral soils for forest land, wetlands, settlements and other land and report them in CRF table 4(IV), and explain the estimations in the NIR. Both direct and indirect N_2O emissions associated with the mineralization of the N content of SOC losses in mineral soils were explained as not estimated in the NIR for forest land (p.6-50) and settlements (p.6-112) and therefore not included in the reported indirect N_2O emissions in CRF table 4(IV) (the ERT notes that this is relevant to N fertilization only). During the review, the Party clarified that indirect N_2O emissions associated with the mineralization of the N content of SOC losses in mineral soils for wetlands and other land are not estimated	Work is planned to report on this information in a future submission.

		either. The Party explained that estimating indirect N_2O from N mineralization for all land-use categories is a planned improvement that will be implemented for either the 2020 or 2021 inventory submission.	
L.39	4(V) Biomass burning – CO_2, CH_4 and N_2O (L.35, 2018) (L.42, 2016) (L.33, 2015) Completeness	Not resolved. Noting that CH_4 and N_2O emissions from forest fires are key categories, estimate CH_4 and N_2O emissions from biomass burning for land converted to forest land, land converted to wetlands, cropland, grassland and settlements; and populate CRF table 4(V). CH_4 and N_2O emissions from biomass burning from forest land and grassland are estimated but all burning is reported under forest land remaining forest land and grassland remaining grassland. The Party explained that it is currently unable to report separately the emissions from land converted to forest land and land converted to grassland. Biomass burning from wildfires on cropland and biomass burning on wetlands and settlements were not estimated owing to a lack of data.	Work is planned over the next few years to utilize supplemental data sources to improve our ability to go back to 1971 as part of the land representation.
L.41	4. General (LULUCF) – CO2, CH4 and N2O Transparency	The United States indicated for the first time in its inventory the preliminary estimates of the land areas of the United States territories (Puerto Rico, Virgin Islands, Guam, Northern Mariana Islands, and American Samoa) in the planned improvements section of the NIR (box 6-2, p.6-21), showing the efforts made so far to incorporate area data by land-use type fully for the United States territories (see ID# L.2 in table 3). The NIR states that the preliminary estimates of these land areas represent 0.1 per cent of the total land base of the United States. The ERT is of the view that the Party could also report preliminary estimates of emissions or removals and provide a preliminary analysis of the impact and significance of emissions or removals from each of these land areas compared with the total LULUCF emission estimates, in order to increase the transparency of the information in the inventory. The ERT recommends that the United States report in the NIR preliminary emission or removal estimates for the land areas of the United States territories reported as a preliminary result of the planned improvement carried out in the Party's inventory.	Work to improve the land representation and tracking of managed/unmanaged land will be initiated in 2021 with the goal of updating this chapter for the 2022 or 2023 submission.
L.42	Land Representation – CO2, CH4 and N2O. Accuracy	The United States reported that, for land converted to cropland, grassland and settlements, the historical areas cumulate from 1979, so that for 1999 onward a 20-year cumulated area is reported (NIR pp.6-53, 6-68 and 6-102), and for land converted to forest land, the historical areas are cumulated from 1982, so that for 2002 onward, a 20- year cumulated area is reported (NIR p.6-44). The ERT noted that the gap in historical data from 1971 to 1978 for land converted to cropland, grassland and settlements, and from 1971 to 1981 for land converted to forest land, has an impact on the level of, and trend in, carbon stock changes and associated emissions and removals reported in all land conversion and land remaining categories. The ERT further noted that this leads to an underestimation of the areas of land	We will improve the transparency of reporting for the 2021 submission.

		conversion categories for 1990–1997 (for cropland, grassland and settlements) and 1990–2001 (for forest land) and therefore must have some impact on the time-series trend of emissions and removals in the LULUCF sector. During the review, the Party explained that it is planning to use Landsat data to fill gaps in the area data up to 1971 and that this will be included in future submissions. The ERT recommends that the United States include the land-use changes that occurred during the periods 1971– 1978 for land converted to cropland, grassland and settlements, and 1971–1981 for land converted to forest land, in order to ensure that the areas of land converted categories for all inventory years since 1990 contain the accumulated total of the land-use changes over the past 20 years.	
L.43	Land Representation – CO2, CH4 and N2O Accuracy	The United States classified its national land into managed land and unmanaged land, as reported in the NIR (table 6-6, p. 6-9). The area of unmanaged grassland has increased over the time series owing to the conversion from managed grassland to unmanaged grassland. During the review, in response to a previous recommendation (see ID# L.22), the Party clarified its approach to classifying managed and unmanaged land, which is that land is classified as unmanaged 20 years after the last direct human intervention on that land. The Party further clarified that this is consistent with the period of time for tracking the influence of land-use change on GHG emissions and removals. In the case of conversions from managed to unmanaged land, the land is no longer directly influenced by human activity, so there are no further effects on anthropogenic emissions and removals to be estimated after the 20- year period. The Party also informed the ERT that the current area of unmanaged grassland is considered to be overestimated for Alaska and will be corrected in the next submission. The ERT recommends that the United States revise the area of unmanaged grassland for Alaska and report on the changes in the NIR. The ERT also recommends that the Party increase the transparency regarding the approach to classifying managed and unmanaged land and include a specific example of the change from managed land to unmanaged land in the NIR, because this type of land-use change is not common in the inventory reporting of other Parties.	This issue was resolved with the 2020 submission, see page 6-95, Table 6-54.
L.44	4.A Forest land 4(II) Emissions and removals from drainage and rewetting and other management of organic/mineral soils – CO2, CH4 and N2O Transparency	In response to a previous recommendation (see ID# L.12), the United States explained that carbon stock changes in forest organic soils (reported in CRF table 4.A) and CO2 emissions from drained forest organic soils (reported in CRF table 4(II)) are calculated separately. The Party also explained that these emissions are not double- counted. The ERT checked the method applied by the Party and concluded that the emission estimates are consistent, but that the information should be more clearly explained in the NIR. The ERT recommends that the United States provide information regarding which emissions or removals are estimated under carbon stock	Work is planned to report on this information in a future submission.

		change in forest organic soils (category 4.A) and drained forest organic soils (category 4(II)) and how it avoids double counting of emissions between the two sources in the NIR and in the relevant documentation boxes of CRF tables 4.A and 4(II).	
L.45	4(II) Emissions and removals from drainage and rewetting and other management of organic/mineral soils – N2O. Convention reporting adherence	The United States made the assumption that 100 t peat are extracted from 1 ha peat area in a single year (NIR p.6- 86). Therefore, for the same soil types (nutrient-rich or nutrient-poor), the area of peat production (ha) should be represented as a number 10 times higher than the peat production amount (kt). However, the ERT noted that the area of nutrient-rich peat production in NIR table 6-50 (660 ha) is correlated to the amount of nutrient-poor peat production (NIR table 6-48: 66 kt) for the entire time series instead of being correlated to nutrient-rich peat production (NIR table 6-48: 374 kt). During the review, the Party clarified that the area of nutrient-rich peat production in NIR table 6-50 was reported incorrectly but that the correct values (e.g. 3,740 ha in 2017) were used in the inventory to calculate N2O emissions. The ERT checked CRF table 4(II) and confirmed that N2O emissions were estimated using the correct area for nutrient-rich peat production. The ERT recommends that the United States correct the area of nutrient-rich peat production in NIR table 6-50.	Work is planned to improve reporting of HWP in the CRF for the 2021 submission.
Waste			
W.1	5. General (waste) – CO_2, CH_4 and N_2O (W.1, 2018) (W.9, 2016) (W.9, 2015) Transparency	Not resolved. Provide background information that is consistent with the data actually used for the emission estimates, including the waste management practices. The United States did not provide background information that is consistent with the data used for emission estimates. The Party continues to report data from different data sources in table 3-27 (p.3-53, energy section), figure 7-3 (p.7-17) and table A-235 (annex 3.14, p.A-387). During the review, the Party explained that it provided information on waste management practices in accordance with national circumstances and is still looking into differences between the data provided by BioCycle and the Earth Engineering Center of Columbia University in surveys on the state of waste in the country and EPA data on MSW in the country, including for AD for waste incineration. The Party indicated that this issue will be resolved in future submissions.	Explanation of the differences between the waste quantity data sources is provided. See 2020 NIR submission starting on pp A-461. See response to W.11 below.
W.2	5.A Solid waste disposal on land – CH_4 (W.3, 2018) (W.3, 2016) (W.3, 2015) (101 and 104, 2013) Accuracy	Not resolved. Revise the estimates of emissions from solid waste disposal on land by incorporating the revised DOC values into the emission estimation. The United States continues to use a constant value for DOC across the time series which does not capture any changes in waste composition over the time series. During the review, the Party explained that the composition of MSW sent to landfill is generally not available for many of the 1,500 active MSW landfills in the United States and therefore the composition is estimated at the national level. The Party is investigating possible variations on the national waste	With regard to municipal solid waste (MSW) landfills, the United States has collected all publicly available and online MSW characterization study data since 1990. A limited number of studies are available that are not representative of the large number of landfills nationwide. In addition, the level of detail in individual waste composition studies varies significantly. While we can provide the list of studies examined, we will not be conducting additional activities to refine the DOC

		composition on the basis of site-specific waste composition studies and will summarize this information in the 2021 submission at the earliest. See ID# W.3 below.	value for MSW landfills. The DOC value of 0.2 is applied for 1990-2004 only and is considered representative of waste disposed. The methodology for 2005 to 2016 uses directly reported methane emissions to the GHGRP, a regulation that defines DOC values that can be applied. Updates to DOC value(s) for 2005 to 2016 must be considered in context of updates to methods in the GHGRP via the regulatory process.
W.3	5.A Solid waste disposal on land – CH_4 (W.4, 2018) (W.4, 2016) (W.4, 2015) (104, 2013) (125, 2012) Transparency	Not resolved. Report the composition of waste landfilled, with the amounts/shares and corresponding coefficients, including DOC. The United States clarified during the review that it is still investigating studies of waste characteristics which are due to be completed across the country, including any variations on the national waste composition. The Party also clarified that landfill-specific waste composition studies are only available for a small number of landfills and for specific years and that, owing to national circumstances, it is unlikely that efforts to obtain such information will be supported in the near future, as it would jeopardize resources for estimating other key categories. It therefore requested that the ERT consider this issue to be resolved on the basis of national circumstances. However, the ERT noted that, as per the original recommendation, this issue relates to ID# W.2 above. Therefore, as soon as the Party provides the summary of the results of the investigation (as mentioned in ID# W.2 above) the ERT will be able to evaluate this issue further.	See response to W.2 from ARR for 2019.
W.4	5.A.1 Managed waste disposal sites – CH_4	Not resolved. Include detailed information on the methods and parameters used by the facilities to estimate net CH_4 emissions and how the estimates are chosen for the national inventory when alternative estimates of net CH_4 emissions (e.g. from facilities that recover CH_4) are also produced. The United State clarified during the review that this recommendation will be addressed in the 2020 submission.	This was addressed in the 2020 submission. Significant detail was added to Annex 3.14 to address the methods used to estimate net CH_4 emissions including those for facilities that recover CH_4 across the time series. See 2020 NIR submission starting on pp. A-460.
W.5	5.A.1 Managed waste disposal sites – CH_4 (W.15, 2018) Transparency	Not resolved. The Party used the top-down tier 2 first-order decay method from the 2006 IPCC Guidelines (volume 5, chapter 3, section 3.2.1) for estimating CH_4 emissions for 1990–2004. To estimate CH_4 emissions for 2005 onward, the Party used a country-specific bottom-up method using directly reported net CH_4 emissions (i.e. the difference between the CH_4 generated and the CH_4 recovered) from GHGRP in combination with a scale-up factor to account for facilities that do not need to report to GHGRP. The ERT notes that (1) the methodologies that the facilities are using to produce estimates of net CH_4 emissions reported in GHGRP are not described in detail in the NIR, which makes it difficult to assess the accuracy of those estimates; (2) the rationale for choosing 2005 as the start of the bottom-up estimation method is not provided in the NIR; and (3) the assumption of a 9	This was addressed in the 2020 submission. See 2020 NIR submission starting on pp. A-460

		per cent scale-up factor for estimating emissions from non-reporting facilities for 2005 onward is not described in the NIR. As a result, the ERT finds it impossible to assess both the accuracy of the bottom-up method and the consistency of the time series 1990–2016. During the review (e.g. 2018 submission), the Party provided information on the methods and parameters that the facilities use to produce the estimates of net CH4 emissions. The Party also explained that facilities that recover CH4 also produce alternative estimates of net CH4 emissions using a back-calculation method, and clarified how it selects which of the two estimates provided by the facilities to use in the national inventory. The Party also provided information on the analysis that was done in order to select a suitable year to start using the new bottom-up method. In that regard, it provided and discussed a relevant technical report (RTI International, 2017). Another technical report (RTI International, 2018) was provided by the Party and discussed, which covers the methodologies used and analysis conducted in order to produce a scale-up factor for non-reporting facilities. Include in the NIR a summary of the process to select the year to start using the new bottom-up method. See ID# W.4 above.	
W.6	5.A.1 Managed waste disposal sites – CH4 (W.15, 2018) Transparency	Not resolved. Include in the NIR a summary of the methodologies used and analysis conducted in order to produce a scale-up factor for non- reporting facilities. The United States provided a link during the review to the same technical report (RTI, 2018) that was provided to the previous ERT. The report covers the methodologies used and analysis conducted in order to produce a scale-up factor for non-reporting facilities. However, the Party did not include a summary of the methodologies or provide a text with a reference to the link for the technical report (RTI, 2018) to clarify the methodologies used or analysis conducted. During the review, the Party clarified that it will address this recommendation in the 2020 submission.	This was addressed in the 2020 submission. See 2020 NIR submission pp. A-469
W.7	5.A.1.a Anaerobic – CH4 (W.16, 2018) Comparability	Addressing. Estimate and report the amounts of CH4 flared and CH4 for energy recovery for anaerobic waste disposal sites, but, until that is possible, report them as “NE” instead of “IE” in CRF table 5.A. The Party reported both the amount of CH4 flared and the amount of CH4 for energy recovery using “NE” in CRF table 5.A instead of estimating the amount of CH4 flared and the amount of CH4 for energy recovery. During the review, the Party explained the use of directly reported GHGRP net emissions and the rule that does not require facilities to report separately the total amounts of CH4 recovered for energy versus CH4 flared. The 2006 IPCC Guidelines (vol. 5, chap. 3, p. 3.18) state that emissions from flaring are however not significant, as the CO2 emissions are of biogenic origin and the CH4 and N2O emissions are very small. However, in the case of the amount of CH4 for energy recovery, the Party identified the quantity of recovered CH4 using equation HH-4 of the GHGRP (NIR p. A-391) and explained that CH4 recovery was based on data from the LandFill Gas-to-Energy project (NIR p. A-390). The ERT notes that the 2006 IPCC Guidelines (vol. 5, chap. 3, p. 3.18) state that if the recovered	This was addressed in the 2020 submission. See CRF Tables 5.A and Table 9 of the 2020 submission and NIR Annex 5. The CH4 has been reported as NE.

		gas is used for energy, then the resulting GHG emissions should be reported under the energy sector. They also state (p. 3.19) that reporting based on metering of all gas recovered for energy and flaring, or reporting gas recovery based on the monitoring of produced amount of electricity from the gas, is consistent with good practice. The ERT is of the view that CH4 recovery for energy could be calculated using the estimation from electricity monitoring (in accordance with the 2006 IPCC Guidelines). The Party could report the amount of CH4 for energy recovery in CRF table 5.A and include an explanation in the NIR, taking into account the good practice outlined in the 2006 IPCC Guidelines.	
W.8	5.A.1.a Anaerobic – CH4 (W.7, 2018) (W.12, 2016) (W.11, 2015) Accuracy	Addressing. Obtain up-to-date data on the type and fractions of organic waste placed in industrial waste landfills; and revise the CH4 estimates for all major industrial waste landfills. The NIR (p.7-11) referred to a technical memorandum mentioned during the previous review (RTI, 2018). The Party explained during the review that this technical memorandum provides information on an EPA analysis to validate the assumption that most of the organic waste which would result in CH4 emissions is disposed of at pulp, paper and food processing facilities (54 per cent) and food manufacturing facilities (7 per cent). According to the analysis, the total waste disposed of by facilities under each primary North American Industrial Classification System reported in 2016 was calculated in order to determine that 93 per cent of the total organic waste quantity originates from either the pulp and paper, or food and beverages sector (NIR p.7-11). The Party also made reference to the uncertainty section (NIR p.7-13), which explains the uncertainty values applied to the waste disposal and CH4 generation information on industrial waste landfills. The ERT notes that there are approximately 1,200 industrial waste landfills in the country but only 172 meet the reporting threshold of the GHGRP (for which data are available).	This is ongoing work, progress and/or results of which will be addressed in the 2021 submission.
W.9	5.B.2 Anaerobic digestion at biogas facilities – CH4 (W.8, 2018) (W.14, 2016) (W.13, 2015) Transparency	Not resolved. Estimate and report CH4 emissions from unintentional leakages using the default value of 5 per cent provided in the 2006 IPCC Guidelines. The United States did not estimate CH4 emissions as required. The Party explained during the review that it is investigating the data sources and practices of anaerobic digestion and will assess the addition of a 5 per cent factor to account for unintentional leakages for the 2021 submission.	Addressing. Party intends to include emissions from stand alone anaerobic digestion facilities starting in the 2021 submission.
W.10	5.B.2 Anaerobic digestion at biogas facilities – CH4 and N2O (W.17, 2018) Transparency	Not resolved. The Party did not add the required information for “NE” used for CH4 and N2O under category 2.B.2.b (other) in CRF table 9. During the review the Party explained that basic research has been initiated which indicates that some activity for this category occurs in the United States, but EPA needs to conduct further research on available AD for estimating emissions.	This was addressed in the 2020 submission. See CRF table 9.

W.11	5.C.1 Waste incineration – CO_2, CH_4 and N_2O (W.10, 2018) (W.15, 2016) (W.14, 2015) Transparency	Not resolved. Provide in the NIR consistent information on the data that are used for the estimation of emissions from waste incineration (e.g. on the percentage of waste incinerated in 2013 reported in figure 7-2 and tables 3-26 and A- 272 of the 2016 NIR). There are still inconsistencies in the information on MSW incineration in the NIR, such as between figure 7-2 (p.7-16) (12.8 per cent) and table 3-27 (p.3-53) (7.6 per cent). The ERT also notes that table A-133 (p.A-214) presents the amount of plastic incinerated (7 per cent). The table A-272 mentioned by the previous ERT corresponds to table A-235 (p. A- 387) in the 2019 submission, but the ERT could not find any reference to the amount of waste incinerated in this table. The main difference between table A-235 and figure 7-2 relates to the amount of waste landfilled (52.5 per cent in figure 7-2 and 64 per cent in table A-235) (see ID# W.1 above). During the review, the United States explained that the percentage of waste incineration shown in figure 7.2 comes from a different source from that used in table 3-27 and does not represent the data used in the analysis for estimating emissions from waste incineration. However, the ERT is of the view that data in the NIR should be consistent across the waste and energy sectors and cross-references should be provided in the NIR for the descriptions of the methodology and AD used and any inconsistencies should be clearly explained.	The United States reiterates that different methods and data are used for determining emissions from Waste Incineration and emissions from Landfilling. The methods (i.e. tiers) applied to estimate emissions differ so therefore data listed will not necessarily be consistent, however this is not inconsistent with the 2006 IPCC Guidelines. See for example Annex 3.7 of the NIR where the Party describes the differences between the main data sources used to determine waste incineration emissions. Data from the Biocycle's State of Garbage in America report is assumed to be the best data to determine overall percent of waste incinerated however it does not have data on waste characterization. The U.S. EPA Facts and Figures report has data on waste characterization which is combined with the overall amount of waste incinerated to determine emissions. Emissions from landfilling is based on different data sources including direct data from the GHRP. The differences in the two waste reports are what leads to the inconsistencies shown in the different tables and figures in the report across the waste incineration and landfilling sections in terms of percent of waste incinerated and landfilled. However, since that data is not used directly in the calculations (as indicated in the report) there are no inconsistencies in the methodology and AD used.
W.12	5.C.1 Waste incineration – CO_2, CH_4 and N_2O (W.18, 2018) Transparency	Not resolved. Ensure that the 2019 NIR indicates that the emissions from the incineration of non-hazardous industrial waste referred to in the 2018 NIR are in fact emissions from the incineration of hazardous industrial waste and already included in the inventory by (a) correcting the entry in annex 5 to the NIR, p.A-427, section on category 1.A.5.a (CO_2 emissions from non-hazardous industrial waste incineration and medical waste incineration); (b) correcting the entry in annex 5 to the NIR, table A-266, row on category 1.A.5.a; and (c) changing the notation key reported for CO_2, CH_4 and N_2O emissions for category 5.C.1 (non-biogenic (other)) from "NA" to "IE" in CRF table 5.C and explaining in CRF table 9 where the	This issue was addressed in the latest submission. Annex 5 of the NIR was updated as well as the CRF category 5.C.1 (non-biogenic (other)) now reads "IE" and information is included in Table 9 that incineration emissions are included under energy.

		emissions are included. There are no changes to the NIR or CRF table 5.C in the 2019 submission. The Party indicated during the review that this recommendation will be addressed in the 2020 submission.	
W.13	5.D.2 Industrial wastewater – CH4 (W.14, 2018) (W.5, 2016) (W.5, 2015) (105, 2013) Completeness	Not resolved. Include information on the non-estimation of CH_4 emissions from sludge under industrial wastewater. The Party did not include information on emissions from sludge in the NIR. During the review, the Party explained that sludge removed from industrial wastewater is not estimated owing to insufficient data and that an explanation will be added in annex 5 to the next submission in line with paragraph 37(b) of the UNFCCC Annex I inventory reporting guidelines.	This will be included in Annex 5 in the 2021 submission.
W.14	5.A Solid waste disposal on land – CH4 Transparency	The United States reported in the NIR (annex 3.14, p. A-391) the use of a default value (0.75) for collection efficiency at landfills. The 2006 IPCC Guidelines (vol. 5, chap. 3, box 3.1) note that the use of a collection efficiency will need to be researched and justified in order to be used with confidence. During the review, the United States informed the ERT that the collection efficiency value was developed by EPA and is referenced in EPA AP-42 section 2.4 (see https://www3.epa.gov/ttn/chief/ap42/ch02/index.html). The justification for the use of a collection efficiency of 0.75 includes a consideration of the availability of data such as surface monitoring under the EPA new source performance standards for MSW landfills. During the review, the Party explained that the categories of collection efficiency used in landfill gas estimation vary according to the gas collection activity and types and thickness of final soil cover included in the formula of weighted average collection efficiency of the landfill. The Party also indicated that the collection efficiency range of United States landfills with gas collection is between 60 and 85 per cent, with the average value of 75 per cent considered as the default value. The ERT considers that the information on collection efficiency used in the NIR is based on well-documented research and is justified but, for improved transparency, more information should be included in the NIR. The ERT recommends that the United States include in the NIR the explanation provided to the ERT above on how the collection efficiency default value of 0.75 was derived to justify its confidence in the collection efficiency value used.	This was addressed in the 2020 submission. See 2020 NIR submission pp. A-472
W.15	5.A.1 Managed waste disposal sites – CH4 Transparency	The ERT noted that the United States reported in the NIR (pp.7-7, 7-11 and A-394) that the oxidation factor is directly reported to the GHGRP. The GHGRP allows facilities to use varying oxidation factors depending on their facility-specific calculated CH4 flux rate (i.e. 0, 10, 25 or 35 per cent) and an average value of 20 per cent was used in the inventory. The 2006 IPCC Guidelines state that the oxidation factor is very uncertain because it is	This was addressed in the 2020 submission. See 2020 NIR submission starting at bottom of pp. A-473

		difficult to measure, varies considerably with the thickness and nature of the cover material, atmospheric conditions and climate, the flux of methane, and the escape of methane through cracks/fissures in the cover material (vol. 5, chap. 3, p.3.26) and that the use of an oxidation value higher than 0.1 should be clearly documented, referenced and supported by data relevant to national circumstances (vol. 5, chap. 3, p.3.15). During the review, the Party explained that the methodology and oxidation factors used in the GHGRP were developed on the basis of published, peer-reviewed literature and through external stakeholder engagement. Justification for the use of an oxidation factor higher than 0.1 considers cover types of material including the thickness of the soil (RTI, 2012). This document contains default values for oxidation with seven categories of oxidation factor used. Thickness of soil cover greater than 12 inches is the main condition for considering an oxidation factor above 0.1. The 2006 IPCC Guidelines (vol. 5, chap. 3, table 3.5) indicate the uncertainty analysis of the oxidation factor for a non-zero value. The ERT considers that, according to the 2006 IPCC Guidelines, the use of an oxidation factor higher than 0.1 should be documented clearly with references and supported by data relevant to national circumstances, including an uncertainty analysis. The ERT recommends that the United States include information to justify the oxidation factor used, including references and supporting data relevant to national circumstances as well as an uncertainty analysis for the oxidation factor applied in the estimation.	

ANNEX 9 Use of EPA Greenhouse Gas Reporting Program in Inventory

This Annex provides background information on the Greenhouse Gas Reporting Program (GHGRP) and its relationship to this Inventory. The U.S. Environmental Protection Agency (EPA) tracks U.S. greenhouse gas emissions through two complementary programs: the Inventory (estimates in this report), and the GHGRP. The Inventory provides a comprehensive accounting of all emissions from source categories identified in the *2006 IPCC Guidelines* needed to understand the United States' total net greenhouse gas emissions in line with the UNFCCC reporting guidelines, while the GHGRP provides bottom-up detailed information that helps improve understanding of the sources and types of greenhouse gas emissions at individual facilities and suppliers. The GHGRP provides facility-level greenhouse gas data from major industrial sources across the United States, it does not provide full coverage of total annual U.S. GHG emissions (e.g. the GHGRP excludes emissions from the agricultural, land use, and forestry sectors).

On October 30, 2009, the EPA published a regulation requiring annual reporting of greenhouse gas data from large facilities[168] in the United States. The program implementing the regulation, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP). The GHGRP covers sources or suppliers in 41 industrial categories ("Subparts"[169]), including direct greenhouse gas emitters,[170] fossil fuel suppliers, industrial gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons.[171] In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year.[172]

Facilities in most source categories subject to the GHGRP began collecting data in 2010 while additional types of industrial operations began collecting data in 2011. Currently, more than 8,000 facilities and suppliers are required to report their data annually. Facilities calculate their emissions using methodologies that are specified at 40 CFR Part 98, and they report their data to EPA using the electronic Greenhouse Gas Reporting Tool (e-GGRT). Annual reports covering emissions from the prior calendar year are due by March 31st of each year. EPA verifies reported data through a multi-step process to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. All reports submitted to EPA are evaluated by electronic validation and verification checks, including industry-specific checks. If potential errors are identified, EPA will notify the reporter, who can resolve the issue either by providing an acceptable response describing why the flagged issue is not an error or by correcting the flagged issue and resubmitting their annual greenhouse gas report.[173]

The reported data are made available to the public each fall. EPA presents the data collected by its GHGRP in a number of ways, such as through a data publication tool known as the Facility Level Information on GHGs Tool (FLIGHT). FLIGHT allows data to be viewed in several formats including maps, tables, charts and graphs for individual facilities or groups of facilities.[174] More information on the GHGRP can be found at https://www.epa.gov/ghgreporting.

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[168] Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases (i.e., reporting at the corporate level).
[169] See <https://www.epa.gov/ghgreporting/resources-subpart-ghg-reporting>.
[170] Data reporting by affected facilities includes the reporting of emissions from fuel combustion at that affected facility.
[171] See <https://www.epa.gov/ghgreporting/resources-subpart-ghg-reporting> and <http://ghgdata.epa.gov/ghgp/main.do>.
[172] For some industrial categories ("Subparts") under the GHGRP, facilities must report if their combined emissions from stationary fuel combustion and all applicable source categories are above a given threshold (e.g., 25,000 metric tons CO_2 Eq. or more per year or another industry-specific threshold). For other source categories, new facilities must report regardless of their quantity of annual emissions. These categories include, for example, cement production (Subpart H) and aluminum production (Subpart F). However, any facility regardless of threshold can cease reporting if its emissions fall below 25,000 metric tons CO_2 Eq. for five years or below 15,000 metric tons CO_2 Eq for three years, and it informs EPA of its intention to cease reporting and the reason(s) for any reduction in emissions. See 40 CFR 98.2(a), 98.2(i), and Tables A-3, A-4, and A-4 for more information.
[173] See GHGRP Verification Fact Sheet https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.
[174] See <http://ghgdata.epa.gov>.

The GHGRP dataset is an important resource for the Inventory. EPA uses GHGRP data in a number of categories to improve the national estimates, consistent with IPCC Guidance, as summarized in Table A-258 below. Methodologies used in the GHGRP are consistent with methods in 2006 IPCC Guidelines, in particular "higher tier" methods which include collecting facility or plant-specific measurements. The GHGRP provides not only annual emissions information for reporting facilities and suppliers, but also other annual information, such as activity data and emission factors that can be used to improve and refine national emission estimates and trends over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing application of QA/QC procedures and assessment of uncertainties. Consistent with considerations outlined in the *Technical Bulletin 1 on Use of Facility-Specific Data in National Greenhouse Gas Inventories* from the IPCC Task Force on National Greenhouse Gas Inventories, (IPCC 2011),[175] EPA has paid particular attention both to ensuring completeness in national coverage of emission estimates over time and to ensuring time-series consistency by recalculating emissions for 1990 to 2010/2011 when incorporating GHGRP data into source categories estimates.[176] These issues are discussed further in the chapters where source category emissions estimates use GHGRP data. Source category definitions are also considered in order to ensure completeness when using GHGRP data. For certain source categories in the Industrial Process and Product Use chapter, EPA has relied on data values that have been calculated by aggregating GHGRP data that are considered confidential business information (CBI) at the facility level. EPA, with industry engagement, has put forth criteria to confirm that a given data aggregation shields underlying CBI from public disclosure. EPA is only publishing data values that meet these aggregation criteria.[177] Specific uses of aggregated facility-level data that are CBI are described in the respective methodological sections in Chapter 4 of the Inventory. Beyond the current uses, EPA continues to analyze the GHGRP data on an annual basis to identify other source categories where it could be further integrated in future editions of this report (see the Planned Improvement sections of those specific source categories for details).

[175] IPCC Task Force on National Greenhouse Gas Inventories (TFI) (2011). *Technical Bulletin 1: Use of Facility-Specific Data National Greenhouse Gas Inventories*. Available at https://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.
[176] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.
[177] U.S. EPA Greenhouse Gas Reporting Program. Confidential Business Information GHG Reporting. See <http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting>.

1 **Table A-258: Summary of EPA GHGRP Data Use in U.S. GHG Inventory**

GHG Inventory Category	GHGRP Industry Subpart	Initial Calendar Year of Reporting under GHGRP	Reporting Threshold[178]	Type of GHGRP Data Use				National GHG Inventory Report (NIR) Section with details on data use
				Emissions or Quantity Supplied	Emission Factor (EF)	Activity Data (AD)	QA/QC[179]	
Energy Sector								
Fossil Fuel Combustion: Industrial Sector	C - General Stationary Fuel Combustion Sources	2010	Y	•				Section 3.1 and Box 3-4
Coal Mining: Underground Mines	FF – Underground Coal Mines	2011	Y	•			•	3.4
Petroleum Systems	W – Petroleum and Natural Gas Systems; Y – Petroleum Refineries	2010, 2011	Y, N	•	•	•	•	3.6
Natural Gas Systems	W – Petroleum and Natural Gas Systems	2011	Y		•	•	•	3.7
Waste Incineration	C - General Stationary Fuel Combustion Sources	2010	Y			•		3.3
Industrial Processes and Product Use Sector								
Adipic Acid Production	E – Adipic Acid Production	2010	N	•				4.8
Aluminum Production	F – Aluminum Production	2010	N	•				4.19
Urea Consumption from Non-Agricultural Use	G – Ammonia Manufacturing	2010	N			•		4.6

[178] Y=25, 000 $MTCO_2$ Eq., or industry-specific threshold other than 25, 000 $MTCO_2$ Eq.; N = all facilities in industry category must report regardless of annual emissions. Information on industry-specific threshold and implications of the reporting threshold or lack of threshold in estimating national GHG emissions is discussed in the respective source category methodology sections.

[179] Consistent with IPCC good practices, QA/QC using GHGRP may not be appropriate if this is the primary data source for estimating emissions. Depending on use, other data sets may be more appropriate for QA/QC of Inventory estimates.

GHG Inventory Category	GHGRP Industry Subpart	Initial Calendar Year of Reporting under GHGRP	Reporting Threshold[178]	Type of GHGRP Data Use				National GHG Inventory Report (NIR) Section with details on data use
				Emissions or Quantity Supplied	Emission Factor (EF)	Activity Data (AD)	QA/QC[179]	
Carbon Dioxide Consumption	PP – Suppliers of Carbon Dioxide	2010	Y	•				4.15
Cement Production	H – Cement Production	2010	N			•	•	4.1
Electrical Transmission and Distribution	DD – Use of Electric Transmission and Distribution Equipment; SS - Manufacture of Electric Transmission and Distribution Equipment	2011	Y	•	•	•		4.25
HCFC-22 Production	O – HCFC-22 Production and HFC-23 Destruction	2010	Y	•				4.14
Lead Production	R – Lead Production	2010	Y				•	4.21
Lime Production	S – Lime Production	2010	N	•				4.2
Magnesium Production and Processing	T – Magnesium Production	2011	Y	•				4.20
Nitric Acid Production	V – Nitric Acid Production	2010	N	•	•	•		4.7
Petrochemical Production	X – Petrochemical Production	2010	N	•	•	•		4.13
Electronics Industry	I – Electronics Manufacturing	2011	Y	•				4.23

GHG Inventory Category	GHGRP Industry Subpart	Initial Calendar Year of Reporting under GHGRP	Reporting Threshold[178]	Type of GHGRP Data Use				National GHG Inventory Report (NIR) Section with details on data use
				Emissions or Quantity Supplied	Emission Factor (EF)	Activity Data (AD)	QA/QC[179]	
Substitution of ODS	OO – Suppliers of Industrial Gases; QQ - Imports and Exports of Equipment Pre–charged with Fluorinated GHGs or Containing Fluorinated GHGs in Closed–cell Foams	2010, 2011	N (producers) Y (all others)				•	4.24
Waste Sector								
MSW Landfills	HH - Municipal Solid Waste Landfills	2010	Y	•	•		•	7.1
Industrial Landfills	TT - Industrial Waste Landfills	2011	Y				•	7.1
Industrial Wastewater	II - Industrial Wastewater Treatment	2011	Y				•	7.2