2011 through 2013

For 2011 through 2013, for the primary and secondary producers, GHGRP-reported cover and carrier gases emissions data were used. For die and sand casting, some emissions data was obtained through EPA's GHGRP. The balance of the emissions for these industry segments were estimated based on previous Partner reporting (i.e., for Partners that did not report emissions through EPA's GHGRP) or were estimated by multiplying emission factors by the amount of metal produced or consumed. Partners who did not report through EPA's GHGRP were assumed to have continued to emit SF_6 at the last reported level, which was from 2010 in most cases. All Partners were assumed to have continued to consume magnesium at the last reported level. Where the total metal consumption estimated for the Partners fell below the U.S. total reported by USGS, the difference was multiplied by the emission factors discussed in the section above. For the other types of production and processing (i.e., permanent mold, wrought, and anode casting), emissions were estimated by multiplying the industry emission factors with the metal production or consumption statistics obtained from USGS. For 2013, pre-published USGS consumption statistics were obtained via communications with USGS (USGS 2013)

Uncertainty and Time Series Consistency

Uncertainty surrounding the total estimated emissions in 2013 is attributed to the uncertainties around SF_6, HFC-134a and CO_2 emission estimates. To estimate the uncertainty surrounding the estimated 2013 SF_6 emissions from magnesium production and processing, the uncertainties associated with three variables were estimated: (1) emissions reported by magnesium producers and processors for 2013 through EPA's GHGRP, (2) emissions estimated for magnesium producers and processors that reported via the Partnership in prior years but did not report 2013 emissions through EPA's GHGRP, and (3) emissions estimated for magnesium producers and processors that did not participate in the Partnership or report through EPA's GHGRP. An uncertainty of 5 percent was assigned to the emissions (usage) data reported by each GHGRP reporter for all the cover and carrier gases (per the *2006 IPCC Guidelines*). If facilities did not report emissions data during the current reporting year through EPA's GHGRP reporting program, SF_6 emissions data were held constant at the most recent available value reported through the Partnership. The uncertainty associated with these values was estimated to be 30 percent for each year of extrapolation. Alternate cover gas and carrier gases data was set equal to zero if the facilities did not report via the GHGRP program. One known sand caster (the lone Partner) has not reported since 2007 and its activity and emission factor were held constant at 2005 levels due to a reporting anomaly in 2006 because of malfunctions at the facility. The uncertainty associated with the SF_6 usage for the sand casting Partner was 85 percent. For those industry processes that are not represented in the Partnership, such as permanent mold and wrought casting, SF_6 emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-84). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. Emissions associated with die casting and sand casting activities utilized emission factors based on Partner reported data with an uncertainties of 75 percent. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Additional uncertainties exist in these estimates that are not addressed in this methodology, such as the basic assumption that SF_6 neither reacts nor decomposes during use. The melt surface reactions and high temperatures associated with molten magnesium could potentially cause some gas degradation. Previous measurement studies have identified SF_6 cover gas degradation in die casting applications on the order of 20 percent (Bartos et al. 2007). Sulfur hexafluoride may also be used as a cover gas for the casting of molten aluminum with high magnesium content; however, the extent to which this technique is used in the United States is unknown.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-84. Total emissions associated with magnesium production and processing were estimated to be between 1.3 and 1.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 11 percent below to 12 percent above the 2013 emission estimate of 1.5 MMT CO_2 Eq. The uncertainty estimates for 2013 are similar relative to the uncertainty reported for 2012 in the previous Inventory report.

Table 4-84: Approach 2 Quantitative Uncertainty Estimates for SF_6, HFC-134a and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq. and Percent)

Source	Gas	2013 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Magnesium Production	SF_6, HFC-134a, CO_2	1.5	1.3	1.7	-11%	+12%

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

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

In the current Inventory, emission estimates for alternate cover gases and carrier gas has been incorporated as the information is now available from EPA's GHGRP. The alternative cover gases have lower GWPs than SF_6, and tend to quickly degrade during their exposure to the molten metal. Magnesium producers and processors began using these cover gases starting in around 2006, as based on Partnership reported data. The amounts being used by companies on the whole are low and have a minor effect on the overall emissions from the industry. This is also attributable to their relatively lower GWPs. SF_6 has a GWP of 22,800, whereas HFC-134a has a GWP of 1,430. Similarly, EPA's GHGRP now provides access to data on carrier gases, allowing for this information to be integrated in the Inventory. Emissions of CO_2 have also been included in the total emissions from the industry. This has led to slight increase in overall emissions for each year compared to the previous Inventory. CO_2 carrier gas emissions have been included across the entire time series to ensure time series consistency.

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for SF_6. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

As a net result, emission estimates for each year from 1990 to 2013 have slightly decreased, relative to the previous Inventory report.

For one facility, a recalculation for 2011 SF_6 emissions was performed to ensure methodological consistency. The emissions for this facility and year were previously estimated using a company-specific growth rate based on data reported through the Partnership. This estimate has been revised by interpolating the reported emissions between 2010 and 2012, reported via the Partnership and EPA's GHGRP respectively. This has caused a slight increase in the SF_6 emissions for 2011 compared to the previous Inventory.

Planned Improvements

Cover gas research conducted over the last decade has found that SF_6 used for magnesium melt protection can have degradation rates on the order of 20 percent in die casting applications (Bartos et al. 2007). Current emission estimates assume (per the *2006 IPCC Guidelines*) that all SF_6 utilized is emitted to the atmosphere. Additional research may lead to a revision of the *2006 IPCC Guidelines* to reflect this phenomenon and until such time, developments in this sector will be monitored for possible application to the inventory methodology.

Usage and emission details of carrier gases in permanent mold, wrought and anode processes will be researched as part of a future inventory. Based on this research, it will be determined if CO_2 carrier gas emissions are to be estimated.

4.20 Lead Production (IPCC Source Category 2C5)

Lead production in the United States consists of both primary and secondary processes—both of which emit CO_2 (Sjardin 2003). Emissions from fuels consumed for energy purposes during the production of lead are accounted for in the Energy chapter.

Primary production of lead through the direct smelting of lead concentrate produces CO_2 emissions as the lead concentrates are reduced in a furnace using metallurgical coke (Sjardin 2003). Primary lead production, in the form of direct smelting, previously occurred at a single smelter in Missouri. This primary lead smelter was closed at the end of 2013. In 2014, the smelter processed a small amount of residual lead during demolition of the site (USGS 2015).

Similar to primary lead production, CO_2 emissions from secondary lead production result when a reducing agent, usually metallurgical coke, is added to the smelter to aid in the reduction process. Carbon dioxide emissions from secondary production also occur through the treatment of secondary raw materials (Sjardin 2003). Secondary production primarily involves the recycling of lead acid batteries and post-consumer scrap at secondary smelters. Of all the domestic secondary smelters operational in 2014, 12 smelters had capacities of 30,000 tons or more and were collectively responsible for more than 95 percent of secondary lead production in 2014 (USGS 2015). Secondary lead production has increased in the United States over the past decade while primary lead production has decreased. In 2014, secondary lead production accounted for nearly 100 percent of total lead production. The lead-acid battery industry accounted for about 90 percent of the reported U.S. lead consumption in 2014 (USGS 2015).

In 2014, total secondary lead production in the United States was slightly greater than that in 2013. Increased production at a couple of smelters was offset by temporary closure of one smelter. In March 2014, a producer temporarily shut down operations of a lead smelter in Vernon, CA (90,000 metric ton capacity smelter) due to environmental concerns from state regulators. The company intends to restart operations in 2015, after making improvements to the plant. Increases in exports of spent lead-acid batteries in recent years have decreased the amount of scrap available to secondary smelters (USGS 2015).

U.S. primary lead production decreased by approximately 99 percent from 2013 to 2014, and has decreased by almost 100 percent since 1990. This is due to the closure of the only domestic primary lead smelter in 2013 (year end). In 2014, U.S. secondary lead production was unchanged from 2013 levels, and has increased by 25 percent since 1990 (USGS 1995 through 2013, USGS 2014, 2015).

In 2014, U.S. primary and secondary lead production totaled 1,151,000 metric tons (USGS 2015). The resulting emissions of CO_2 from 2014 lead production were estimated to be 0.5 MMT CO_2 Eq. (518 kt) (see Table 4-85). The majority of 2014 lead production is from secondary processes, which accounted for almost 100 percent of total 2014 CO_2 emissions from lead production. At last reporting, the United States was the third largest mine producer of lead in the world, behind China and Australia, accounting for approximately 7 percent of world production in 2014 (USGS 2015).

Table 4-85: CO_2 Emissions from Lead Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	0.5	516
2005	0.6	553
2010	0.5	542
2011	0.5	538
2012	0.5	527

2013	0.5	546
2014	0.5	518

After a steady increase in total emissions from 1995 to 2000, total emissions have gradually decreased since 2000 and are currently at the 1990 levels.

Methodology

The methods used to estimate emissions for lead production are based on Sjardin's work (Sjardin 2003) for lead production emissions and Tier 1 methods from the *2006 IPCC Guidelines* (IPCC 2006). The Tier 1 equation is as follows:

$$CO_2\ Emissions = (DS \times EF_{DS}) + (S \times EF_S)$$

Where,

DS = Lead produced by direct smelting, metric ton
S = Lead produced from secondary materials
EF_{DS} = Emission factor for direct Smelting, metric tons CO_2/metric ton lead product
EF_S = Emission factor for secondary materials, metric tons CO_2/metric ton lead product

For primary lead production using direct smelting, Sjardin (2003) and the IPCC (2006) provide an emission factor of 0.25 metric tons CO_2/metric ton lead. For secondary lead production, Sjardin (2003) and IPCC (2006) provide an emission factor of 0.25 metric tons CO_2/metric ton lead for direct smelting, as well as an emission factor of 0.2 metric tons CO_2/metric ton lead produced for the treatment of secondary raw materials (i.e., pretreatment of lead acid batteries). Since the secondary production of lead involves both the use of the direct smelting process and the treatment of secondary raw materials, Sjardin recommends an additive emission factor to be used in conjunction with the secondary lead production quantity. The direct smelting factor (0.25) and the sum of the direct smelting and pretreatment emission factors (0.45) are multiplied by total U.S. primary and secondary lead production, respectively, to estimate CO_2 emissions.

The 1990 through 2014 activity data for primary and secondary lead production (see Table 4-86) were obtained from the USGS (USGS 1995 through 2013, 2014, 2015).

Table 4-86: Lead Production (Metric Tons)

Year	Primary	Secondary
1990	404,000	922,000
2005	143,000	1,150,000
2010	115,000	1,140,000
2011	118,000	1,130,000
2012	111,000	1,110,000
2013	114,000	1,150,000
2014	1,000	1,150,000

Uncertainty and Time-Series Consistency

Uncertainty associated with lead production relates to the emission factors and activity data used. The direct smelting emission factor used in primary production is taken from Sjardin (2003) who averaged the values provided by three other studies (Dutrizac et al. 2000, Morris et al. 1983, Ullman 1997). For secondary production, Sjardin (2003) added a CO_2 emission factor associated with battery treatment. The applicability of these emission factors to plants in the United States is uncertain. There is also a smaller level of uncertainty associated with the accuracy of primary and secondary production data provided by the USGS.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-87. Lead production CO_2 emissions were estimated to be between 0.4 and 0.6 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 15 percent below and 16 percent above the emission estimate of 0.5 MMT CO_2 Eq.

Table 4-87: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lead Production (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lead Production	CO_2	0.5	0.4	0.6	-15%	+16%

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

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, primary and secondary lead production quantities were revised to reflect the most recent USGS publication (USGS 2015). In the previous Inventory report, the 2013 primary and secondary lead production quantities were based on preliminary USGS estimates that were available at the time. This change resulted in a 4 percent increase in the 2013 emission estimate compared to the previous Inventory report.

Planned Improvements

Future improvements will involve evaluating and analyzing data reported under EPA’s GHGRP to improve the emission estimates for the Lead Production source category. Particular attention will be made to ensure time series consistency of the emission estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA’s GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA’s GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[32]

4.21 Zinc Production (IPCC Source Category 2C6)

Zinc production in the United States consists of both primary and secondary processes. Of the primary and secondary processes used in the United States, only the electrothermic and Waelz kiln secondary processes result in non-energy CO_2 emissions (Viklund-White 2000). Emissions from fuels consumed for energy purposes during the production of zinc are accounted for in the Energy chapter.

The majority of zinc produced in the United States is used for galvanizing. Galvanizing is a process where zinc coating is applied to steel in order to prevent corrosion. Zinc is used extensively for galvanizing operations in the automotive and construction industry. Zinc is also used in the production of zinc alloys and brass and bronze alloys (e.g., brass mills, copper foundries, copper ingot manufacturing, etc.). Zinc compounds and dust are also used, to a lesser extent, by the agriculture, chemicals, paint, and rubber industries.

---

[32] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

Primary production in the United States is conducted through the electrolytic process, while secondary techniques include the electrothermic and Waelz kiln processes, as well as a range of other metallurgical, hydrometallurgical, and pyrometallurgical processes. Worldwide primary zinc production also employs a pyrometallurgical process using the Imperial Smelting Furnace process; however, this process is not used in the United States (Sjardin 2003).

In the electrothermic process, roasted zinc concentrate and secondary zinc products enter a sinter feed where they are burned to remove impurities before entering an electric retort furnace. Metallurgical coke is added to the electric retort furnace as a carbon-containing reductant. This concentration step, using metallurgical coke and high temperatures, reduces the zinc oxides and produces vaporized zinc, which is then captured in a vacuum condenser. This reduction process also generates non-energy CO_2 emissions.

$$ZnO + C \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 1)}$$

$$ZnO + CO \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 2)}$$

In the Waelz kiln process, electric arc furnace (EAF) dust, which is captured during the recycling of galvanized steel, enters a kiln along with a reducing agent (typically carbon-containing metallurgical coke). When kiln temperatures reach approximately 1100-1200°C, zinc fumes are produced, which are combusted with air entering the kiln. This combustion forms zinc oxide, which is collected in a baghouse or electrostatic precipitator, and is then leached to remove chloride and fluoride. The use of carbon-containing metallurgical coke in a high-temperature fuming process results in non-energy CO_2 emissions. Through this process, approximately 0.33 metric tons of zinc is produced for every metric ton of EAF dust treated (Viklund-White 2000).

The only companies in the United States that use emissive technology to produce secondary zinc products are Horsehead, PIZO, and Steel Dust Recycling. For Horsehead, EAF dust is recycled in Waelz kilns at their Beaumont, TX; Calumet, IL; Palmerton, PA; Rockwood, TN; and Barnwell, SC facilities. These Waelz kiln facilities produce intermediate zinc products (crude zinc oxide or calcine), most of which was transported to their Monaca, PA facility where the products were smelted into refined zinc using electrothermic technology. In April 2014, Horsehead permanently shut down their Monaca smelter. This was replaced by their new facility in Mooresboro, NC. The new Mooresboro facility uses a hydrometallurgical process (i.e., solvent extraction with electrowinning technology) to produce zinc products. The current capacity of the new facility is 155,000 short tons, with plans to expand to 170,000 short tons per year. Direct consumption of coal, coke, and natural gas have been replaced with electricity consumption at the new Mooresboro facility. The new facility is reported to have a significantly lower greenhouse gas and other air emissions than the Monaca smelter (Horsehead 2012b).

The Mooresboro facility uses leaching and solvent extraction (SX) technology combined with electrowinning, melting, and casting technology. In this process, Waelz Oxide (WOX) is first washed in water to remove soluble elements such as chlorine, potassium, and sodium, and then is leached in a sulfuric acid solution to dissolve the contained zinc creating a pregnant liquor solution (PLS). The PLS is then processed in a solvent extraction step in which zinc is selectively extracted from the PLS using an organic solvent creating a purified zinc-loaded electrolyte solution. The loaded electrolyte solution is then fed into the electrowinning process in which electrical energy is applied across a series of anodes and cathodes submerged in the electrolyte solution causing the zinc to deposit on the surfaces of the cathodes. As the zinc metal builds up on these surfaces, the cathodes are periodically harvested in order to strip the zinc from their surfaces (Horsehead 2015). Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003).

PIZO and Steel Dust Recycling recycle EAF dust into intermediate zinc products using Waelz kilns, and then sell the intermediate products to companies who smelt it into refined products.

In 2014, U.S. primary and secondary refined zinc production were estimated to total 185,000 metric tons (USGS 2015) (see Table 4-88). Domestic zinc mine production increased slightly in 2014 compared to 2013 levels, primarily owing to an increase in zinc production at the Red Dog mine in Alaska. Zinc metal production decreased by 20 percent owing to a decline in secondary production; Horsehead closed its smelter in Monaca, PA, while starting up its new recycling facility in Mooresboro, NC. However, the new facility experienced delayed ramp-up efforts due to technical issues and did not reach optimum production levels until the end of 2014 (USGS 2015). Primary zinc production (primary slab zinc) increased slightly in 2014, while, secondary zinc production in 2014 decreased relative to 2013.

Emissions of CO_2 from zinc production in 2014 were estimated to be 1.0 MMT CO_2 Eq. (956 kt CO_2) (see Table 4-89). All 2014 CO_2 emissions resulted from secondary zinc production processes. Emissions from zinc production in the U.S. have increased overall since 1990 due to a gradual shift from non-emissive primary production to emissive secondary production. In 2014, emissions were estimated to be 51 percent higher than they were in 1990.

Table 4-88: Zinc Production (Metric Tons)

Year	Primary	Secondary
1990	262,704	95,708
2005	191,120	156,000
2010	120,000	129,000
2011	110,000	138,000
2012	114,000	147,000
2013	106,000	127,000
2014	115,000	70,000

Table 4-89: CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	0.6	632
2005	1.0	1,030
2010	1.2	1,182
2011	1.3	1,286
2012	1.5	1,486
2013	1.4	1,429
2014	1.0	956

Methodology

The methods used to estimate non-energy CO_2 emissions from zinc production using the electrothermic primary production and Waelz kiln secondary production processes are based on Tier 1 methods from the *2006 IPCC Guidelines* (IPCC 2006). The Tier 1 equation used to estimate emissions from zinc production is as follows:

$$E_{CO2} = Zn \times EF_{default}$$

where,

E_{CO2} = CO_2 emissions from zinc production, metric tons
Zn = Quantity of zinc produced, metric tons
$EF_{default}$ = Default emission factor, metric tons CO_2/metric ton zinc produced

The Tier 1 emission factors provided by IPCC for Waelz kiln-based secondary production were derived from coke consumption factors and other data presented in Vikland-White (2000). These coke consumption factors as well as other inputs used to develop the Waelz kiln emission factors are shown below. IPCC does not provide an emission factor for electrothermic processes due to limited information; therefore, the Waelz kiln-specific emission factors were also applied to zinc produced from electrothermic processes. Starting in 2014, refined zinc produced in the U.S. used hydrometallurgical processes and is assumed to be non-emissive.

For Waelz kiln-based production, IPCC recommends the use of emission factors based on EAF dust consumption, if possible, rather than the amount of zinc produced since the amount of reduction materials used is more directly dependent on the amount of EAF dust consumed. Since only a portion of emissive zinc production facilities consume EAF dust, the emission factor based on zinc production is applied to the non-EAF dust consuming facilities while the emission factor based on EAF dust consumption is applied to EAF dust consuming facilities.

The Waelz kiln emission factor based on the amount of zinc produced was developed based on the amount of metallurgical coke consumed for non-energy purposes per ton of zinc produced (i.e., 1.19 metric tons coke/metric ton zinc produced) (Viklund-White 2000), and the following equation:

$$EF_{Waelz\ Kiln} = \frac{1.19\ metric\ tons\ coke}{metric\ tons\ zinc} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{3.70\ metric\ tons\ CO_2}{metric\ tons\ zinc}$$

The Waelz kiln emission factor based on the amount of EAF dust consumed was developed based on the amount of metallurgical coke consumed per ton of EAF dust consumed (i.e., 0.4 metric tons coke/metric ton EAF dust consumed) (Viklund-White 2000), and the following equation:

$$EF_{EAF\ Dust} = \frac{0.4\ metric\ tons\ coke}{metric\ tons\ EAF\ Dust} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{1.24\ metric\ tons\ CO_2}{metric\ tons\ EAF\ Dust}$$

The total amount of EAF dust consumed by Horsehead at their Waelz kilns was available from Horsehead financial reports for years 2006 through 2014 (Horsehead 2007, 2008, 2010a, 2011, 2012a, 2013, 2014, and 2015). Consumption levels for 1990 through 2005 were extrapolated using the percentage change in annual refined zinc production at secondary smelters in the United States as provided by *USGS Minerals Yearbook: Zinc* (USGS 1995 through 2006). The EAF dust consumption values for each year were then multiplied by the 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor to develop CO_2 emission estimates for Horsehead's Waelz kiln facilities.

The amount of EAF dust consumed by Steel Dust Recycling (SDR) and their total production capacity were obtained from SDR's facility in Alabama for the years 2011 through 2014 (SDR 2012, 2014, and 2015). SDR's facility in Alabama underwent expansion in 2011 to include a second unit (operational since early- to mid-2012). SDR's facility has been operational since 2008. Annual consumption data for SDR was not publicly available for the years 2008, 2009, and 2010. These data were estimated using data for Horsehead's Waelz kilns for 2008-2010 (Horsehead 2007, 2008, 2010a, 2010b, and 2011). Annual capacity utilization ratios were calculated using Horsehead's annual consumption and total capacity for the years 2008 through 2010. Horsehead's annual capacity utilization ratios were multiplied with SDR's total capacity to estimate SDR's consumption for each of the years, 2008 through 2010 (SDR 2013).

PIZO Technologies Worldwide LLC's facility in Arkansas has been operational since 2009. The amount of EAF dust consumed by PIZO's facility for 2009 through 2014 was not publicly available. EAF dust consumption for PIZO's facility for 2009 and 2010 were estimated by calculating annual capacity utilization of Horsehead's Waelz kilns and multiplying this utilization ratio by PIZO's total capacity (PIZO 2012). EAF dust consumption for PIZO's facility for 2011 through 2014 were estimated by applying the average annual capacity utilization rates for Horsehead and SDR (Grupo PROMAX) to PIZO's annual capacity (Horsehead 2012, 2013, 2014, and 2015; SDR 2012 and 2014; PIZO 2012 and 2014). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to PIZO's and Steel Dust Recycling's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

Refined zinc production levels for Horsehead's Monaca, PA facility (utilizing electrothermic technology) were available from the company for years 2005 through 2013 (Horsehead 2008, 2011, 2012, 2013, and 2014). The Monaca facility was permanently shut down in April 2014 and was replaced by Horsehead's new facility in Mooresboro, NC. The new facility uses hydrometallurgical process to produce refined zinc products. This process is assumed to be non-emissive. Production levels for 1990 through 2004 were extrapolated using the percentage changes in annual refined zinc production at secondary smelters in the United States as provided by USGS *Minerals Yearbook: Zinc* (USGS 1995 through 2005). The 3.70 metric tons CO_2/metric ton zinc emission factor was then applied to the Monaca facility's production levels to estimate CO_2 emissions for the facility. The Waelz kiln production emission factor was applied in this case rather than the EAF dust consumption emission factor since Horsehead's Monaca facility did not consume EAF dust.

Uncertainty and Time-Series Consistency

The uncertainty associated with these estimates is two-fold, relating to activity data and emission factors used.

First, there is uncertainty associated with the amount of EAF dust consumed in the United States to produce secondary zinc using emission-intensive Waelz kilns. The estimate for the total amount of EAF dust consumed in Waelz kilns is based on (1) an EAF dust consumption value reported annually by Horsehead Corporation as part of its financial reporting to the Securities and Exchange Commission (SEC), and (2) an EAF dust consumption value obtained from the Waelz kiln facility operated in Alabama by Steel Dust Recycling LLC. Since actual EAF dust consumption information is not available for PIZO's facility (2009 through 2010) and SDR's facility (2008 through 2010), the amount is estimated by multiplying the EAF dust recycling capacity of the facility (available from the company's website) by the capacity utilization factor for Horsehead Corporation (which is available from Horsehead's financial reports). Also, the EAF dust consumption for PIZO's facility for 2011 through 2013 was estimated by multiplying the average capacity utilization factor developed from Horsehead Corp. and SDR's annual capacity utilization rates by PIZO's EAF dust recycling capacity. Therefore, there is uncertainty associated with the assumption used to estimate PIZO and SDR's annual EAF dust consumption values (except SDR's EAF dust consumption for 2011 through 2013, which were obtained from SDR's recycling facility in Alabama).

Second, there is uncertainty associated with the emission factors used to estimate CO_2 emissions from secondary zinc production processes. The Waelz kiln emission factors are based on materials balances for metallurgical coke and EAF dust consumed as provided by Viklund-White (2000). Therefore, the accuracy of these emission factors depend upon the accuracy of these materials balances. Data limitations prevented the development of emission factors for the electrothermic process. Therefore, emission factors for the Waelz kiln process were applied to both electrothermic and Waelz kiln production processes. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-90. Zinc production CO_2 emissions were estimated to be between 0.8 and 1.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 21 percent above the emission estimate of 1.0 MMT CO_2 Eq.

Table 4-90: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Zinc Production	CO_2	1.0	0.8	1.2	-19%	+21%

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

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

EPA continues to evaluate use of facility-level data reported under EPA's GHGRP to improve the emission estimates for the Zinc Production source category, provided aggregated data meet criteria for safe disclosure and will not reveal confidential business information. In particular, EPA is assessing feasibility to derive an average emission factor based on reported production and emissions. Particular attention will be made to ensure time series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's

GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[33]

4.22 Semiconductor Manufacture (IPCC Source Category 2E1) (TO BE UPDATED)

The semiconductor industry uses multiple long-lived fluorinated greenhouse gases in plasma etching and plasma enhanced chemical vapor deposition (PECVD) processes to produce semiconductor products. The gases most commonly employed are trifluoromethane (HFC-23 or CHF_3), perfluoromethane (CF_4), perfluoroethane (C_2F_6), nitrogen trifluoride (NF_3), sulfur hexafluoride (SF_6), and nitrous oxide (N_2O), although other compounds such as perfluoropropane (C_3F_8) and perfluorocyclobutane (c-C_4F_8) are also used. The exact combination of compounds is specific to the process employed.

A single 300 mm silicon wafer that yields between 400 to 600 semiconductor products (devices or chips) may require more than 100 distinct fluorinated-gas-using process steps, principally to deposit and pattern dielectric films. Plasma etching (or patterning) of dielectric films, such as silicon dioxide and silicon nitride, is performed to provide pathways for conducting material to connect individual circuit components in each device. The patterning process uses plasma-generated fluorine atoms, which chemically react with exposed dielectric film to selectively remove the desired portions of the film. The material removed as well as undissociated fluorinated gases flow into waste streams and, unless emission abatement systems are employed, into the atmosphere. PECVD chambers, used for depositing dielectric films, are cleaned periodically using fluorinated and other gases. During the cleaning cycle the gas is converted to fluorine atoms in plasma, which etches away residual material from chamber walls, electrodes, and chamber hardware. Undissociated fluorinated gases and other products pass from the chamber to waste streams and, unless abatement systems are employed, into the atmosphere.

In addition to emissions of unreacted gases, some fluorinated compounds can also be transformed in the plasma processes into different fluorinated compounds which are then exhausted, unless abated, into the atmosphere. For example, when C_2F_6 is used in cleaning or etching, CF_4 is generated and emitted as a process byproduct. Besides dielectric film etching and PECVD chamber cleaning, much smaller quantities of fluorinated gases are used to etch polysilicon films and refractory metal films like tungsten.

Nitrous oxide is used in manufacturing semiconductor devices to produce thin films by CVD and nitridation processes as well as for N-doping of compound semiconductors and reaction chamber conditioning (Doering 2000).

For 2013, total CO_2 weighted emissions of all fluorinated greenhouse gases and nitrous oxide by the U.S. semiconductor industry were estimated to be 4.2 MMT CO_2 Eq. Combined emissions of all greenhouse gases are presented in Table 4-91 and Table 4-92 below for years 1990, 2005 and the period 2009 to 2013. The rapid growth of this industry and the increasing complexity (growing number of layers[34]) of semiconductor products led to an increase in emissions of 153 percent between 1990 and 1999, when emissions peaked at 9.1 MMT CO_2 Eq. The emissions growth rate began to slow after 1999, and emissions declined by 54 percent between 1999 and 2013. Together, industrial growth, adoption of emissions reduction technologies, including but not limited to abatement technologies, and shift in gas usages resulted in a net increase in emissions of 16 percent between 1990 and 2013.

There was a sizable dip seen in emissions between 2008 and 2009, a 28 percent decrease, due to the slowed economic growth, and hence production, during this time. The industry recovered and emissions rose between 2009 and 2010 by more than 25 percent and between 2010 and 2011 by 29 percent; reductions in emissions were observed between 2011 and 2012, and 2012 and 2013 at 9 percent and 7 percent, respectively.

---

[33] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

[34] Complexity is a term denoting the circuit required to connect the active circuit elements (transistors) on a chip. Increasing miniaturization, for the same chip size, leads to increasing transistor density, which, in turn, requires more complex interconnections between those transistors. This increasing complexity is manifested by increasing the levels (i.e., layers) of wiring, with each wiring layer requiring fluorinated gas usage for its manufacture.

Table 4-91: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Semiconductor Manufacture (MMT CO_2 Eq.)

Year	1990	2005	2009	2010	2011	2012	2013
CF_4	0.8	1.1	0.8	1.1	1.4	1.3	1.2
C_2F_6	2.0	1.9	1.1	1.4	1.8	1.6	1.5
C_3F_8	+	0.1	0.1	0.1	0.2	0.1	0.1
C_4F_8	+	0.1	+	+	0.1	0.1	0.1
HFC-23	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SF_6	0.5	0.7	0.3	0.4	0.4	0.4	0.4
NF_3	+	0.5	0.4	0.5	0.7	0.6	0.6
Total F-GHGs	**3.6**	**4.6**	**2.9**	**3.7**	**4.7**	**4.3**	**4.0**
N_2O	+	0.1	0.1	0.1	0.2	0.2	0.2
Total	**3.6**	**4.7**	**3.1**	**3.8**	**4.9**	**4.5**	**4.2**

Note: Totals may not sum due to independent rounding.

\+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-92: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Semiconductor Manufacture (kt)

Year	1990	2005	2009	2010	2011	2012	2013
CF_4	0.11	0.14	0.11	0.14	0.19	0.17	0.16
C_2F_6	0.16	0.16	0.09	0.11	0.14	0.13	0.12
C_3F_8	+	+	+	+	+	+	+
C_4F_8	+	+	+	+	+	+	+
HFC-23	+	+	+	+	+	+	+
SF_6	+	+	+	+	+	+	+
NF_3	+	+	+	+	+	+	+
N_2O	0.12	0.41	0.45	0.49	0.79	0.65	0.61

\+ Does not exceed 0.05 kt

Methodology

Emissions are based on data reported through Subpart I, Electronics Manufacture, of EPA's GHGRP, Partner reported emissions data received through the EPA's PFC[35] Reduction/Climate Partnership, EPA's PFC Emissions Vintage Model (PEVM)—a model that estimates industry emissions in the absence of emission control strategies (Burton and Beizaie 2001)[36], and estimates of industry activity (i.e., total manufactured layer area). The availability and applicability of reported data from the EPA Partnership and EPA's GHGRP differs across the 1990 through 2013 time series. Consequently, F-GHG emissions from semiconductor manufacturing were estimated using five distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, 2000 through 2006, 2007 through

---

[35] In the context of the EPA Partnership and PEVM, PFC refers to perfluorocompounds, not perfluorocarbons.

[36] A Partner refers to a participant in the U.S. EPA PFC Reduction/Climate Partnership for the Semiconductor Industry. Through a Memorandum of Understanding (MoU) with the EPA, Partners voluntarily reported their PFC emissions to the EPA by way of a third party, which aggregated the emissions through 2010. For 2011, while no MOU existed, it was assumed that the same companies that were Partners in 2010 were "Partners" in 2011 for purposes of estimating inventory emissions.

2010, and 2011 through 2013. N_2O emissions were estimated using three distinct methods, one each for the period 1990 through 1994, 1995 through 2010, and 2011 through 2013.

1990 through 1994

From 1990 through 1994, Partnership data were unavailable and emissions were modeled using the PEVM (Burton and Beizaie 2001).[37] The 1990 to 1994 emissions are assumed to be uncontrolled, since reduction strategies such as chemical substitution and abatement were yet to be developed.

PEVM is based on the recognition that fluorinated greenhouse gas emissions from semiconductor manufacturing vary with: (1) the number of layers that comprise different kinds of semiconductor devices, including both silicon wafer and metal interconnect layers, and (2) silicon consumption (i.e., the area of semiconductors produced) for each kind of device. The product of these two quantities, Total Manufactured Layer Area (TMLA), constitutes the activity data for semiconductor manufacturing. PEVM also incorporates an emission factor that expresses emissions per unit of layer-area. Emissions are estimated by multiplying TMLA by this emission factor.

PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest manufactured feature size),[38] and (2) product type (discrete, memory or logic).[39] For each linewidth technology, a weighted average number of layers is estimated using VLSI product-specific worldwide silicon demand data in conjunction with complexity factors (i.e., the number of layers per Integrated Circuit (IC)) specific to product type (Burton and Beizaie 2001, ITRS 2007). PEVM derives historical consumption of silicon (i.e., square inches) by linewidth technology from published data on annual wafer starts and average wafer size (VLSI Research, Inc. 2012).

The emission factor in PEVM is the average of four historical emission factors, each derived by dividing the total annual emissions reported by the Partners for each of the four years between 1996 and 1999 by the total TMLA estimated for the Partners in each of those years. Over this period, the emission factors varied relatively little (i.e., the relative standard deviation for the average was 5 percent). Since Partners are believed not to have applied significant emission reduction measures before 2000, the resulting average emission factor reflects uncontrolled emissions. The emission factor is used to estimate world uncontrolled emissions using publicly-available data on world silicon consumption.

As it was assumed for this time period that there was no consequential adoption of fluorinated-gas-reducing measures, a fixed distribution of fluorinated-gas use was assumed to apply to the entire U.S. industry to estimate gas-specific emissions. This distribution was based upon the average fluorinated-gas purchases made by semiconductor manufacturers during this period and the application of IPCC default emission factors for each gas (Burton and Beizaie 2001).

To estimate N_2O emissions, it is assumed the proportion of N_2O emissions estimated for 1995 (discussed below) remained constant for the period of 1990 through1994.

---

[37] Various versions of the PEVM exist to reflect changing industrial practices. From 1990 to 1994 emissions estimates are from PEVM v1.0, completed in September 1998. The emission factor used to estimate 1990 to 1994 emissions is an average of the 1995 and 1996 emissions factors, which were derived from Partner reported data for those years.

[38] By decreasing features of Integrated Circuit components, more components can be manufactured per device, which increases its functionality. However, as those individual components shrink it requires more layers to interconnect them to achieve the functionality. For example, a microprocessor manufactured with 65 nm feature sizes might contain as many as 1 billion transistors and require as many as 11 layers of component interconnects to achieve functionality, while a device manufactured with 130 nm feature size might contain a few hundred million transistors and require 8 layers of component interconnects (ITRS 2007).

[39] Memory devices manufactured with the same feature sizes as microprocessors (a logic device) require approximately one-half the number of interconnect layers, whereas discrete devices require only a silicon base layer and no interconnect layers (ITRS 2007). Since discrete devices did not start using PFCs appreciably until 2004, they are only accounted for in the PEVM emissions estimates from 2004 onwards.

1995 through 1999

For 1995 through 1999, total U.S. emissions were extrapolated from the total annual emissions reported by the Partners (1995 through 1999). Partner-reported emissions are considered more representative (e.g., in terms of capacity utilization in a given year) than PEVM estimated emissions, and are used to generate total U.S. emissions when applicable. The emissions reported by the Partners were divided by the ratio of the total capacity of the plants operated by the Partners and the total capacity of all of the semiconductor plants in the United States; this ratio represents the share of capacity attributable to the Partnership. This method assumes that Partners and non-Partners have identical capacity utilizations and distributions of manufacturing technologies. Plant capacity data is contained in the World Fab Forecast (WFF) database and its predecessors, which is updated quarterly (Semiconductor Equipment and Materials Industry 2012 and 2013). Gas-specific emissions were estimated using the same method as for 1990 through 1994.

For this time period, the N_2O emissions were estimated using an emission factor that is applied to the annual, total U.S. TMLA manufactured. The emission factor was developed using a regression-through-the-origin (RTO) model: GHGRP reported N_2O emissions were regressed against the corresponding TMLA of facilities that reported no use of abatement systems. Details on the GHGRP reported emissions and development of emission factor using the RTO model are presented in the 2011 through 2013 section. The total U.S. TMLA manufactured were estimated using PEVM.

2000 through 2006

Emissions for the years 2000 through 2006—the period during which Partners began the consequential application of fluorinated greenhouse gas-reduction measures—were estimated using a combination of Partner-reported emissions and adjusted PEVM modeled emissions. The emissions reported by Partners for each year were accepted as the quantity emitted from the share of the industry represented by those Partners. Remaining emissions, those from non-Partners, were estimated using PEVM, with one change. To ensure time series consistency and to reflect the increasing use of remote clean technology (which increases the efficiency of the production process while lowering emissions of fluorinated greenhouse gases), the average non-Partner emission factor was assumed to begin declining gradually during this period. Specifically, the non-Partner emission factor for each year was determined by linear interpolation, using the end points of 1999 (the original PEVM emission factor) and 2011 (a new emission factor determined for the non-Partner population based on GHGRP-reported data, described below).

The portion of the U.S. total attributed to non-Partners is obtained by multiplying PEVM's total U.S. emissions figure by the non-Partner share of U.S. total silicon capacity for each year as described above.[40] Gas-specific emissions from non-Partners were estimated using linear interpolation of gas-specific emission distribution of 1999 (assumed same as total U.S. Industry in 1994) and 2011 (calculated from a subset of non-Partner facilities from GHGRP reported emissions data). Annual updates to PEVM reflect published figures for actual silicon consumption from VLSI Research, Inc., revisions and additions to the world population of semiconductor manufacturing plants, and changes in IC fabrication practices within the semiconductor industry (see ITRS 2008 and Semiconductor

---

[40] This approach assumes that the distribution of linewidth technologies is the same between Partners and non-Partners. As discussed in the description of the method used to estimate 2007 emissions, this is not always the case.

Equipment and Materials Industry 2011).[41,42,43]

The N_2O emissions were estimated using the same methodology as 1995-1999 methodology.

2007 through 2010

For the years 2007 through 2010, emissions were also estimated using a combination of Partner reported emissions and adjusted PEVM modeled emissions to provide estimates for non-Partners; however, two improvements were made to the estimation method employed for the previous years in the time series. First, the 2007 through 2010 emission estimates account for the fact that Partners and non-Partners employ different distributions of manufacturing technologies, with the Partners using manufacturing technologies with greater transistor densities and therefore greater numbers of layers.[44] Second, the scope of the 2007 through 2010 estimates was expanded relative to the estimates for the years 2000 through 2006 to include emissions from research and development (R&D) fabs. This additional enhancement was feasible through the use of more detailed data published in the WFF. PEVM databases were updated annually as described above. The published world average capacity utilization for 2007 through 2010 was used for production fabs, while for R&D fabs a 20 percent figure was assumed (SIA 2009).

In addition, publicly-available actual utilization data was used to account for differences in fab utilization for manufacturers of discrete and IC products for 2010 emissions for non-Partners. PEVM estimates were adjusted using technology-weighted capacity shares that reflect the relative influence of different utilization. Gas-specific emissions for non-Partners were estimated using the same method as for 2000 through 2006.

The N_2O emissions were estimated using the same methodology as 1995 through 1999 methodology.

2011 through 2013

The fifth and final method for estimating emissions from semiconductor manufacturing covers the period 2011 through 2013, the years after EPA's Partnership with the semiconductor industry ended (in 2010) and reporting under the GHGRP began. Manufacturers whose estimated uncontrolled emissions equal or exceed 25,000 mt CO_2 Eq. per year (based on default emission factors and total capacity in terms of substrate area) are required to report their emissions to the EPA. This population of reporters to EPA's GHGRP included both historical Partners of

---

[41] Special attention was given to the manufacturing capacity of plants that use wafers with 300 mm diameters because the actual capacity of these plants is ramped up to design capacity, typically over a 2–3 year period. To prevent overstating estimates of partner-capacity shares from plants using 300 mm wafers, *design* capacities contained in WFW were replaced with estimates of *actual installed* capacities for 2004 published by Citigroup Smith Barney (2005). Without this correction, the partner share of capacity would be overstated, by approximately 5 percent. For perspective, approximately 95 percent of all new capacity additions in 2004 used 300 mm wafers, and by year-end those plants, on average, could operate at approximately 70 percent of the design capacity. For 2005, actual installed capacities were estimated using an entry in the World Fab Watch database (April 2006 Edition) called "wafers/month, 8-inch equivalent," which denoted the actual installed capacity instead of the fully-ramped capacity. For 2006, actual installed capacities of new fabs were estimated using an average monthly ramp rate of 1100 wafer starts per month (wspm) derived from various sources such as semiconductor fabtech, industry analysts, and articles in the trade press. The monthly ramp rate was applied from the first-quarter of silicon volume (FQSV) to determine the average design capacity over the 2006 period.

[42] In 2006, the industry trend in co-ownership of manufacturing facilities continued. Several manufacturers, who are Partners, now operate fabs with other manufacturers, who in some cases are also Partners and in other cases are not Partners. Special attention was given to this occurrence when estimating the Partner and non-Partner shares of U.S. manufacturing capacity.

[43] Two versions of PEVM are used to model non-Partner emissions during this period. For the years 2000 to 2003 PEVM v3.2.0506.0507 was used to estimate non-Partner emissions. During this time, discrete devices did not use PFCs during manufacturing and therefore only memory and logic devices were modeled in the PEVM v3.2.0506.0507. From 2004 onwards, discrete device fabrication started to use PFCs, hence PEVM v4.0.0701.0701, the first version of PEVM to account for PFC emissions from discrete devices, was used to estimate non-Partner emissions for this time period.

[44] EPA considered applying this change to years before 2007, but found that it would be difficult due to the large amount of data (i.e., technology-specific global and non-Partner TMLA) that would have to be examined and manipulated for each year. This effort did not appear to be justified given the relatively small impact of the improvement on the total estimate for 2007 and the fact that the impact of the improvement would likely be lower for earlier years because the estimated share of emissions accounted for by non-Partners is growing as Partners continue to implement emission-reduction efforts.

EPA's PFC Reduction/Climate Partnership as well as non-Partners. In EPA's GHGRP, the population of non-Partner facilities also included manufacturers that use GaAs technology in addition to Si technology[45]. Emissions from the population of manufacturers that were below the reporting threshold were also estimated for this time period using EPA-developed emission factors and estimates of facility-specific production obtained from WFF. Inventory totals reflect the emissions from both populations.

Under EPA's GHGRP, semiconductor manufacturing facilities report emissions of fluorinated GHGs used in etch and clean processes and as heat transfer fluids. They also report N_2O emissions from CVD and other processes. The fluorinated GHGs, and N_2O were aggregated, by gas, across all semiconductor manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry.

For the segment of the semiconductor industry, which is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP, emission estimates are based on EPA-developed emission factors for the fluorinated GHGs and N_2O. The new emission factors (in units of mass of CO_2 Eq. / TMLA [MSI]) are based on the emissions reported by facilities under EPA's GHGRP and TMLA estimates for these facilities from the WFF (SEMI 2012 and SEMI 2013). In a refinement of the method used in prior years to estimate emissions for the non-Partner population, different emission factors were developed for different subpopulations of fabs, one for facilities that manufacture devices on Si wafers and one for facilities that manufacture on GaAs wafers. An analysis of the emission factors of reporting fabs showed that the characteristics that had the largest impacts on emission factors were the substrate (i.e., Si or GaAs) used at the fab, whether the fab contained R&D activities, and whether the fab reported using point-of-use fluorinated greenhouse gas abatement[46]. For each of these groups, a subpopulation-specific emission factor was obtained using a regression-through-the-origin (RTO) model: facility-reported aggregate emissions of seven fluorinated GHGs (CF_4, C_2F_6, C_3F_8, C_4F_8, CHF_3, SF_6 and NF_3)[47] were regressed against the corresponding TMLA to estimate an aggregate F-GHG emissions factor (CO_2 Eq./MSI TMLA) and facility-reported N_2O emissions were regressed against the corresponding TMLA to estimate a N_2O emissions factor (CO_2 Eq./MSI TMLA). For each subpopulation, the slope of the RTO model is the emission factor for that subpopulation. To estimate emissions from fabs that are solely doing research and development (R&D) or are Pilot fabs (i.e., fabs that are excluded from subpart I reporting requirements), emission factors were estimated based on GHGRP reporting fabs containing R&D activities. EPA applied a scaling factor of 1.15 to the slope of the RTO model to estimate the emission factor applicable to the non-reporting fabs that are only R&D or Pilot fabs. This was done as R&D activities lead to use of more F-GHGs and N_2O for development of chips that are not counted towards the final estimated TMLA. Hence, it is assumed that the fabs with only R&D activities use 15 percent more F-GHGs and N_2O per TMLA. However, as was assumed for 2007 through 2010, fabs with only R&D activities were assumed to utilize only 20 percent of their manufacturing capacity. Other fabs were assumed to utilize 89 percent of their manufacturing capacity, held constant at 2012 levels which is slightly lower than 2011 levels. Fabs that produce discrete products are assumed to utilize 84 percent of their manufacturing capacity, held constant at 2011 levels. These utilizations at 2011 levels are based on the Semiconductor Industry Association report (SICAS, 2011).

Non-reporting fabs were then broken out into similar subpopulations. Information on the technology and R&D activities of non-reporting fabs was available through the WFF. Information on the use of point-of-use abatement by non-reporting fabs was not available; thus, EPA conservatively assumed that non-reporting facilities did not use point-of-use abatement. The appropriate emission factor was applied to the total TMLA of each subpopulation of non-reporting facilities to estimate the GWP-weighted emissions of that subpopulation.

Gas-specific, GWP-weighted emissions for each subpopulation of non-reporting facilities were estimated using the corresponding reported distribution of gas-specific, GWP-weighted emissions from which the aggregate emission factors were developed. Estimated in this manner, the non-reporting population accounted for 9, 10 and 10 percent

---

[45] GaAs and Si technologies refer to the wafer on which devices are manufactured, which use the same PFCs but in different ways.

[46] For the non-reporting segment of the industry using GaAs technology, emissions were estimated only for those fabs that manufactured the same products as manufactured by reporters. The products manufactured were categorized as discrete (emissions did not scale up with decreasing feature size).

[47] Only seven gases were aggregated because inclusion of fluorinated GHGs that are not reported in the inventory results in overestimation of emission factor that is applied to the various non-reporting subpopulations.

of U.S. emissions in 2011, 2012 and 2013, respectively. The GHGRP-reported emissions and the calculated non-reporting population emissions are summed to estimate the total emissions from semiconductor manufacturing.

The methodology used for this time period included, for the first time, emissions from facilities employing Si- and GaAs-using technologies. The use of GaAs technology became evident via analysis of GHGRP emissions and WFF data. However, no adjustment of pre-2011 emissions was made because (1) the use of these technologies appears relatively new, (2) in the aggregate make a relatively small contribution to total industry emissions (i.e., 4 percent in 2013), and (3) would require a large effort to retroactively adjust pre-2011 emissions.

Data Sources

GHGRP reporters estimated their emissions using a default emission factor method established by EPA. This method is very similar to the Tier 2b Method in the *2006 IPCC Guidelines*, but it goes beyond that method by establishing different default emission and byproduct generation factors for different wafer sizes (i.e., 300mm vs. 150 and 200mm) and CVD clean subtypes (in situ thermal, in situ thermal, and remote plasma). Partners estimated their emissions using a range of methods. It is assumed that most Partners used a method at least as accurate as the IPCC's Tier 2a Methodology, recommended in the *2006 IPCC Guidelines*. Estimates of operating plant capacities and characteristics for Partners and non-Partners were derived from the Semiconductor Equipment and Materials Industry (SEMI) WFF (formerly World Fab Watch) database (1996 through 2013) (e.g., Semiconductor Materials and Equipment Industry, 2013). Actual worldwide capacity utilizations for 2011 were obtained from Semiconductor International Capacity Statistics (SICAS) (SIA, 2011). Estimates of the number of layers for each linewidth was obtained from International Technology Roadmap for Semiconductors: 2013 Edition (Burton and Beizaie 2001, ITRS 2007, ITRS 2008, ITRS 2011, ITRS 2013). PEVM utilized the WFF, SICAS, and ITRS, as well as historical silicon consumption estimates published by VLSI.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The equation used to estimate uncertainty is:

Total Emissions (E_T) = GHGRP Reported F-GHG Emissions ($E_{R,F\text{-}GHG}$) + Non-Reporters' Estimated F-GHG
E

where E_R and E_{NR} denote totals for the indicated subcategories of emissions for F-GHG and N_2O, respectively.

The uncertainty in E_T presented in Table 4-93 below results from the convolution of four distributions of emissions, each reflecting separate estimates of possible values of $E_{R,F\text{-}GHG}$, E_{R,N_2O}, $E_{NR,F\text{-}GHG}$, and E_{NR,N_2O}. The approach and methods for estimating each distribution and combining them to arrive at the reported 95 percent CI are described in the remainder of this section.

The uncertainty estimate of $E_{R,\ F\text{-}GHG}$, or GHGRP reported F-GHG emissions, is developed based on gas-specific uncertainty estimates of emissions for two industry segments, one processing 200 mm wafers and one processing 300 mm wafers. Uncertainties in emissions for each gas and industry segment were developed during the assessment of emission estimation methods for the subpart I GHGRP rulemaking in 2012 (see *Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart* I, docket EPA–HQ–OAR–2011–0028).[48] The 2012 analysis did not take into account the use of

---

[48] On November 13, 2013, EPA published a final rule revising subpart I (Electronics Manufacturing) of the GHGRP (78 FR 68162). The revised rule includes updated default emission factors and updated default destruction and removal efficiencies that are slightly different from those that semiconductor manufacturers were required to use to report their 2012 emissions. The uncertainty analyses that were performed during the development of the revised rule focused on these updated defaults, but are expected to be reasonably representative of the uncertainties associated with the older defaults, particularly for estimates at the country level. (They may somewhat underestimate the uncertainties associated with the older defaults at the facility level.) For simplicity, the 2012 estimates are assumed to be unbiased although in some cases, the updated (and therefore more

abatement. For the industry segment that processed 200 mm wafers, estimates of uncertainties at a 95 percent CI ranged from ±29 percent for C_3F_8 to ±10 percent for CF_4. For the corresponding 300 mm industry segment, estimates of the 95 percent CI ranged from ±36 percent for C_4F_8 to ±16 percent for CF_4. These gas and wafer-specific uncertainty estimates are applied to the total emissions of the facilities that did not abate emissions as reported under EPA's GHGRP.

For those facilities reporting abatement of emissions under EPA's GHGRP, estimates of uncertainties for the no abatement industry segments are modified to reflect the use of full abatement (abatement of *all* gases from *all* cleaning and etching equipment) and partial abatement. These assumptions used to develop uncertainties for the partial and full abatement facilities are identical for 200 mm and 300 mm wafer processing facilities. For all facilities reporting gas abatement, a triangular distribution of destruction or removal efficiency is assumed for each gas. The triangular distributions range from an asymmetric and highly uncertain distribution of 0 percent minimum to 90 percent maximum with 70 percent most likely value for CF_4 to a symmetric and less uncertain distribution of 85 percent minimum to 95 percent maximum with 90 percent most likely value for C_4F_8, NF_3 and SF_6. For facilities reporting partial abatement, the distribution of fraction of the gas fed through the abatement device, for each gas, is assumed to be triangularly distributed as well. It is assumed that no more than 50 percent of the gases area abated (i.e., the maximum value) and that 50 percent is the most likely value and the minimum is 0 percent. Consideration of abatement then resulted in four additional industry segments, two 200 mm wafer-processing segments (one fully and one partially abating each gas) and two 300 mm wafer-processing segment (one fully and the other partially abating each gas). Gas-specific emission uncertainties were estimated by convolving the distributions of unabated emissions with the appropriate distribution of abatement efficiency for fully and partially abated facilities using a Montel Carlo simulation.

The uncertainty in $E_{R,F\text{-}GHG}$ is obtained by allocating the estimates of uncertainties to the total GHGRP-reported emissions from each of the six industry segments, and then running a Monte Carlo simulation which results in the 95 percent CI for emissions from GHGRP reporting facilities ($E_{R,F\text{-}GHG}$).

The uncertainty in $E_{R,N2O}$ is obtained by assuming that the uncertainty in the emissions reported by each of the GHGRP reporting facilities results from the uncertainty in quantity of N_2O consumed and the N_2O emission factor (or utilization). Similar to analyses completed for subpart I (see *Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart* I, docket EPA–HQ–OAR–2011–0028), the uncertainty of N_2O consumed was assumed to be 20 percent. Consumption of N_2O for GHGRP reporting facilities was estimated by back- calculating from emissions reported and assuming no abatement. The quantity of N_2O utilized (the complement of the emission factor) was assumed to have a triangular distribution with a minimum value of 0 percent, mode of 20 percent and maximum value of 84 percent. The minimum was selected based on physical limitations, the mode was set equivalent to the subpart I default N_2O utilization rate for chemical vapor deposition, and the maximum was set equal to the maximum utilization rate found in ISMI Analysis of Nitrous Oxide Survey Data (ISMI, 2009). The inputs were used to simulate emissions for each of the GHGRP reporting, N_2O-emitting facilities. The uncertainty for the total reported N_2O emissions was then estimated by combining the uncertainties of each of the facilities reported emissions using Monte Carlo simulation.

The estimate of uncertainty in $E_{NR,F\text{-}GHG}$ and $E_{NR,N2O}$ entailed developing estimates of uncertainties for the emissions factors for each non-reporting sub-category and the corresponding estimates of TMLA.

The uncertainty in TMLA depends on the uncertainty of two variables—an estimate of the uncertainty in the average annual capacity utilization for each level of production of fabs (e.g., full scale or R&D production) and a corresponding estimate of the uncertainty in the number of layers manufactured. For both variables, the distributions of capacity utilizations and number of manufactured layers are assumed triangular for all categories of non-reporting fabs. For production fabs the most probable utilization is assumed to be 89 percent, with the highest and lowest utilization assumed to be 100 percent and 63 percent, respectively. The corresponding values for facilities that manufacture discrete devices are, 84 percent, 100 percent, and 66 percent, respectively, while the values for utilization for R&D facilities, are assumed to be 20 percent, 33 percent, and 9 percent, respectively. The most probable utilizations are unchanged compared to 2012 Inventory year. To address the uncertainty in the capacity

---

representative) defaults are higher or lower than the older defaults. Multiple models and sensitivity scenarios were run for the subpart I analysis. The uncertainty analysis presented here made use of the Input gas and wafer size model (Model 1) under the following conditions: Year = 2010, f = 20, n = SIA3.

utilization for Inventory year 2013, the lower bound has been decreased by 10 percent, and the upper bound has been increased by 10 percent (or 100 percent if greater than 100 percent) compared to the bounds used in the 2012 Inventory year. For the triangular distributions that govern the number of possible layers manufactured, it is assumed the most probable value is one layer less than reported in the ITRS; the smallest number varied by technology generation between one and two layers less than given in the ITRS and largest number of layers corresponded to the figure given in the ITRS.

The uncertainty bounds for the average capacity utilization and the number of layers manufactured are used as inputs in a separate Monte Carlo simulation to estimate the uncertainty around the TMLA of both individual facilities as well as the total non-reporting TMLA of each sub-population.

The uncertainty around the emission factors for each non-reporting category of facilities is dependent on the uncertainty of the total emissions (MMT CO_2 Eq. units) and the TMLA of each reporting facility in that category. For each subpopulation of reporting facilities, total emissions were regressed on TMLA (with an intercept forced to zero) for 10,000 emissions and 10,000 TMLA values in a Monte Carlo simulation, which results in 10,000 total regression coefficients (emission factors). The 2.5th and the 97.5th percentile of these emission factors are determined and the bounds are assigned as the percent difference from the estimated emission factor.

For simplicity, the results of the Monte Carlo simulations on the bounds of the gas- and wafer size-specific emissions as well as the TMLA and emission factors are assumed to be normally distributed and the uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean. The departures from normality were observed to be small.

The final step in estimating the uncertainty in emissions of non-reporting facilities is convolving the distribution of emission factors with the distribution of TMLA using Monte Carlo simulation.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-93, which is also obtained by convolving—using Monte Carlo simulation—the distributions of emissions for each reporting and non-reporting facility. The emissions estimate for total U.S. F-GHG and N_2O emissions from semiconductor manufacturing were estimated to be between 4.0 and 4.4 MMT CO_2 Eq. at a 95 percent confidence level. This range represents 5 percent below to 5 percent above the 2013 emission estimate of 4.2 MMT CO_2 Eq. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate, but were not explicitly modeled.

Table 4-93: Approach 2 Quantitative Uncertainty Estimates for HFC, PFC, SF_6, NF_3 and N_2O Emissions from Semiconductor Manufacture (MMT CO_2 Eq. and Percent)

Source	Gas	2013 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound	Upper Bound
Semiconductor Manufacture	HFC, PFC, SF_6, NF_3, and N_2O	4.2	4.0	4.4	-5%	5%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[b] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in emissions from CH_4, HFCs, PFCs, SF_6, and NF_3. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

The decrease in the GWP of SF_6 and increase in the GWP of all other gases had several impacts on Inventory estimates. In the 1990 through 1994 time period, an overall increase in total annual GWP-weighted emissions is seen. In the 1995 through 2010 time period, the Inventory methodology relies on various gas distributions based on Partner reported emissions and PEVM estimated emissions. The changes in GWP carry through to changes in the estimated gas distributions, and hence changes in gas-by-gas emission estimates, in CO_2 Eq., and total annual fluorinated greenhouse gas emission estimates, in CO_2 Eq..

For the first time, NF_3 and N_2O have been included in total annual GWP-weighted emission estimates for the United States. This, along with an increased weighted GWP from SAR to AR4 led to increase in total emissions for all years as compared to previous Inventories. The emissions of each gas were impacted by the increase in overall emissions as well as the percent distribution of each gas as a result of changes in their GWPs.

Emissions in years 2011 and 2012 were updated to reflect updated emissions reporting in EPA's GHGRP. For the non-reporting population, the methodology to determine the non-reporting population for GaAs using facilities has been updated. In the updated methodology, revised assumptions were made about the GaAs using facilities that use fluorinated greenhouse gases (e.g., only the non-reporters that use wafers greater than or equal to four inches have been assumed to use fluorinated greenhouse gases, facilities that use wafers less than 4 inches are assumed to use wet etching and hence do not consume or emit any fluorinated greenhouse gases). Further, EPA has drawn an analogy between GaAs-using GHGRP reporters and non-reporters provided the non-reporters use wafers greater than 4 inches and manufacture the many versions of high electron mobility transistors (HEMT, PHEMT, MHEMT, HET, MOFETs), which are discrete devices and may be made to specific order by certain foundries. By virtue of this analogy, EPA has estimated emissions only from the non-reporters that use GaAs technology and manufacture HEMT and their variations. While other devices may be made using GaAs technology, EPA has no reporters under the GHGRP that manufacture them and hence has no basis for estimating an emission factor. EPA has thus assumed that they do not use or emit F-GHGs. This has decreased the non-reporting facilities subpopulation, and subsequently total emissions for the years 2011 and 2012.

Planned Improvements

This Inventory contains estimates of seven fluorinated gases for semiconductor manufacturing. However, other fluorinated gases (e.g., C_5F_8) are used in relatively smaller, but significant amounts. Previously, emissions data for these other fluorinated gases was not reported through the EPA Partnership. Through EPA's GHGRP, these data, as well as heat transfer fluid emission data, are available. Therefore, a point of consideration for future Inventory reports is the inclusion of other fluorinated gases, and emissions from heat transfer fluid (HTF) loss to the atmosphere.

Fluorinated heat transfer fluids, of which some are liquid perfluorinated compounds, are used for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of semiconductor manufacturing production processes. Evaporation of these fluids is a source of fluorinated emissions (EPA 2006). The GHGRP-reported HTF emissions along with WFF database could be used to develop emission factors for identified subpopulations. Further research needs to be done to determine if the same subpopulations identified in developing new emission factors for F-GHGs are applicable or new subpopulations have to be studied as HTFs are used primarily by manufacturers of wafer size 300 mm and above.

Along with more emissions information for semiconductor manufacturing, EPA's GHGRP requires the reporting of emissions from other types of electronics manufacturing, including micro-electro-mechanical systems, flat panel displays, and photovoltaic cells. There currently are no flat panel displays, and photovoltaic cell manufacturing facilities that are reporting to EPA's GHGRP, and five reporting MEMs manufacturers. The MEMs manufacturers also report emissions from semiconductor manufacturing and do not distinguish between these two types of manufacturing in their report; thus, emissions from MEMs manufacturers are included in the totals here. Emissions from manufacturing of flat panel displays and photovoltaic cells may be included in future Inventory reports; however, estimation methodologies would need to be developed.

4.23 Substitution of Ozone Depleting Substances (IPCC Source Category 2F)

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used as alternatives to several classes of ozone-depleting substances (ODSs) that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990.[49] Ozone depleting substances—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—are used in a variety of industrial applications including refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. Although HFCs and PFCs are not harmful to the stratospheric ozone layer, they are potent greenhouse gases. Emission estimates for HFCs and PFCs used as substitutes for ODSs are provided in Table 4-94 and Table 4-95.

Table 4-94: Emissions of HFCs and PFCs from ODS Substitutes (MMT CO_2 Eq.)

Gas	1990	2005	2010	2011	2012	2013	2014
HFC-23	+	+	+	+	+	+	+
HFC-32	+	0.3	2.6	3.4	4.4	5.4	6.4
HFC-125	+	11.9	32.5	38.1	44.2	50.3	56.1
HFC-134a	+	82.0	87.0	82.0	77.2	72.2	70.2
HFC-143a	+	11.7	22.1	23.9	25.5	26.8	27.7
HFC-236fa	+	1.2	1.4	1.4	1.5	1.5	1.4
CF_4	+	+	+	+	+	+	+
Others[a]	0.3	5.9	7.8	8.2	8.6	9.0	9.4
Total	**0.3**	**113.0**	**153.5**	**157.1**	**161.4**	**165.3**	**171.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-43-10mee, HFO-1234yf, C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon C_6F_{14}.

Note: Totals may not sum due to independent rounding.

Table 4-95: Emissions of HFCs and PFCs from ODS Substitution (Metric Tons)

Gas	1990	2005	2010	2011	2012	2013	2014
HFC-23	+	1	2	2	2	2	3
HFC-32	+	508	3,906	5,022	6,467	7,972	9,460
HFC-125	+	3,390	9,294	10,874	12,627	14,378	16,036
HFC-134a	+	57,335	60,848	57,356	54,013	50,516	49,101
HFC-143a	+	2,613	4,937	5,354	5,699	5,991	6,204
HFC-236fa	+	125	146	147	148	151	148
CF_4	+	2	3	4	4	4	4
Others[a]	M	M	M	M	M	M	M

M (Mixture of Gases)

+ Does not exceed 0.5 MT

[a] Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-43-10mee, HFO-1234yf, C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—used as an aerosol propellant and also a component of the refrigerant blend R-500 used in chillers—and HFC-134a in refrigeration end-uses. Beginning in 1992, HFC-134a was used in growing amounts as a refrigerant in motor vehicle air-conditioners and in refrigerant blends such as R-404A.[50] In 1993, the use of HFCs

---

[49] [42 U.S.C § 7671, CAA Title VI]

[50] R-404A contains HFC-125, HFC-143a, and HFC-134a.

in foam production began, and in 1994 ODS substitutes for halons entered widespread use in the United States as halon production was phased-out. In 1995, these compounds also found applications as solvents.

The use and subsequent emissions of HFCs and PFCs as ODS substitutes has been increasing from small amounts in 1990 to 171.4 MMT CO_2 Eq. in 2014. This increase was in large part the result of efforts to phase out CFCs and other ODSs in the United States. In the short term, this trend is expected to continue, and will likely continue over the next decade as HCFCs, which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*. Improvements in the technologies associated with the use of these gases and the introduction of alternative gases and technologies, however, may help to offset this anticipated increase in emissions.

Table 4-96 presents emissions of HFCs and PFCs as ODS substitutes by end-use sector for 1990 through 2014. The end-use sectors that contributed the most toward emissions of HFCs and PFCs as ODS substitutes in 2014 include refrigeration and air-conditioning (149.4 MMT CO_2 Eq., or approximately 87 percent), aerosols (10.8 MMT CO_2 Eq., or approximately 6 percent), and foams (8.0 MMT CO_2 Eq., or approximately 4 percent). Within the refrigeration and air-conditioning end-use sector, motor vehicle air-conditioning was the highest emitting end-use (40.9 MMT CO_2 Eq.), followed by refrigerated retail food and refrigerated transport. Each of the end-use sectors is described in more detail below.

Table 4-96: Emissions of HFCs and PFCs from ODS Substitutes (MMT CO_2 Eq.) by Sector

Sector	1990	2005	2010	2011	2012	2013	2014
Refrigeration/Air Conditioning	+	101.1	135.1	137.7	141.2	144.2	149.4
Aerosols	0.3	7.6	9.7	10.1	10.3	10.5	10.8
Foams	+	2.1	5.9	6.4	6.9	7.4	8.0
Solvents	+	1.7	1.7	1.7	1.7	1.8	1.8
Fire Protection	+	0.7	1.1	1.2	1.3	1.3	1.4
Total	**0.3**	**113.0**	**153.5**	**157.1**	**161.4**	**165.3**	**171.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

Refrigeration/Air Conditioning

The refrigeration and air-conditioning sector includes a wide variety of equipment types that have historically used CFCs or HCFCs. End-uses within this sector include motor vehicle air-conditioning, retail food refrigeration, refrigerated transport (e.g., ship holds, truck trailers, railway freight cars), household refrigeration, residential and small commercial air-conditioning and heat pumps, chillers (large comfort cooling), cold storage facilities, and industrial process refrigeration (e.g., systems used in food processing, chemical, petrochemical, pharmaceutical, oil and gas, and metallurgical industries). As the ODS phaseout is taking effect, most equipment is being or will eventually be retrofitted or replaced to use HFC-based substitutes. Common HFCs in use today in refrigeration/air-conditioning equipment are HFC-134a, R-410A,[51] R-404A, and R-507A.[52] Low-GWP options such as HFO-1234yf in motor vehicle air-conditioning, R-717 (ammonia) in cold storage and industrial applications, and R-744 (carbon dioxide) in retail food refrigeration, are also being used. These refrigerants are emitted to the atmosphere during equipment manufacture and operation (as a result of component failure, leaks, and purges), as well as at servicing and disposal events.

Aerosols

Aerosol propellants are used in metered dose inhalers (MDIs) and a variety of personal care products and technical/specialty products (e.g., duster sprays and safety horns). Many pharmaceutical companies that produce MDIs—a type of inhaled therapy used to treat asthma and chronic obstructive pulmonary disease—have replaced the use of CFCs with HFC-propellant alternatives. The earliest ozone-friendly MDIs were produced with HFC-134a, but the industry has started to use HFC-227ea as well. Conversely, since the use of CFC propellants was banned in 1978, most non-medical consumer aerosol products have not transitioned to HFCs, but to "not-in-kind"

---

[51] R-410A contains HFC-32 and HFC-125.

[52] R-507A, also called R-507, contains HFC-125 and HFC-143a.

technologies, such as solid roll-on deodorants and finger-pump sprays. The transition away from ODS in specialty aerosol products has also led to the introduction of non-fluorocarbon alternatives (e.g., hydrocarbon propellants) in certain applications, in addition to HFC-134a or HFC-152a. Other low-GWP options such as HFO-1234ze(E) are being used as well. These propellants are released into the atmosphere as the aerosol products are used.

Foams

CFCs and HCFCs have traditionally been used as foam blowing agents to produce polyurethane (PU), polystyrene, polyolefin, and phenolic foams, which are used in a wide variety of products and applications. Since the *Montreal Protocol*, flexible PU foams as well as other types of foam, such as polystyrene sheet, polyolefin, and phenolic foam, have transitioned almost completely away from fluorocompounds, into alternatives such as CO_2, methylene chloride, and hydrocarbons. The majority of rigid PU foams have transitioned to HFCs—primarily HFC-134a and HFC-245fa. Today, these HFCs are used to produce polyurethane appliance, PU commercial refrigeration, PU spray, and PU panel foams—used in refrigerators, vending machines, roofing, wall insulation, garage doors, and cold storage applications. In addition, HFC-152a, HFC-134a and CO_2 are used to produce polystyrene sheet/board foam, which is used in food packaging and building insulation. Low-GWP fluorinated foam blowing agents in use include HFO-1234ze(E) and -1233zd(E). Emissions of blowing agents occur when the foam is manufactured as well as during the foam lifetime and at foam disposal, depending on the particular foam type.

Solvents

CFCs, methyl chloroform (1,1,1-trichloroethane or TCA), and to a lesser extent carbon tetrachloride (CCl_4) were historically used as solvents in a wide range of cleaning applications, including precision, electronics, and metal cleaning. Since their phaseout, metal cleaning end-use applications have primarily transitioned to non-fluorocarbon solvents and not-in-kind processes. The precision and electronics cleaning end-uses have transitioned in part to high-GWP gases, due to their high reliability, excellent compatibility, good stability, low toxicity, and selective solvency. These applications rely on HFC-43-10mee, HFC-365mfc, HFC-245fa, and to a lesser extent, PFCs. Electronics cleaning involves removing flux residue that remains after a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or to metal surfaces, and is characterized by products, such as disk drives, gyroscopes, and optical components, that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges. The use of solvents yields fugitive emissions of these HFCs and PFCs.

Fire Protection

Fire protection applications include portable fire extinguishers (“streaming” applications) that originally used halon 1211, and total flooding applications that originally used halon 1301, as well as some halon 2402. Since the production and import of virgin halons were banned in the United States in 1994, the halon replacement agent of choice in the streaming sector has been dry chemical, although HFC-236fa is also used to a limited extent. In the total flooding sector, HFC-227ea has emerged as the primary replacement for halon 1301 in applications that require clean agents. Other HFCs, such as HFC-23 and HFC-125, are used in smaller amounts. The majority of HFC-227ea in total flooding systems is used to protect essential electronics, as well as in civil aviation, military mobile weapons systems, oil/gas/other process industries, and merchant shipping. Fluoroketone FK-5-1-12 is also used as a low-GWP option. As fire protection equipment is tested or deployed, emissions of these HFCs occur.

Methodology

A detailed Vintaging Model of ODS-containing equipment and products was used to estimate the actual—versus potential—emissions of various ODS substitutes, including HFCs and PFCs. The name of the model refers to the fact that it tracks the use and emissions of various compounds for the annual “vintages” of new equipment that enter service in each end-use. The Vintaging Model predicts ODS and ODS substitute use in the United States based on modeled estimates of the quantity of equipment or products sold each year containing these chemicals and the amount of the chemical required to manufacture and/or maintain equipment and products over time. Emissions for each end-use were estimated by applying annual leak rates and release profiles, which account for the lag in emissions from equipment as they leak over time. By aggregating the data for more than 60 different end-uses, the model produces estimates of annual use and emissions of each compound. Further information on the Vintaging Model is contained in Annex 3.9.

Uncertainty and Time-Series Consistency

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates must be made using analytical tools such as the Vintaging Model or the methods outlined in IPCC (2006). Though the model is more comprehensive than the IPCC default methodology, significant uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

The Vintaging Model estimates emissions from 60 end-uses. The uncertainty analysis, however, quantifies the level of uncertainty associated with the aggregate emissions resulting from the top 21 end-uses, comprising over 95 percent of the total emissions, and 6 other end-uses. These 27 end-uses comprise 97 percent of the total emissions, equivalent to 166.4 MMT CO_2 Eq. In an effort to improve the uncertainty analysis, additional end-uses are added annually, with the intention that over time uncertainty for all emissions from the Vintaging Model will be fully characterized. Any end-uses included in previous years' uncertainty analysis were included in the current uncertainty analysis, whether or not those end-uses were included in the top 95 percent of emissions from ODS Substitutes.

In order to calculate uncertainty, functional forms were developed to simplify some of the complex "vintaging" aspects of some end-use sectors, especially with respect to refrigeration and air-conditioning, and to a lesser degree, fire extinguishing. These sectors calculate emissions based on the entire lifetime of equipment, not just equipment put into commission in the current year, thereby necessitating simplifying equations. The functional forms used variables that included growth rates, emission factors, transition from ODSs, change in charge size as a result of the transition, disposal quantities, disposal emission rates, and either stock for the current year or original ODS consumption. Uncertainty was estimated around each variable within the functional forms based on expert judgment, and a Monte Carlo analysis was performed. The most significant sources of uncertainty for this source category include the emission factors for residential unitary AC, as well as the percent of non-MDI aerosol propellant that is HFC-152a.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-97. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 153.0 and 172.3 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 0.22 percent below to 12.4 percent above the emission estimate of 158.6 MMT CO_2 Eq.

Table 4-97: Approach 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes (MMT CO_2 Eq. and Percent)

Source	Gases	2014 Emission Estimate (MMT CO_2 Eq.)[a]	Uncertainty Range Relative to Emission Estimate[b] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	158.6	153.0	172.3	-0.22%	+12.4%

[a] 2014 emission estimates and the uncertainty range presented in this table correspond to selected end-uses within the aerosols, foams, solvents, fire extinguishing agents, and refrigerants sectors that comprise 97 percent of total emissions, but not for other remaining categories. Therefore, because the uncertainty associated with emissions from "other" ODS substitutes was not estimated, they were excluded in the uncertainty estimates reported in this table.

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

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Comparison of Reported Consumption to Modeled Consumption of HFCs

Data from EPA's Greenhouse Gas Reporting Program (GHGRP) was also used to perform quality control on the modeled emissions from this source category. To do so, reported consumption patterns demonstrated through GHGRP Subpart OO: Suppliers of Industrial Greenhouse Gases reported data were compared to the modeled demand for new saturated HFCs (excluding HFC-23) used as ODS substitutes from the Vintaging Model. The collection of data from suppliers of HFCs enables EPA to calculate the reporters' aggregated net supply–the sum of the quantities of chemical produced or imported into the United States less the sum of the quantities of chemical transformed (used as a feedstock in the production of other chemicals), destroyed, or exported from the United States.53 This allows for a quality control check on emissions from this source because the Vintaging Model uses modeled demand for new chemical as a proxy for total amount supplied, which is similar to net supply, as an input to the emission calculations in the model.

Reported Net Supply (GHGRP Top-Down Estimate)

Under EPA's GHGRP, suppliers (i.e., producers, importers and exporters) of HFCs began annually reporting their production, transformation, destruction, imports, and exports to EPA in 2011 (for supply that occurred in 2010). For the first time in 2015, bulk consumption data for aggregated HFCs were made publicly available under EPA's GHGRP. Data include all saturated HFCs (except HFC-23) reported to EPA across the GHGRP-reporting time series (2010 through 2014). The data include all 19 such saturated HFCs listed in Table A-1 of 40 CFR Part 98, where regulations for the GHGRP are promulgated, though not all species were reported in each reporting year.

Modeled Consumption (Vintaging Model Bottom-Up Estimate)

The Vintaging Model, used to estimate emissions from this source category, calculates chemical demand based on the quantity of equipment and products sold, serviced and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment and products.[54] It is assumed that the total demand equals the amount supplied by either new production, chemical import, or quantities recovered (usually reclaimed) and placed back on the market. In the Vintaging Model, demand for new chemical, as a proxy for consumption, is calculated as any chemical demand (either for new equipment or for servicing existing equipment) that cannot be met through recycled or recovered material. No distinction is made in the Vintaging Model between whether that need is met through domestic production or imports. To calculate emissions, the Vintaging Model estimates the quantity released from equipment over time. Thus, verifying the Vintaging Model's calculated consumption against GHGRP reported data is one way to check the Vintaging Model's emission estimates.

There are ten saturated HFC species modeled in the Vintaging Model: HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa, and HFC-43-10mee. For the purposes of this comparison, only nine HFC species are included (HFC-23 is excluded), to more closely align with the aggregated total reported under the GHGRP. While some amounts of less-used saturated HFCs, including isomers of those included in the Vintaging Model, are reportable under the GHGRP, the data are believed to represent an amount comparable to the modeled estimates as a quality control check.

Comparison Results and Discussion

Comparing the estimates of consumption from these two approaches ultimately supports and improves estimates of emissions, as noted in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (which refer to fluorinated greenhouse gas consumption based on supplies as "potential emissions"):

> [W]hen considered along with estimates of actual emissions, the potential emissions approach can assist in validation of completeness of sources covered and as a QC check by comparing total domestic

---

[53] Chemical that is exported, transformed, or destroyed—unless otherwise imported back to the United States—will never be emitted in the United States.

[54] The model builds an inventory of the in-use stock of equipment and products and ODSs and HFCs in each of the sub-applications. Emissions are subsequently estimated by applying annual and disposal emission rates to each population of equipment and products.

consumption as calculated in this 'potential emissions approach' per compound with the sum of all activity data of the various uses (IPCC 2006).

Table 4-98 compares the net supply of saturated HFCs (excluding HFC-23) in million metric tons of CO_2 Eq. as determined from Subpart OO of EPA's GHGRP for the years 2010 through 2014 and the chemical demand as calculated by the Vintaging Model for the same time series.

Table 4-98: U.S. HFC Consumption (MMT CO_2 Eq.)

	2010	2011	2012	2013	2014
Reported Net Supply (GHGRP)	235	241	227	278	254
Modeled Supply (Vintaging Model)	268	267	284	289	292
Percent Difference	**14%**	**11%**	**25%**	**4%**	**15%**

As shown, the estimates from the Vintaging Model are higher than the GHGRP estimates by an average of 13 percent across the time series (i.e., 2010-2014). Potential reasons for these differences include:

- The Vintaging Model includes fewer HFCs than are reported to EPA's GHGRP. However, the additional reported HFCs represent a small fraction of total HFC use for this source category, both in GWP-weighted and unweighted terms, and as such, it is not expected that the additional HFCs reported to EPA are a major driver for the difference between the two sets of estimates. To the extent lower-GWP isomers were used in lieu of the modeled chemicals (e.g., HFC-134 instead of HFC-134a), lower CO_2 Eq. amounts in the GHGRP data compared to the modeled estimates would be expected.

- Because the top-down data are reported at the time of actual production or import and the bottom-up data are calculated at the time of actual placement on the market, there could be a temporal discrepancy when comparing data. Because the GHGRP data generally increases over time (although some year-to-year variations exist) and the Vintaging Model estimates also increase, EPA would expect the modeled estimates to be slightly higher than the corresponding GHGRP data due to this temporal effect.

- Under EPA's GHGRP, all facilities that produce HFCs are required to report their quantities, whereas importers or exporters of HFCs are only required to report if either their total imports or their total exports of greenhouse gases are greater than or equal to 25,000 metric tons of CO_2 Eq. per year. Thus, some imports may not be accounted for in the GHGRP data. On the other hand, some exports might also not be accounted for in this data.

- In some years, imports and exports may be greater than consumption because the excess is being used to increase chemical stockpiles; in other years, the opposite may hold true. Averaging imports and exports over multiple years can minimize the impact of such fluctuations. For example, when the 2012 and 2013 net additions to the supply are averaged, the difference between the consumption estimates decreases compared to the 2012-only estimates.

Table 4-99: Averaged U.S. HFC Demand (MMT CO_2 Eq.)

	2010-2011 Avg.	2011-2012 Avg.	2012-2013 Avg.	2013-2014 Avg.
Reported Net Supply (GHGRP)	238	234	253	266
Modeled Demand (Vintaging Model)	268	276	286	290
Percent Difference	**12%**	**18%**	**13%**	**9%**

- The Vintaging Model does not reflect the dynamic nature of reported HFC consumption, with significant differences seen in each year. Whereas the Vintaging Model projects a slowly increasing overall demand, actual consumption for specific chemicals may vary over time and could even switch from positive to negative (indicating more chemical exported, transformed, or destroyed than produced or imported in a given year). Furthermore, consumption as calculated in the Vintaging Model is a function of demand not met by disposal recovery. If, in any given year, a significant number of units are disposed, there will be a large amount of additional recovery in that year that can cause an unexpected and not modeled decrease in demand and thus a decrease in consumption. On the other hand, if market, economic or other factors cause less than expected disposal and recovery, actual supply would decrease, and hence consumption would increase to meet that demand not satisfied by recovered quantities, increasing the GHGRP data and bringing those totals closer to the Vintaging Model estimates.

- The Vintaging Model is used to estimate the emissions that occur in the United States. As such, equipment or products that contain ODS or alternatives, including saturated HFCs, are assumed to consume and emit chemicals equally as like equipment or products originally produced in the United States. Therefore, the GHGRP data may include HFCs produced or imported and used to fill or manufacture products that are then exported from the United States. The Vintaging Model estimates of demand and supply are not meant to incorporate such chemical. Likewise, chemicals may be used outside the United States to create products or charge equipment that is then imported to and used in the United States. The Vintaging Model estimates of demand and supply are meant to capture this chemical, as it will lead to emissions inside the United States. Depending on whether the U.S. is a net importer or net exporter of such chemical, this factor may account for some of the difference shown above or might lead to a further discrepancy. Reporting under the GHGRP Subpart QQ: Importers and Exporters of Fluorinated Greenhouse Gases Contained in Pre-Charged Equipment or Closed-Cell Foams could be analyzed in the future to investigate this issue further.

One factor however would only lead to modeled estimates to be even higher than the estimates shown and hence higher than EPA’s GHGRP data:

- Saturated HFCs are also known to be used as a cover gas in the production of magnesium. The Vintaging Model estimates here do not include the amount of HFCs for this use, but rather only the amount for uses that traditionally were served by ODS. Nonetheless, EPA expects that this supply not included in the Vintaging Model estimates to be very small compared to the ODS substitute use for the years analyzed. An indication of the different magnitudes of these categories is seen in the fact that the 2014 emissions from that non-modeled sources (0.2 MMT CO_2 Eq.) are much smaller than those for the ODS substitute sector (171.4 MMT CO_2 Eq).

Using a Tier 2 bottom-up modeling methodology to estimate emissions requires assumptions and expert judgement. Comparing the Vintaging Model’s estimates to GHGRP reported estimates, particularly for more widely used chemicals, can help validate the model but it is expected that the model will have limitations. This comparison shows that Vintaging Model consumption estimates are well within the same order of magnitude as the actual consumption data as reported to EPA’s GHGRP although the differences in reported net supply and modeled demand are still significant in some of the years. Although it can be difficult to capture the observed market variability, the Vintaging Model is periodically reviewed and updated to ensure that the model reflects the current and future trajectory of ODS and ODS substitutes across all end-uses and the Vintaging Model will continue to be compared to available top-down estimates in order to ensure the model accurately estimates HFC consumption and emissions.

Recalculations Discussion

For the current Inventory, a review of the large retail food end-use resulted in revisions to the Vintaging Model since the previous Inventory report. In addition, a vending machine end-use was added to the Vintaging Model since the previous Inventory. Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014.

For the large retail food end-use, assumptions regarding new installations by system type and refrigerant transitions were revised based on a review of data collected by EPA's GreenChill Partnership and the California Air Resources Board's Refrigerant Management Program. The vending machine end-use was added based on a review of technical reports and sales data. Combined, these assumption changes and additions decreased greenhouse gas emissions on average by 3 percent between 1990 and 2002 and increased greenhouse gas emissions on average by 4 percent between 2003 and 2014.

4.24 Electrical Transmission and Distribution (IPCC Source Category 2G1) (TO BE UPDATED)

The largest use of sulfur hexafluoride (SF_6), both in the United States and internationally, is as an electrical insulator and interrupter in equipment that transmits and distributes electricity (RAND 2004). The gas has been employed by the electric power industry in the United States since the 1950s because of its dielectric strength and arc-quenching characteristics. It is used in gas-insulated substations, circuit breakers, and other switchgear. SF_6 has replaced flammable insulating oils in many applications and allows for more compact substations in dense urban areas.

Fugitive emissions of SF_6 can escape from gas-insulated substations and switchgear through seals, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and disposal. Emissions of SF_6 from equipment manufacturing and from electrical transmission and distribution systems were estimated to be 5.1 MMT CO_2 Eq. (0.2 kt) in 2013. This quantity represents an 80 percent decrease from the estimate for 1990 (see Table 4-100 and Table 4-101). There are two potential causes for this decrease: a sharp increase in the price of SF_6 during the 1990s and a growing awareness of the magnitude and environmental impact of SF_6 emissions through programs such as EPA's voluntary SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership) and EPA's GHGRP. Utilities participating in the Partnership have lowered their emission factor (kg SF_6 emitted per kg of nameplate capacity) by more than 75 percent since the Partnership began in 1999. A recent examination of the SF_6 emissions reported by electric power systems to EPA's GHGRP revealed that SF_6 emissions from reporters has decreased by 25 percent from 2011 to 2013, with much of the reduction seen from utilities that are not participants in the Partnership. These utilities may be making relatively large reductions in emissions as they take advantage of relatively large and/or inexpensive emission reduction opportunities (i.e., "low hanging fruit," such as replacing major leaking circuit breakers) that Partners have already taken advantage of under the voluntary program (Ottinger et al. 2014).

Table 4-100: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (MMT CO_2 Eq.)

Year	Electric Power Systems	Electrical Equipment Manufacturers	Total
1990	25.1	0.3	25.4
2005	9.8	0.8	10.6
2009	6.7	0.6	7.3
2010	6.2	0.9	7.0
2011	5.7	1.1	6.8
2012	4.6	1.1	5.7
2013	4.2	0.9	5.1

Note: Totals may not sum due to independent rounding.

Table 4-101: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (kt)

Year	Emissions
1990	1.1
2005	0.5
2009	0.3
2010	0.3
2011	0.3

2012	0.2
2013	0.2

Methodology

The estimates of emissions from Electrical Transmission and Distribution are comprised of emissions from electric power systems and emissions from the manufacture of electrical equipment. The methodologies for estimating both sets of emissions are described below.

1990 through 1998 Emissions from Electric Power Systems

Emissions from electric power systems from 1990 through 1998 were estimated based on (1) the emissions estimated for this source category in1999, which, as discussed in the next section, were based on the emissions reported during the first year of EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership), and (2) the RAND survey of global SF_6 emissions. Because most utilities participating in the Partnership reported emissions only for 1999 through 2011, modeling was used to estimate SF_6 emissions from electric power systems for the years 1990 through 1998. To perform this modeling, U.S. emissions were assumed to follow the same trajectory as global emissions from this source during the 1990 to 1999 period. To estimate global emissions, the RAND survey of global SF_6 sales were used, together with the following equation for estimating emissions, which is derived from the mass-balance equation for chemical emissions (Volume 3, Equation 7.3) in the *2006 IPCC Guidelines* (IPCC 2006).[55] (Although Equation 7.3 of the *2006 IPCC Guidelines* appears in the discussion of substitutes for ozone-depleting substances, it is applicable to emissions from any long-lived pressurized equipment that is periodically serviced during its lifetime.)

Emissions (kilograms SF_6) = SF_6 purchased to refill existing equipment (kilograms) + nameplate capacity of retiring equipment (kilograms) [56]

Note that the above equation holds whether the gas from retiring equipment is released or recaptured; if the gas is recaptured, it is used to refill existing equipment, thereby lowering the amount of SF_6 purchased by utilities for this purpose.

Gas purchases by utilities and equipment manufacturers from 1961 through 2003 are available from the RAND (2004) survey. To estimate the quantity of SF_6 released or recovered from retiring equipment, the nameplate capacity of retiring equipment in a given year was assumed to equal 81.2 percent of the amount of gas purchased by electrical equipment manufacturers 40 years previous (e.g., in 2000, the nameplate capacity of retiring equipment was assumed to equal 81.2 percent of the gas purchased in 1960). The remaining 18.8 percent was assumed to have been emitted at the time of manufacture. The 18.8 percent emission factor is an average of IPCC default SF_6 emission rates for Europe and Japan for 1995 (IPCC 2006). The 40-year lifetime for electrical equipment is also based on IPCC (2006). The results of the two components of the above equation were then summed to yield estimates of global SF_6 emissions from 1990 through 1999.

U.S. emissions between 1990 and 1999 are assumed to follow the same trajectory as global emissions during this period. To estimate U.S. emissions, global emissions for each year from 1990 through 1998 were divided by the estimated global emissions from 1999. The result was a time series of factors that express each year's global emissions as a multiple of 1999 global emissions. Historical U.S. emissions were estimated by multiplying the factor for each respective year by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (estimated to be 14.3 MMT CO_2 Eq.).

Two factors may affect the relationship between the RAND sales trends and actual global emission trends. One is utilities' inventories of SF_6 in storage containers. When SF_6 prices rise, utilities are likely to deplete internal inventories before purchasing new SF_6 at the higher price, in which case SF_6 sales will fall more quickly than emissions. On the other hand, when SF_6 prices fall, utilities are likely to purchase more SF_6 to rebuild inventories,

---

[55] Ideally, sales to utilities in the U.S. between 1990 and 1999 would be used as a model. However, this information was not available. There were only two U.S. manufacturers of SF_6 during this time period, so it would not have been possible to conceal sensitive sales information by aggregation.

[56] Nameplate capacity is defined as the amount of SF_6 within fully charged electrical equipment.

in which case sales will rise more quickly than emissions. This effect was accounted for by applying 3-year smoothing to utility SF_6 sales data. The other factor that may affect the relationship between the RAND sales trends and actual global emissions is the level of imports from and exports to Russia and China. SF_6 production in these countries is not included in the RAND survey and is not accounted for in any another manner by RAND. However, atmospheric studies confirm that the downward trend in estimated global emissions between 1995 and 1998 was real (see the Uncertainty discussion below).

1999 through 2013 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2013 were estimated based on: (1) reporting from utilities participating in EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partners), which began in 1999; (2) reporting from utilities covered by the EPA's GHGRP, which began in 2012 for emissions occurring in 2011 (GHGRP-Only Reporters); and (3) the relationship between utilities' reported emissions and their transmission miles as reported in the 2001, 2004, 2007, 2010, and 2013 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004, 2007, 2010, 2013), which was applied to the electric power systems that do not report to EPA (Non-Reporters). (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV).

Partners

Over the period from 1999 to 2013, Partner utilities, which for inventory purposes are defined as utilities that either currently are or previously have been part of the Partnership, represented between 42 percent and 48 percent of total U.S. transmission miles. Partner utilities estimated their emissions using a Tier 3 utility-level mass balance approach (IPCC 2006). If a Partner utility did not provide data for a particular year, emissions were interpolated between years for which data were available or extrapolated based on Partner-specific transmission mile growth rates. In 2012, many Partners began reporting their emissions (for 2011 and later years) through EPA's GHGRP (discussed further below) rather than through the Partnership. In 2013, approximately 0.3 percent of the total emissions attributed to Partner utilities were reported through Partnership reports. Approximately 91 percent of the total emissions attributed to Partner utilities were reported and verified through EPA's GHGRP. Partners without verified 2013 data accounted for approximately 9 percent of the total emissions attributed to Partner utilities.[57]

GHGRP-Only Reporters

EPA's GHGRP requires users of SF_6 in electric power systems to report emissions if the facility has a total SF_6 nameplate capacity that exceeds 17,820 pounds. (This quantity is the nameplate capacity that would result in annual SF_6 emissions equal to 25,000 metric tons of CO_2 equivalent at the historical emission rate reported under the Partnership.) As under the Partnership, electric power systems that report their SF_6 emissions under EPA's GHGRP are required to use the Tier 3 utility-level mass-balance approach. Many Partners began reporting their emissions through EPA's GHGRP in 2012 (reporting emissions for 2011 and later years) because their nameplate capacity exceeded the reporting threshold. Partners who did not report through EPA's GHGRP continued to report through the Partnership.

In addition, many non-Partners began reporting to EPA for the first time through its GHGRP in 2012. Non-Partner emissions reported and verified under EPA's GHGRP were compiled to form a new category of reported data

---

[57] It should be noted that data reported through EPA's GHGRP must go through a verification process; only data verified as of September 1, 2014 could be used in the emission estimates for 2013. For Partners whose GHGRP data was not yet verified, emissions were extrapolated based upon historical Partner-specific transmission mile growth rates, and those Partners are included in the 'non-reporting Partners' category.

For electric power systems, verification involved a series of electronic range, completeness, and algorithm checks for each report submitted. In addition, EPA manually reviewed the reported data and compared each facility's reported transmission miles with the corresponding quantity in the UDI 2013 database (UDI 2013). In the first year of GHGRP reporting, EPA followed up with reporters where the discrepancy between the reported miles and the miles published by UDI was greater than 10 percent, with a goal to improve data quality. Only GHGRP data verified as of September 1, 2014 was included in the emission estimates for 2011, 2012, and 2013.

(GHGRP-Only Reporters). GHGRP-Only Reporters accounted for 24 percent of U.S. transmission miles and 26 percent of estimated U.S. emissions from electric power system in 2013.[58]

Non-Reporters

Emissions from Non-Reporters (i.e., utilities other than Partners and GHGRP-Only Reporters) in every year since 1999 were estimated using the results of a regression analysis that correlated emissions from reporting utilities (using verified data from both Partners and GHGRP-Only Reporters) with their transmission miles.[59] Two equations were developed, one for "non-large" and one for "large" utilities (i.e., with fewer or greater than 10,000 transmission miles, respectively). The distinction between utility sizes was made because the regression analysis showed that the relationship between emissions and transmission miles differed for non-large and large transmission networks. As noted above, non-Partner emissions were reported to the EPA for the first time through its GHGRP in 2012 (representing 2011 emissions). This set of reported data was of particular interest because it provided insight into the emission rate of non-Partners, which previously was assumed to be equal to the historical (1999) emission rate of Partners for both large and non-large utilities.[60] The availability of non-Partner emissions estimates allowed the regression analysis to be modified for both large and non-large groups. Specifically, emissions were estimated for Non-Reporters as follows:

- Non-Reporters, 1999 to 2011: First, the 2011 emission rates (per kg nameplate capacity and per transmission mile) reported by Partners and GHGRP-Only Reporters were reviewed to determine whether there was a statistically significant difference between these two groups. Transmission mileage data for 2011 was reported through GHGRP, with the exception of transmission mileage data for Partners that did not report through GHGRP, which was obtained from UDI. It was determined that there is no statistically significant difference between the emission rates of Partners and GHGRP-Only reporters; therefore, Partner and GHGRP-Only reported data for 2011 were combined to develop regression equations to estimate the emissions of Non-Reporters for both "non-large" and "large" utilities. Historical emissions from Non-Reporters for both "non-large" and "large" utilities were estimated by linearly interpolating between the 1999 regression coefficients (based on 1999 Partner data) and the 2011 regression coefficients.

- Non-Reporters, 2012 - Present: It was determined that there continued to be no statistically significant difference between the emission rates reported by Partners and by GHGRP-Only Reporters. Therefore, the emissions data from both groups were combined to develop regression equations for 2012. This was repeated for 2013 using Partner and GHGRP-Only Reporter data for 2013.

    - *"Non-large" utilities (less than 10,000 transmission miles):* The 2013 regression equation for "non-large" utilities was developed based on the emissions reported by a subset of 89 Partner utilities and GHGRP-Only utilities (representing approximately 47 percent of total U.S. transmission miles for utilities with fewer than 10,000 transmission miles). The regression equation for 2013 is:

$$\text{Emissions (kg)} = 0.217 \times \text{Transmission Miles}$$

    - *"Large" utilities (more than 10,000 transmission miles)*: The 2013 regression equation was developed based on the emissions reported by a subset of 17 Partners and GHGRP-only utilities (representing approximately 83 percent of total U.S. transmission miles for utilities with greater than 10,000 transmission miles). The regression equation for 2013 is:

---

[58] Also, GHGRP-reported emissions from 17 facilities that had one or fewer transmission miles were included in the emission estimates for 2011. Emissions from these facilities comprise approximately 1.2 percent of total reported and verified emissions. In 2012, 16 facilities had one or fewer transmission miles, comprising 1.4 percent of verified emissions and in 2013, 16 facilities had one or fewer transmission miles, comprising 3.2 percent of verified emissions. These facilities were not included in the development of the regression equations (discussed further below). EPA is continuing to investigate whether or not these emissions are already implicitly accounted for in the relationship between transmission miles and emissions, and whether to update the regression analysis to better capture emissions from non-reporters that may have zero transmission miles.

[59] In the United States, SF_6 is contained primarily in transmission equipment rated above 34.5 kV.

[60] Partners in EPA's SF_6 Emission Reduction Partnership reduced their emissions by approximately 77 percent from 1999 to 2013.

$$\text{Emissions (kg)} = 0.225 \times \text{Transmission Miles}$$

Table 4-102 below shows the percentage of transmission miles covered by reporters (i.e., associated with reported data) and the regression coefficient for both large and non-large reporters for 1999 (the first year data was reported), and for 2011 through 2013 (the first three years with GHGRP reported data). The coefficients for non-large utilities and large utilities both decreased slightly between 2012 and 2013.

Table 4-102: Transmission Mile Coverage and Regression Coefficients for Large and Non-Large Utilities, Percent

	Non-large				Large			
	1999	2011	2012	2013	1999	2011	2012	2013
Percentage of Miles Covered by Reporters	31	45	44	47	86	97	88	83
Regression Coefficient[a]	0.89	0.33	0.23	0.22	0.58	0.27	0.24	0.22

[a] Regression coefficient is defined as emissions (in kg) divided by transmission miles.

Note: "Non-large" represents reporters with fewer than 10,000 transmission miles.

Data on transmission miles for each Non-Reporter for the years 2000, 2003, 2006, and 2009, and 2012 were obtained from the 2001, 2004, 2007, 2010, and 2013 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007, 2010, 2013). The U.S. transmission system grew by over 25,000 miles between 2000 and 2003 yet declined by almost 4,000 miles between 2003 and 2006. Given these fluctuations, periodic increases are assumed to occur gradually. Therefore, transmission mileage was assumed to increase at an annual rate of 1.2 percent between 2000 and 2003 and decrease by -0.20 percent between 2003 and 2006. This growth rate grew to 3 percent from 2006 to 2009 as transmission miles increased by more than 59,000 miles. The annual growth rate for 2009 through 2012 was calculated to be 2.0 percent as transmission miles grew by approximately 43,000 during this time period.

Total Industry Emissions

As a final step, total electric power system emissions from 1999 through 2013 were determined for each year by summing the Partner reported and estimated emissions (reported data was available through the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems), the GHGRP-Only reported emissions, and the non-reporting utilities' emissions (determined using the regression equations).

1990 through 2013 Emissions from Manufacture of Electrical Equipment

The 1990 to 2013 emission estimates for original equipment manufacturers (OEMs) were derived by assuming that manufacturing emissions equal 10 percent of the quantity of SF_6 provided with new equipment. The quantity of SF_6 provided with new equipment was estimated based on statistics compiled by the National Electrical Manufacturers Association (NEMA). These statistics were provided for 1990 to 2000; the quantities of SF_6 provided with new equipment for 2001 to 2013 were estimated using Partner reported data and the total industry SF_6 nameplate capacity estimate (198.2 MMT CO_2 Eq. in 2013). Specifically, the ratio of new nameplate capacity to total nameplate capacity of a subset of Partners for which new nameplate capacity data was available from 1999 to 2013 was calculated. These ratios were then multiplied by the total industry nameplate capacity estimate for each year to derive the amount of SF_6 provided with new equipment for the entire industry. The 10 percent emission rate is the average of the "ideal" and "realistic" manufacturing emission rates (4 percent and 17 percent, respectively) identified in a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE) in February 2002 (O'Connell et al. 2002).

Uncertainty and Time-Series Consistency

To estimate the uncertainty associated with emissions of SF_6 from Electrical Transmission and Distribution, uncertainties associated with four quantities were estimated: (1) emissions from Partners, (2) emissions from GHGRP-Only Reporters, (3) emissions from Non-Reporters, and (4) emissions from manufacturers of electrical equipment. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emissions estimate.

Total emissions from the SF_6 Emission Reduction Partnership include emissions from both reporting (through the Partnership or GHGRP) and non-reporting Partners. For reporting Partners, individual Partner-reported SF_6 data was assumed to have an uncertainty of 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all Partner-reported data was estimated to be 2.5 percent. The uncertainty associated with extrapolated or interpolated emissions from non-reporting Partners was assumed to be 20 percent.

For GHGRP-Only Reporters, reported SF_6 data was assumed to have an uncertainty of 20 percent.[61] Based on a Monte Carlo analysis, the cumulative uncertainty of all GHGRP-Only reported data was estimated to be 5.8 percent.

There are two sources of uncertainty associated with the regression equations used to estimate emissions in 2013 from Non-Reporters: (1) uncertainty in the coefficients (as defined by the regression standard error estimate), and (2) the uncertainty in total transmission miles for Non-Reporters. Uncertainties were also estimated regarding (1) the quantity of SF_6 supplied with equipment by equipment manufacturers, which is projected from Partner provided nameplate capacity data and industry SF_6 nameplate capacity estimates, and (2) the manufacturers' SF_6 emissions rate.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-103. Electrical Transmission and Distribution SF_6 emissions were estimated to be between 4.0 and 6.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 20 percent below and 19 percent above the emission estimate of 5.1 MMT CO_2 Eq.

Table 4-103: Approach 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Electrical Transmission and Distribution (MMT CO_2 Eq. and Percent)

Source	Gas	2013 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to 2013 Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Transmission and Distribution	SF_6	5.1	4.0	6.0	-20%	+19%

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

In addition to the uncertainty quantified above, there is uncertainty associated with using global SF_6 sales data to estimate U.S. emission trends from 1990 through 1999. However, the trend in global emissions implied by sales of SF_6 appears to reflect the trend in global emissions implied by changing SF_6 concentrations in the atmosphere. That is, emissions based on global sales declined by 29 percent between 1995 and 1998 (RAND 2004), and emissions based on atmospheric measurements declined by 17 percent over the same period (Levin et al. 2010).

Several pieces of evidence indicate that U.S. SF_6 emissions were reduced as global emissions were reduced. First, the decreases in sales and emissions coincided with a sharp increase in the price of SF_6 that occurred in the mid-1990s and that affected the United States as well as the rest of the world. A representative from DILO, a major manufacturer of SF_6 recycling equipment, stated that most U.S. utilities began recycling rather than venting SF_6 within two years of the price rise. Finally, the emissions reported by the one U.S. utility that reported its emissions for all the years from 1990 through 1999 under the Partnership showed a downward trend beginning in the mid-1990s.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations

---

[61] Uncertainty is assumed to be higher for the GHGRP-Only category, because 2011 is the first year that those utilities have reported to EPA.

for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2 Eq. emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2 Eq. emissions for SF_6. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

Only taking this change into consideration, emissions estimates for each year from 1990 to 2012 would have slightly decreased, relative to the emissions estimates in the previous Inventory report. However, other changes to the historical calculations, as noted below, resulted in emission estimates fluctuating slightly (increasing for some years and decreasing for other years) across the time series.

The historical emissions estimated for this source category have undergone several minor revisions. SF_6 emission estimates for the period 1990 through 2012 were updated relative to the previous report based on revisions to interpolated and extrapolated non-reported Partner data as well as resubmissions of estimates through the GHGRP for 2011 and 2012.[62] The previously-described interpolation between 1999 and 2012 regression coefficients to estimate emissions from non-reporting utilities were updated using revised GHGRP reports, which impacted historical estimates for the period 2000 through 2012. Additionally, updated leak rates were calculated from resubmitted Partner data through the GHGRP. These leak rates are used to estimate the nameplate capacity of non-reporters during these years, and are interpolated back through 1999 to calculate Non-Reporter nameplate capacity over the entire time series.[63] Finally, revisions were made regarding the incorporation of transmission mile data from the UDI database to remove instances of double counting transmission miles between parent and subsidiary companies. Reductions in the total transmission miles reduced the total number of non-reporter transmission miles, which reduced non-reporter emissions, and therefore total emissions.

As a result of the recalculations, SF_6 emissions from electrical transmission and distribution decreased by 6 percent for 2012 relative to the previous report. On average, the change in SF_6 emission estimates for the entire time series is approximately 0.5 percent per year.

Planned Improvements

EPA is exploring the use of OEM data that is reported under EPA's GHGRP to use for future Inventory reports instead of estimating those emissions based on elements reported by utilities to the GHGRP and Partner data. Specifically, using the GHGRP-reported OEM emissions and the estimated nameplate capacity increase estimated for users of electrical equipment (available in the existing methodology), a leak rate would be calculated. This approach would require estimating the portion of industry not reporting to the GHGRP program, which would require market research. Once a new leak rate is established, leak rates could be interpolated for years between 2000 (at 10 percent) and 2011. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[64]

Box 4-2: Potential Emission Estimates of HFCs, PFCs, SF_6, and NF_3

Emissions of HFCs, PFCs, SF_6, and NF_3 from industrial processes can be estimated in two ways, either as potential emissions or as actual emissions. Emission estimates in this chapter are "actual emissions," which are defined by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) as estimates that take into account the time lag between consumption and emissions. In contrast, "potential emissions" are defined to be equal to the amount of a chemical consumed in a country, minus the amount of a chemical recovered for destruction or export in the year of consideration. Potential emissions will generally be greater for a given year than actual emissions, since

---

[62] The earlier year estimates within the time series (i.e., 1990-1998) were updated based on revisions to the 1999 U.S. emission estimate because emissions for 1990-1998 are estimated by multiplying a series of annual factors by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (see Methodology section).

[63] Nameplate capacity estimates affect sector emissions because OEM emission estimation is calculated using total industry nameplate capacity.

[64] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

some amount of chemical consumed will be stored in products or equipment and will not be emitted to the atmosphere until a later date, if ever. Although actual emissions are considered to be the more accurate estimation approach for a single year, estimates of potential emissions are provided for informational purposes.

Separate estimates of potential emissions were not made for industrial processes that fall into the following categories:

- *Byproduct emissions*. Some emissions do not result from the consumption or use of a chemical, but are the unintended byproducts of a process. For such emissions, which include emissions of CF_4 and C_2F_6 from aluminum production and of HFC-23 from HCFC-22 production, the distinction between potential and actual emissions is not relevant.
- *Potential emissions that equal actual emissions*. For some sources, such as magnesium production and processing, no delay between consumption and emission is assumed and, consequently, no destruction of the chemical takes place. In this case, actual emissions equal potential emissions.

Table 4-104 presents potential emission estimates for HFCs and PFCs from the substitution of ozone depleting substances, HFCs, PFCs, SF_6, and NF_3 from semiconductor manufacture, and SF_6 from magnesium production and processing and electrical transmission and distribution.[65] Potential emissions associated with the substitution for ozone depleting substances were calculated using the EPA's Vintaging Model. Estimates of HFCs, PFCs, and SF_6 consumed by semiconductor manufacture were developed by dividing chemical-by-chemical emissions by the appropriate chemical-specific emission factors from the *2006 IPCC Guidelines* (Tier 2c). Estimates of CF_4 consumption were adjusted to account for the conversion of other chemicals into CF_4 during the semiconductor manufacturing process, again using the default factors from the *2006 IPCC Guidelines*. Potential SF_6 emissions estimates for electrical transmission and distribution were developed using U.S. utility purchases of SF_6 for electrical equipment. From 1999 through 2013, estimates were obtained from reports submitted by participants in EPA's SF_6 Emission Reduction Partnership for Electric Power Systems as well as EPA's Greenhouse Gas Reporting Program (GHGRP). U.S. utility purchases of SF_6 for electrical equipment from 1990 through 1998 were backcasted based on world sales of SF_6 to utilities. Purchases of SF_6 by utilities were added to SF_6 purchases by electrical equipment manufacturers to obtain total SF_6 purchases by the electrical equipment sector.

Table 4-104: 2013 Potential and Actual Emissions of HFCs, PFCs, SF_6, and NF_3 from Selected Sources (MMT CO_2 Eq.)

Source	Potential	Actual
Substitution of Ozone Depleting Substances	306.9	158.6
Aluminum Production	NA	3.0
HCFC-22 Production	NA	4.1
Semiconductor Manufacture	43.7	4.0
Magnesium Production and Processing	1.5	1.5
Electrical Transmission and Distribution	33.3	5.1

NA - Not applicable.

Under EPA's GHGRP, producers and larger importers and exporters[66] of fluorinated greenhouse gases (F-GHG) in bulk began annually reporting their production, destruction, imports, and exports in 2011 (for 2010 supplies), and larger importers and exporters of F-GHGs inside of pre-charged equipment began reporting their imports and exports in 2012 (for 2011 supplies). The collection of data from both emitters and suppliers of F-GHGs enables the comparison of consumption that is implied by emissions (downstream estimation method) to the consumption that is implied by balancing of production, destruction, imports, and exports (upstream estimation method). This type of comparison ultimately supports and improves estimates of emissions, as noted in the *2006 IPCC Guidelines*:

> "[W]hen considered along with estimates of actual emissions, the potential emissions approach can assist in validation of completeness of sources covered and as a QC check by comparing total domestic

---

[65] See Annex 5 for a discussion of sources of SF_6 emissions excluded from the actual emissions estimates in this report.

[66] Importers and exporters report only if either their total imports or their total exports of F-GHGs are greater than or equal to 25,000 metric tons of CO_2 Eq. per year

> consumption as calculated in this 'potential emissions approach' per compound with the sum of all activity data of the various uses (IPCC 2006)."

A comparison of upstream and downstream consumption estimates of SF_6 was performed to help evaluate the accuracy and completeness of the emissions inventory. This analysis revealed that the two potential emissions estimates for 2012 (the upstream estimation and downstream estimation methods) differed with the supply-based, upstream consumption estimate significantly larger than emitter-based, downstream consumption estimate (Ottinger et al. 2014). This finding indicates that methods for determining national SF_6 actual emission estimates by industry sector are generating results that, when summed, do not fall within a close proximity to the overall total U.S. supply of SF_6 gas.

While multiple sources of uncertainty affect both data sets, Ottinger et al. (2014) conclude that current SF_6 emission estimates likely do not account for all significant sources of SF_6 in the United States. Additional research is necessary to identify the other significant applications that consume and emit SF_6.

4.25 Nitrous Oxide from Product Uses (IPCC Source Category 2G3)

Nitrous oxide (N_2O) is a clear, colorless, oxidizing liquefied gas, with a slightly sweet odor which is used in a wide variety of specialized product uses and applications. The amount of N_2O that is actually emitted depends upon the specific product use or application.

There are a total of three N_2O production facilities currently operating in the United States (Ottinger 2014). N_2O is primarily used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia, and as an anesthetic in various dental and veterinary applications. The second main use of N_2O is as a propellant in pressure and aerosol products, the largest application being pressure-packaged whipped cream. Small quantities of N_2O also are used in the following applications:

- Oxidizing agent and etchant used in semiconductor manufacturing;
- Oxidizing agent used, with acetylene, in atomic absorption spectrometry;
- Production of sodium azide, which is used to inflate airbags;
- Fuel oxidant in auto racing; and
- Oxidizing agent in blowtorches used by jewelers and others (Heydorn 1997).

Production of N_2O in 2014 was approximately 15 kt (Table 4-105).

Table 4-105: N_2O Production (kt)

Year	kt
1990	16
2005	15
2010	15
2011	15
2012	15
2013	15
2014	15

Nitrous oxide emissions were 4.2 MMT CO_2 Eq. (14 kt N_2O) in 2014 (Table 4-106). Production of N_2O stabilized during the 1990s because medical markets had found other substitutes for anesthetics, and more medical procedures were being performed on an outpatient basis using local anesthetics that do not require N_2O. The use of N_2O as a propellant for whipped cream has also stabilized due to the increased popularity of cream products packaged in reusable plastic tubs (Heydorn 1997).

Table 4-106: N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	4.2	14
2005	4.2	14
2010	4.2	14
2011	4.2	14
2012	4.2	14
2013	4.2	14
2014	4.2	14

Methodology

Emissions from N_2O product uses were estimated using the following equation:

$$E_{pu} = \sum_{a} (P \times S_a \times ER_a)$$

where,

E_{pu} = N_2O emissions from product uses, metric tons
P = Total U.S. production of N_2O, metric tons
a = specific application
S_a = Share of N_2O usage by application *a*
ER_a = Emission rate for application *a*, percent

The share of total quantity of N_2O usage by end use represents the share of national N_2O produced that is used by the specific subcategory (i.e., anesthesia, food processing, etc.). In 2014, the medical/dental industry used an estimated 86.5 percent of total N_2O produced, followed by food processing propellants at 6.5 percent. All other categories combined used the remainder of the N_2O produced. This subcategory breakdown has changed only slightly over the past decade. For instance, the small share of N_2O usage in the production of sodium azide has declined significantly during the 1990s. Due to the lack of information on the specific time period of the phase-out in this market subcategory, most of the N_2O usage for sodium azide production is assumed to have ceased after 1996, with the majority of its small share of the market assigned to the larger medical/dental consumption subcategory (Heydorn 1997). The N_2O was allocated across the following categories: medical applications, food processing propellant, and sodium azide production (pre-1996). A usage emissions rate was then applied for each sector to estimate the amount of N_2O emitted.

Only the medical/dental and food propellant subcategories were estimated to release emissions into the atmosphere, and therefore these subcategories were the only usage subcategories with emission rates. For the medical/dental subcategory, due to the poor solubility of N_2O in blood and other tissues, none of the N_2O is assumed to be metabolized during anesthesia and quickly leaves the body in exhaled breath. Therefore, an emission factor of 100 percent was used for this subcategory (IPCC 2006). For N_2O used as a propellant in pressurized and aerosol food products, none of the N_2O is reacted during the process and all of the N_2O is emitted to the atmosphere, resulting in an emission factor of 100 percent for this subcategory (IPCC 2006). For the remaining subcategories, all of the N_2O is consumed/reacted during the process, and therefore the emission rate was considered to be zero percent (Tupman 2002).

The 1990 through 1992 N_2O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997). Nitrous oxide production data for 1993 through 1995 were not available. Production data for 1996 was specified as a range in two data sources (Heydorn 1997, Tupman 2002). In particular, for 1996, Heydorn (1997) estimates N_2O production to range between 13.6 and 18.1 thousand metric tons. Tupman (2003) provided a narrower range (15.9 to 18.1 thousand metric tons) for 1996 that falls within the production bounds described by Heydorn (1997). Tupman (2003) data are considered more industry-specific and current. Therefore, the midpoint of the narrower production range was used to estimate N_2O emissions for years 1993 through 2001 (Tupman 2003). The 2002 and 2003 N_2O production data were obtained from the Compressed Gas Association Nitrous Oxide Fact Sheet and Nitrous Oxide Abuse Hotline (CGA 2002, 2003). These data were also provided as a range. For example, in 2003, CGA (2003) estimates N_2O production to range between 13.6 and 15.9 thousand metric tons. Due to the unavailability of data, production estimates for years 2004 through 2014 were held constant at the 2003 value.

The 1996 share of the total quantity of N_2O used by each subcategory was obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997). The 1990 through 1995 share of total quantity of N_2O used by each subcategory was kept the same as the 1996 number provided by SRI Consulting. The 1997 through 2001 share of total quantity of N_2O usage by sector was obtained from communication with a N_2O industry expert (Tupman 2002). The 2002 and 2003 share of total quantity of N_2O usage by sector was obtained from CGA (2002, 2003). Due to the unavailability of data, the share of total quantity of N_2O usage data for years 2004 through 2014 was assumed to equal the 2003 value. The emissions rate for the food processing propellant industry was obtained from SRI Consulting's Nitrous Oxide, North America report (Heydorn 1997), and confirmed by a N_2O industry expert (Tupman 2002). The emissions rate for all other subcategories was obtained from communication with a N_2O industry expert (Tupman 2002). The emissions rate for the medical/dental subcategory was obtained from the *2006 IPCC Guidelines*.

Uncertainty and Time-Series Consistency

The overall uncertainty associated with the 2014 N_2O emission estimate from N_2O product usage was calculated using the *2006 IPCC Guidelines* (2006) Approach 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions include production data, total market share of each end use, and the emission factors applied to each end use, respectively.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-107. N_2O emissions from N_2O product usage were estimated to be between 3.2 and 5.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 24 percent below to 24 percent above the emission estimate of 4.2 MMT CO_2 Eq.

Table 4-107: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
N_2O Product Use	N_2O	4.2	3.2	5.2	-24%	+24%

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

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above

Planned Improvements

Pending resources, planned improvements include a continued evaluation of alternative production statistics for cross verification, a reassessment of N_2O product use subcategories to accurately represent trends, investigation of production and use cycles, and the potential need to incorporate a time lag between production and ultimate product use and resulting release of N_2O. Additionally, planned improvements include considering imports and exports of N_2O for product uses. Finally, for future Inventories EPA will examine data from EPA's GHGRP to improve the emission estimates for the N_2O product use subcategory. Particular attention will be made to ensure aggregated information can be published without disclosing confidential business information and time series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as required in this Inventory.

4.26 Industrial Processes and Product Use Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, many industrial processes can result in emissions of various ozone precursors (i.e., indirect greenhouse gases). As some of industrial applications also employ thermal incineration as a control technology, combustion byproducts, such as carbon monoxide (CO) and nitrogen oxides (NO_x), are also reported with this source category. Non-CH_4 volatile organic compounds (NMVOCs), commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum based products, and can also result from the product storage and handling. Accidental releases of greenhouse gases associated with product use and handling can constitute major emissions in this category. In the United States, emissions from product use are primarily the result of solvent evaporation, whereby the lighter hydrocarbon molecules in the solvents escape into the atmosphere. The major categories of product uses include: degreasing, graphic arts, surface coating, other industrial uses of solvents (e.g., electronics), dry cleaning, and non-industrial uses (e.g., uses of paint thinner). Product usage in the United States also results in the emission of small amounts of hydrofluorocarbons (HFCs) and hydrofluoroethers (HFEs), which are included under Substitution of Ozone Depleting Substances in this chapter.

Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) from non-energy industrial processes and product use from 1990 to 2014 are reported in Table 4-108.

Table 4-108: NO_x, CO, and NMVOC Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
NO_x	**592**	**572**	**472**	**452**	**452**	**452**	**452**
Industrial Processes							
Other Industrial Processes	343	437	339	320	320	320	320
Metals Processing	88	60	67	64	64	64	64
Chemical and Allied Product Manufacturing	152	55	48	47	47	47	47
Storage and Transport	3	15	15	18	18	18	18
Miscellaneous[a]	5	2	2	3	3	3	3
Product Use							
Surface Coating	1	3	2	1	1	1	1
Graphic Arts	+	0	0	0	0	0	0
Degreasing	+	0	0	0	0	0	0
Dry Cleaning	+	0	0	0	0	0	0
Other Industrial Processes[b]	+	0	0	0	0	0	0
Non-Industrial Processes[c]	+	0	0	0	0	0	0
Other	NA	0	0	0	0	0	0
CO	**4,129**	**1,557**	**1,280**	**1,229**	**1,229**	**1,229**	**1,229**
Industrial Processes							
Metals Processing	2,395	752	717	695	695	695	695
Other Industrial Processes	487	484	333	306	306	306	306
Chemical and Allied Product Manufacturing	1,073	189	157	152	152	152	152
Miscellaneous[a]	101	32	48	51	51	51	51
Storage and Transport	69	97	22	25	25	25	24

Product Use							
Surface Coating	+	2	3	2	2	2	2
Other Industrial Processes[b]	4	0	0	0	0	0	0
Dry Cleaning	+	0	0	0	0	0	0
Degreasing	+	0	0	0	0	0	0
Graphic Arts	+	0	0	0	0	0	0
Non-Industrial Processes[c]	+	0	0	0	0	0	0
Other	NA	0	0	0	0	0	0
NMVOCs	**7,638**	**5,849**	**4,133**	**3,929**	**3,929**	**3,929**	**3,928**
Industrial Processes							
Storage and Transport	1,352	1,308	992	947	947	947	946
Other Industrial Processes	364	414	308	298	298	298	298
Chemical and Allied Product Manufacturing	575	213	77	76	76	76	75
Metals Processing	111	45	32	31	31	31	31
Miscellaneous[a]	20	17	26	27	27	27	27
Product Use							
Surface Coating	2,289	1,578	1,105	1,045	1,045	1,045	1,045
Non-Industrial Processes[c]	1,724	1,446	1,013	957	957	957	957
Degreasing	675	280	196	186	186	186	186
Dry Cleaning	195	230	161	152	152	152	152
Graphic Arts	249	194	136	128	128	128	128
Other Industrial Processes[b]	85	88	61	58	58	58	58
Other	+	36	25	24	24	24	24

[a] Miscellaneous includes the following categories: catastrophic/accidental release, other combustion, health services, cooling towers, and fugitive dust. It does not include agricultural fires or slash/prescribed burning, which are accounted for under the Field Burning of Agricultural Residues source.

[b] Includes rubber and plastics manufacturing, and other miscellaneous applications.

[c] Includes cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

NA (Not Available)

+ Does not exceed 0.5 kt

Note: Totals may not sum due to independent rounding.

Methodology

Emission estimates for 1990 through 2014 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2015), and disaggregated based on EPA (2003). Data were collected for emissions of carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and sulfur dioxide (SO_2) from metals processing, chemical manufacturing, other industrial processes, transport and storage, and miscellaneous sources. Emission estimates for 2013 for non-EGU and non-mobile sources are held constant from 2011 in EPA (2015). Emissions were calculated either for individual source categories or for many categories combined, using basic activity data (e.g., the amount of raw material processed or the amount of solvent purchased) as an indicator of emissions. National activity data were collected for individual categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Emissions for product use were calculated by aggregating product use data based on information relating to product uses from different applications such as degreasing, graphic arts, etc. Emission factors for each consumption category were then applied to the data to estimate emissions. For example, emissions from surface coatings were mostly due to solvent evaporation as the coatings solidify. By applying the appropriate product-specific emission factors to the amount of products used for surface coatings, an estimate of NMVOC emissions was obtained. Emissions of CO and NO_x under product use result primarily from thermal and catalytic incineration of solvent-laden gas streams from painting booths, printing operations, and oven exhaust.

Activity data were used in conjunction with emission factors, which together relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

Uncertainty and Time-Series Consistency

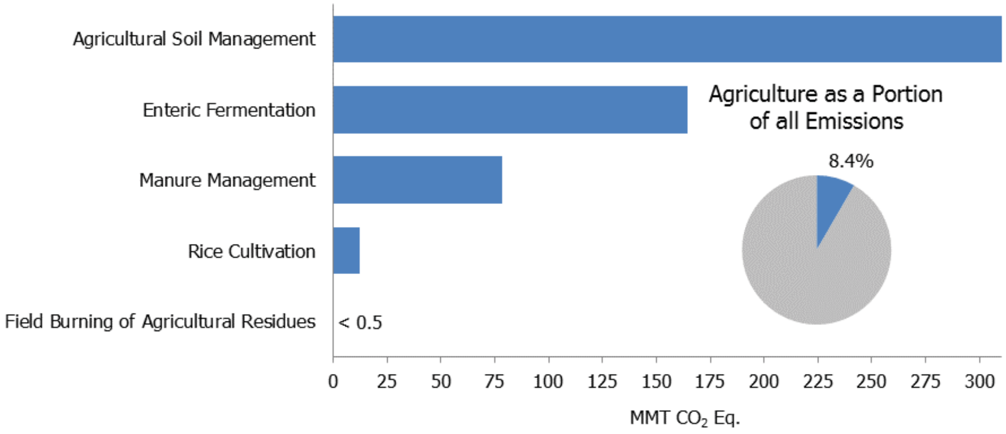
Uncertainties in these estimates are partly due to the accuracy of the emission factors and activity data used. A quantitative uncertainty analysis was not performed.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of non-carbon-dioxide emissions from the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues (see Figure 5-1). Carbon dioxide (CO_2) emissions and removals from agriculture-related land-use activities, such as liming and conversion of grassland to cultivated land, are presented in the Land Use, Land-Use Change, and Forestry chapter. Carbon dioxide emissions from on-farm energy use are accounted for in the Energy chapter.

Figure 5-1: 2014 Agriculture Chapter Greenhouse Gas Emission Sources (MMT CO_2 Eq.)



In 2014, the Agriculture sector was responsible for emissions of 574.1 MMT CO_2 Eq.,[1] or 8.4 percent of total U.S. greenhouse gas emissions. Methane (CH_4) and nitrous oxide (N_2O) were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represent 23.2 percent and 8.6 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of CH_4. Rice cultivation and field burning of agricultural residues were minor sources of CH_4. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 77.4 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions.

Table 5-1 and Table 5-2 present emission estimates for the Agriculture sector. Between 1990 and 2014, CH_4 emissions from agricultural activities increased by 11.8 percent, while N_2O emissions fluctuated from year to year, but overall increased by 6.0 percent.

---

[1] Following the revised reporting requirements under the UNFCCC, this Inventory report presents CO_2 equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

Table 5-1: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CH_4	**212.8**	**239.6**	**244.7**	**242.9**	**242.9**	**239.3**	**238.0**
Enteric Fermentation	164.2	168.9	171.3	168.9	166.7	165.5	164.3
Manure Management	37.2	56.3	60.9	61.5	63.7	61.4	61.2
Rice Cultivation	11.3	14.2	12.2	12.2	12.2	12.2	12.2
Field Burning of Agricultural Residues	0.2	0.2	0.3	0.3	0.3	0.3	0.3
N_2O	**317.0**	**313.3**	**337.7**	**340.4**	**340.5**	**336.0**	**336.1**
Agricultural Soil Management	302.9	296.7	320.4	322.9	322.9	318.4	318.5
Manure Management	14.0	16.5	17.2	17.4	17.5	17.5	17.5
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**529.8**	**552.9**	**582.3**	**583.3**	**583.4**	**575.4**	**574.1**

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (kt)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CH_4	**8,513**	**9,584**	**9,788**	**9,715**	**9,717**	**9,573**	**9,518**
Enteric Fermentation	6,566	6,755	6,853	6,757	6,670	6,619	6,572
Manure Management	1,486	2,254	2,437	2,460	2,548	2,455	2,447
Rice Cultivation	451	567	486	487	488	488	488
Field Burning of Agricultural Residues	10	8	11	11	11	11	11
N_2O	**1,064**	**1,051**	**1,133**	**1,142**	**1,143**	**1,128**	**1,128**
Agricultural Soil Management	1,017	996	1,075	1,084	1,083	1,069	1,069
Manure Management	47	55	58	58	59	59	59
Field Burning of Agricultural Residues	+	+	+	+	+	+	+

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

5.1 Enteric Fermentation (IPCC Source Category 3A)

Methane is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH_4 as a byproduct, which can be exhaled or eructated by the animal. The amount of CH_4 produced and emitted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest CH_4 emissions per unit of body mass among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules and asses) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal-mass basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affect CH_4 emissions. In general, lower feed quality and/or higher feed intake leads to higher CH_4 emissions. Feed intake is positively correlated to animal size, growth rate, level of activity and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types (e.g., animals in feedlots or grazing on pasture).

Methane emission estimates from enteric fermentation are provided in Table 5-3 and Table 5-4. Total livestock CH_4 emissions in 2014 were 164.3 MMT CO_2 Eq. (6,572 kt). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71 percent in 2014. Emissions from dairy cattle in 2014 accounted for 26 percent, and the remaining emissions were from horses, sheep, swine, goats, American bison, mules and asses.

From 1990 to 2014, emissions from enteric fermentation have increased by 0.08 percent. While emissions generally follow trends in cattle populations, over the long term there are exceptions as population decreases have been coupled with production increases or minor decreases. For example, beef cattle emissions decreased 2.0 percent from 1990 to 2014, while beef cattle populations actually declined by 7 percent and beef production increased (USDA 2015), and while dairy emissions increased 6.5 percent over the entire time series, the population has declined by 5 percent and milk production increased 40 percent (USDA 2015). This trend indicates that while emission factors per head are increasing, emission factors per unit of product are going down. Generally, from 1990 to 1995 emissions from beef increased and then decreased from 1996 to 2004. These trends were mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Beef cattle emissions generally increased from 2004 to 2007, as beef populations underwent increases and an extensive literature review indicated a trend toward a decrease in feed digestibility for those years. Beef cattle emissions decreased again from 2008 to 2014 as populations again decreased. Emissions from dairy cattle generally trended downward from 1990 to 2004, along with an overall dairy population decline during the same period. Similar to beef cattle, dairy cattle emissions rose from 2004 to 2007 due to population increases and a decrease in feed digestibility (based on an analysis of more than 350 dairy cow diets). Dairy cattle emissions have continued to trend upward since 2007, in line with dairy population increases. Regarding trends in other animals populations of sheep have steadily declined, with an overall decrease of 54 percent since 1990. Horse populations are 56 percent greater than they were in 1990, but their numbers have been declining by about 2 percent annually since 2007. Goat populations increased by about 20 percent through 2007 but have since dropped below 1990 numbers, while swine populations have increased 19 percent since 1990. The population of American bison more than tripled over the 1990 through 2014 time period, while mules and asses have more than quadrupled.

Table 5-3: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	2005	2010	2011	2012	2013	2014
Beef Cattle	119.1	125.2	124.6	121.8	119.1	118.0	116.7
Dairy Cattle	39.4	37.6	40.7	41.1	41.7	41.6	41.9
Horses	2.0	2.3	2.4	2.5	2.5	2.5	2.4
Sheep	1.0	1.7	1.7	1.7	1.6	1.6	1.6
Swine	2.3	1.2	1.1	1.1	1.1	1.1	1.0
Goats	0.3	0.4	0.4	0.3	0.3	0.3	0.3
American Bison	0.1	0.4	0.4	0.3	0.3	0.3	0.3
Mules and Asses	+	0.1	0.1	0.1	0.1	0.1	0.1
Total	**164.2**	**168.9**	**171.3**	**168.9**	**166.7**	**165.5**	**164.3**

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

Table 5-4: CH_4 Emissions from Enteric Fermentation (kt)

Livestock Type	1990	2005	2010	2011	2012	2013	2014
Beef Cattle	4,763	5,007	4,984	4,873	4,763	4,722	4,667
Dairy Cattle	1,574	1,503	1,627	1,645	1,670	1,664	1,677
Swine	81	92	97	98	100	98	96
Horses	40	70	68	67	65	64	62
Sheep	91	49	45	44	43	43	42
Goats	13	14	14	14	13	13	12

American Bison	4		17		15	14	13	13	12
Mules and Asses	1		2		3	3	3	3	3
Total	**6,566**		**6,755**		**6,853**	**6,757**	**6,670**	**6,619**	**6,572**

Note: Totals may not sum due to independent rounding.

Methodology

Livestock enteric fermentation emission estimate methodologies fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics, account for the majority of enteric fermentation CH_4 emissions from livestock in the United States. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimate emissions for all cattle. Emission estimates for other domesticated animals (horses, sheep, swine, goats, American bison, and mules and asses) were handled using a less detailed approach (i.e., IPCC Tier 1).

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that provides the necessary data to estimate cattle emissions using the IPCC Tier 2 approach. The Cattle Enteric Fermentation Model (CEFM), developed by EPA and used to estimate cattle CH_4 emissions from enteric fermentation, incorporates this information and other analyses of livestock population, feeding practices, and production characteristics.

National cattle population statistics were disaggregated into the following cattle sub-populations:

- Dairy Cattle
    - Calves
    - Heifer Replacements
    - Cows
- Beef Cattle
    - Calves
    - Heifer Replacements
    - Heifer and Steer Stockers
    - Animals in Feedlots (Heifers and Steer)
    - Cows
    - Bulls

Calf birth rates, end-of-year population statistics, detailed feedlot placement information, and slaughter weight data were used to create a transition matrix that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Annex 3.10. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain. Annual cattle population data were obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) QuickStats database (USDA 2015).

Diet characteristics were estimated by region for dairy, foraging beef, and feedlot beef cattle. These diet characteristics were used to calculate digestible energy (DE) values (expressed as the percent of gross energy intake digested by the animal) and CH_4 conversion rates (Y_m) (expressed as the fraction of gross energy converted to CH_4) for each regional population category. The IPCC recommends Y_m ranges of 3.0±1.0 percent for feedlot cattle and 6.5±1.0 percent for other well-fed cattle consuming temperate-climate feed types (IPCC 2006). Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed. The diet characterizations and estimation of DE and Y_m values were based on information from state agricultural extension specialists, a review of published forage quality studies and scientific literature, expert opinion, and modeling of animal physiology.

The diet characteristics for dairy cattle were based on Donovan (1999) and an extensive review of nearly 20 years of literature from 1990 through 2009. Estimates of DE were national averages based on the feed components of the diets observed in the literature for the following year groupings: 1990 through 1993, 1994 through 1998, 1999 through 2003, 2004 through 2006, 2007, and 2008 onward.[2] Base year Y_m values by region were estimated using Donovan (1999). A ruminant digestion model (COWPOLL, as selected in Kebreab et al. 2008) was used to evaluate Y_m for each diet evaluated from the literature, and a function was developed to adjust regional values over time based on the national trend. Dairy replacement heifer diet assumptions were based on the observed relationship in the literature between dairy cow and dairy heifer diet characteristics.

For feedlot animals, the DE and Y_m values used for 1990 were recommended by Johnson (1999). Values for DE and Y_m for 1991 through 1999 were linearly extrapolated based on the 1990 and 2000 data. DE and Y_m values for 2000 onwards were based on survey data in Galyean and Gleghorn (2001) and Vasconcelos and Galyean (2007).

For grazing beef cattle, Y_m values were based on Johnson (2002), DE values for 1990 through 2006 were based on specific diet components estimated from Donovan (1999), and DE values from 2007 onwards were developed from an analysis by Archibeque (2011), based on diet information in Preston (2010) and USDA:APHIS:VS (2010). Weight and weight gains for cattle were estimated from Holstein (2010), Doren et al. (1989), Enns (2008), Lippke et al. (2000), Pinchack et al. (2004), Platter et al. (2003), Skogerboe et al. (2000), and expert opinion. See Annex 3.10 for more details on the method used to characterize cattle diets and weights in the United States.

Calves younger than 4 months are not included in emission estimates because calves consume mainly milk and the IPCC recommends the use of a Y_m of zero for all juveniles consuming only milk. Diets for calves aged 4 to 6 months are assumed to go through a gradual weaning from milk decreasing to 75 percent at 4 months, 50 percent at age 5 months, and 25 percent at age 6 months. The portion of the diet made up with milk still results in zero emissions. For the remainder of the diet, beef calf DE and Y_m are set equivalent to those of beef replacement heifers, while dairy calf DE is set equal to that of dairy replacement heifers and dairy calf Y_m is provided at 4 and 7 months of age by Soliva (2006). Estimates of Y_m for 5 and 6 month old dairy calves are linearly interpolated from the values provided for 4 and 7 months.

To estimate CH_4 emissions, the population was divided into state, age, sub-type (i.e., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, heifers and steers in feedlots, bulls, beef calves 4 to 6 months, and dairy calves 4 to 6 months), and production (i.e., pregnant, lactating) groupings to more fully capture differences in CH_4 emissions from these animal types. The transition matrix was used to simulate the age and weight structure of each sub-type on a monthly basis in order to more accurately reflect the fluctuations that occur throughout the year. Cattle diet characteristics were then used in conjunction with Tier 2 equations from IPCC (2006) to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, heifer feedlot animals, bulls, and calves. To estimate emissions from cattle, monthly population data from the transition matrix were multiplied by the calculated emission factor for each cattle type. More details are provided in Annex 3.10.

Emission estimates for other animal types were based on average emission factors representative of entire populations of each animal type. Methane emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2014. Additionally, the variability in emission factors for each of these other animal types (e.g., variability by age, production system, and feeding practice within each animal type) is less than that for cattle. Annual livestock population data for sheep; swine; goats; horses; mules and asses; and American bison were obtained for available years from USDA NASS (USDA 2015). Horse, goat and mule and ass population data were available for 1987, 1992, 1997, 2002, 2007, and 2012 (USDA 1992, 1997, 2015); the remaining years between 1990 and 2014 were interpolated and extrapolated from the available estimates (with the exception of goat populations being held constant between 1990 and 1992). American bison population estimates were available from USDA for 2002, 2007, and 2012 (USDA 2014) and from the National Bison Association (1999) for 1997 through 1999. Additional years were based on observed trends from the National Bison Association (1999), interpolation between known data points, and extrapolation beyond 2012, as described in more detail in Annex 3.10. Methane emissions from sheep, goats, swine, horses, American bison, and mules and asses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC 2006). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. For American bison the emission factor for buffalo was used and adjusted based on the ratio of live weights to the 0.75 power. The methodology is the same as that recommended by IPCC (2006).

---

[2] Due to inconsistencies in the 2003 literature values, the 2002 values were used for 2003, as well.

See Annex 3.10 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis for this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology based on a Monte Carlo Stochastic Simulation technique as described in ICF (2003). These uncertainty estimates were developed for the 1990 through 2001 Inventory report (i.e., 2003 submission to the UNFCCC). There have been no significant changes to the methodology since that time; consequently, these uncertainty estimates were directly applied to the 2014 emission estimates in this Inventory report.

A total of 185 primary input variables (177 for cattle and 8 for non-cattle) were identified as key input variables for the uncertainty analysis. A normal distribution was assumed for almost all activity- and emission factor-related input variables. Triangular distributions were assigned to three input variables (specifically, cow-birth ratios for the three most recent years included in the 2001 model run) to ensure only positive values would be simulated. For some key input variables, the uncertainty ranges around their estimates (used for inventory estimation) were collected from published documents and other public sources; others were based on expert opinion and best estimates. In addition, both endogenous and exogenous correlations between selected primary input variables were modeled. The exogenous correlation coefficients between the probability distributions of selected activity-related variables were developed through expert judgment.

The uncertainty ranges associated with the activity data-related input variables were plus or minus 10 percent or lower. However, for many emission factor-related input variables, the lower- and/or the upper-bound uncertainty estimates were over 20 percent. The results of the quantitative uncertainty analysis are summarized in Table 5-5. Based on this analysis, enteric fermentation CH_4 emissions in 2014 were estimated to be between 146.2 and 193.9 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 11 percent below to 18 percent above the 2014 emission estimate of 164.3 MMT CO_2 Eq. Among the individual cattle sub-source categories, beef cattle account for the largest amount of CH_4 emissions, as well as the largest degree of uncertainty in the emission estimates—due mainly to the difficulty in estimating the diet characteristics for grazing members of this animal group. Among non-cattle, horses represent the largest percent of uncertainty in the previous uncertainty analysis because the Food and Agricultural Organization of the United Nations (FAO) population estimates used for horses at that time had a higher degree of uncertainty than for the USDA population estimates used for swine, goats, and sheep. The horse populations are now from the same USDA source as the other animal types, and therefore the uncertainty range around horses is likely overestimated. Cattle calves, American bison, mules and asses were excluded from the initial uncertainty estimate because they were not included in emission estimates at that time.

Table 5-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a, b, c] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Enteric Fermentation	CH_4	164.3	146.2	193.9	-11%	18%

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

[b] Note that the relative uncertainty range was estimated with respect to the 2001 emission estimates from the 2003 submission and applied to the 2014 estimates.

[c] The overall uncertainty calculated in 2003, and applied to the 2014 emission estimate, did not include uncertainty estimates for calves, American bison, and mules and asses. Additionally, for bulls the emissions estimate was based on the Tier 1 methodology. Since bull emissions are now estimated using the Tier 2 method, the uncertainty surrounding their estimates is likely lower than indicated by the previous uncertainty analysis.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section.

QA/QC and Verification

In order to ensure the quality of the emission estimates from enteric fermentation, the IPCC Tier 1 and Tier 2 Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. QA/QC plan. Tier 2 QA procedures included independent peer review of emission estimates. Over the past few years, particular importance has been placed on harmonizing the data exchange between the enteric fermentation and manure management source categories. The current Inventory now utilizes the transition matrix from the CEFM for estimating cattle populations and weights for both source categories, and the CEFM is used to output volatile solids and nitrogen excretion estimates using the diet assumptions in the model in conjunction with the energy balance equations from the IPCC (2006). This approach facilitates the QA/QC process for both of these source categories.

Recalculations Discussion

For the current Inventory, differences can be seen in emission estimates for years prior to 2014 when compared against the same years in the previous Inventory—from 2008 through 2013 in particular. These recalculations were due to changes made to historical data and corrections made to erroneous formulas in the CEFM. No modifications were made to the methodology.

Revisions to input data include the following:

- The USDA published minor revisions in several categories that affected historical emissions estimated for cattle for 2008 and subsequent years, including the following:
    - Cattle populations for all animal types were revised for many states for 2009 and subsequent years;
    - Dairy cow milk production values were revised for several states for 2008 and subsequent years;
    - Beef cattle feedlot placement data were revised for 2008 and subsequent years;
    - Slaughter values were revised for 2008 and subsequent years;
    - Calf birth data were revised for 2010 and subsequent years; and
    - Cattle on feed data were revised for many states for 2009 and subsequent years.
- The USDA also revised population estimates for some categories of non-cattle animals, which affected historical emissions estimated for "other" livestock. Changes included:
    - Revised 2008 through 2012 populations for market and breeding swine in some states; and
    - Revised 2011 and 2012 populations of sheep for some states.

In addition to these changes in input data, there were transcription and formula cell reference errors in the CEFM calculations for the state-by-state estimates of cattle on feed. These errors, when corrected, affected emission estimates for 2009 and subsequent years for all stockers and feedlot cattle.

These recalculations had an insignificant impact on the overall emission estimates.

Planned Improvements

Continued research and regular updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. Future improvements for enteric fermentation could include some of the following options:

- Further research to improve the estimation of dry matter intake (as gross energy intake) using data from appropriate production systems;
- Updating input variables that are from older data sources, such as beef births by month and beef cow lactation rates;
- Investigation of the availability of annual data for the DE, Y_m, and crude protein values of specific diet and feed components for foraging and feedlot animals;
- Further investigation on additional sources or methodologies for estimating DE for dairy, given the many challenges in characterizing dairy diets;

- Further evaluation of the assumptions about weights and weight gains for beef cows, such that trends beyond 2007 are updated, rather than held constant;
- Further evaluation of the estimated weight for dairy cows (i.e., 1,500 lbs) that is based solely on Holstein cows as mature dairy cow weight is likely slightly overestimated, based on knowledge of the breeds of dairy cows in the United States;
- Potentially updating to a Tier 2 methodology for other animal types (i.e., sheep, swine, goats, horses);
- Investigation of methodologies and emission factors for including enteric fermentation emission estimates from poultry;
- Comparison of the current CEFM processing of animal population data to estimates developed using annual average populations to determine if the model could be simplified to use annual population data; and
- Recent changes that have been implemented to the CEFM warrant an assessment of the current uncertainty analysis; therefore, a revision of the quantitative uncertainty surrounding emission estimates from this source category will be initiated.

5.2 Manure Management (IPCC Source Category 3B)

The treatment, storage, and transportation of livestock manure can produce anthropogenic CH_4 and N_2O emissions. Methane is produced by the anaerobic decomposition of manure. Nitrous oxide emissions are produced through both direct and indirect pathways. Direct N_2O emissions are produced as part of the N cycle through the nitrification and denitrification of the organic N in livestock dung and urine.[3] There are two pathways for indirect N_2O emissions. The first is the result of the volatilization of N in manure (as NH_3 and NO_x) and the subsequent deposition of these gases and their products (NH_4^+ and NO_3^-) onto soils and the surface of lakes and other waters. The second pathway is the runoff and leaching of N from manure to the groundwater below, in riparian zones receiving drain or runoff water, or in the ditches, streams, rivers, and estuaries into which the land drainage water eventually flows.

When livestock or poultry manure are stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of the volatile solids component in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no CH_4. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production. Manure composition, which varies by animal diet, growth rate, and type, including the animal's digestive system, also affects the amount of CH_4 produced. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. However, some higher-energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal.

The production of direct N_2O emissions from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For direct N_2O emissions to occur, the manure must first be handled aerobically where ammonia (NH_3) or organic N is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to dinitrogen gas (N_2), with intermediate production of N_2O and nitric oxide (NO) (denitrification)

---

[3] Direct and indirect 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.

(Groffman et al. 2000). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. A very small portion of the total N excreted is expected to convert to N_2O in the waste management system (WMS). Indirect N_2O emissions are produced when nitrogen is lost from the system through volatilization (as NH_3 or NO_x) or through runoff and leaching. The vast majority of volatilization losses from these operations are NH_3. Although there are also some small losses of NO_x, there are no quantified estimates available for use, so losses due to volatilization are only based on NH_3 loss factors. Runoff losses would be expected from operations that house animals or store manure in a manner that is exposed to weather. Runoff losses are also specific to the type of animal housed on the operation due to differences in manure characteristics. Little information is known about leaching from manure management systems as most research focuses on leaching from land application systems. Since leaching losses are expected to be minimal, leaching losses are coupled with runoff losses and the runoff/leaching estimate provided in this chapter does not account for any leaching losses.

Estimates of CH_4 emissions in 2014 were 61.2 MMT CO_2 Eq. (2,447 kt); in 1990, emissions were 37.2 MMT CO_2 Eq. (1,486 kt). This represents a 65 percent increase in emissions from 1990. The majority of this increase is due to swine and dairy cow manure, where emissions increased 44 and 118 percent, respectively. Emissions increased on average by 1.0 MMT CO_2 Eq. (2.2 percent) annually over this period. From 2013 to 2014, there was a 0.3 percent decrease in total CH_4 emissions, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

Although the majority of managed manure in the United States is handled as a solid, producing little CH_4, the general trend in manure management, particularly for dairy and swine (which are both shifting towards larger facilities), is one of increasing use of liquid systems. Also, new regulations controlling the application of manure nutrients to land have shifted manure management practices at smaller dairies from daily spread systems to storage and management of the manure on site. Although national dairy animal populations have generally been decreasing since 1990, some states have seen increases in their dairy populations as the industry becomes more concentrated in certain areas of the country and the number of animals contained on each facility increases. These areas of concentration, such as California, New Mexico, and Idaho, tend to utilize more liquid-based systems to manage (flush or scrape) and store manure. Thus the shift toward larger dairy and swine facilities has translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This significant shift in both the dairy and swine industries was accounted for by incorporating state and WMS-specific CH_4 conversion factor (MCF) values in combination with the 1992, 1997, 2002, and 2007 farm-size distribution data reported in the *Census of Agriculture* (USDA 2014a).

In 2014, total N_2O emissions were estimated to be 17.5 MMT CO_2 Eq. (59 kt); in 1990, emissions were 14.0 MMT CO_2 Eq. (47 kt). These values include both direct and indirect N_2O emissions from manure management. Nitrous oxide emissions have remained fairly steady since 1990. Small changes in N_2O emissions from individual animal groups exhibit the same trends as the animal group populations, with the overall net effect that N_2O emissions showed a 25 percent increase from 1990 to 2014 and a 0.1 percent decrease from 2013 through 2014. Overall shifts toward liquid systems have driven down the emissions per unit of nitrogen excreted.

Table 5-6 and Table 5-7 provide estimates of CH_4 and N_2O emissions from manure management by animal category.

Table 5-6: CH_4 and N_2O Emissions from Manure Management (MMT CO_2 Eq.)

Gas/Animal Type	1990	2005	2010	2011	2012	2013	2014
CH_4[a]	**37.2**	**56.3**	**60.9**	**61.5**	**63.7**	**61.4**	**61.2**
Dairy Cattle	14.7	26.4	30.4	31.1	32.6	31.8	32.2
Swine	15.6	22.9	23.6	23.6	24.3	23.0	22.4
Poultry	3.3	3.2	3.2	3.2	3.2	3.2	3.2
Beef Cattle	3.1	3.3	3.3	3.3	3.2	3.0	3.0
Horses	0.2	0.3	0.2	0.2	0.2	0.2	0.2
Sheep	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O[b]	**14.0**	**16.5**	**17.2**	**17.4**	**17.5**	**17.5**	**17.5**

Beef Cattle	5.9	7.2	7.6	7.7	7.7	7.7	7.8
Dairy Cattle	3.1	3.2	3.3	3.3	3.4	3.4	3.4
Dairy Heifers	2.1	2.3	2.5	2.5	2.5	2.5	2.5
Swine	1.2	1.7	1.9	1.9	1.9	1.9	1.8
Poultry	1.4	1.6	1.5	1.5	1.6	1.6	1.6
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
Bison	NA	NA	NA	NA	NA	NA	NA
Total	**51.1**	**72.9**	**78.1**	**78.9**	**81.2**	**78.9**	**78.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS; there are no American bison N_2O emissions from managed systems.

NA: Not available

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

Table 5-7: CH_4 and N_2O Emissions from Manure Management (kt)

Gas/Animal Type	**1990**	**2005**	**2010**	**2011**	**2012**	**2013**	**2014**
CH_4[a]	**1,486**	**2,254**	**2,437**	**2,460**	**2,548**	**2,455**	**2,447**
Dairy Cattle	590	1,057	1,217	1,245	1,306	1,271	1,289
Swine	622	916	945	942	972	920	896
Poultry	131	129	129	127	128	128	130
Beef Cattle	126	133	132	131	128	121	120
Horses	9	12	10	10	10	9	9
Sheep	7	3	3	3	3	3	3
Goats	1	1	1	1	1	1	1
Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O[b]	**47**	**55**	**58**	**58**	**59**	**59**	**59**
Beef Cattle	20	24	25	26	26	26	26
Dairy Cattle	11	11	11	11	11	11	11
Dairy Heifers	7	8	8	8	8	8	8
Swine	4	6	6	6	6	6	6
Poultry	5	5	5	5	5	5	5
Sheep	+	1	1	1	1	1	1
Horses	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
Bison	NA	NA	NA	NA	NA	NA	NA

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS; there are no American bison N_2O emissions from managed systems.

NA: Not available

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

Methodology

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal type. This section presents a summary of the methodologies used to estimate CH_4 and N_2O emissions from manure management. See Annex 3.11 for more detailed information on the methodology and data used to calculate CH_4 and N_2O emissions from manure management.

Methane Calculation Methods

The following inputs were used in the calculation of CH_4 emissions:

- Animal population data (by animal type and state);
- Typical animal mass (TAM) data (by animal type);
- Portion of manure managed in each WMS, by state and animal type;
- Volatile solids (VS) production rate (by animal type and state or United States);
- Methane producing potential (B_o) of the volatile solids (by animal type); and
- Methane conversion factors (MCF), the extent to which the CH_4 producing potential is realized for each type of WMS (by state and manure management system, including the impacts of any biogas collection efforts).

Methane emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources are described below:

- Annual animal population data for 1990 through 2014 for all livestock types, except goats, horses, mules and asses, and American bison were obtained from USDA National Agriculture Statistics Service (NASS). For cattle, the USDA populations were utilized in conjunction with birth rates, detailed feedlot placement information, and slaughter weight data to create the transition matrix in the Cattle Enteric Fermentation Model (CEFM) that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Section 5.1 and in more detail in Annex 3.10. Goat population data for 1992, 1997, 2002, 2007, and 2012; horse and mule and ass population data for 1987, 1992, 1997, 2002 2007, and 2012; and American bison population for 2002, 2007 and 2012 were obtained from the *Census of Agriculture* (USDA 2014a). American bison population data for 1990 through 1999 were obtained from the National Bison Association (1999).

- The TAM is an annual average weight that was obtained for animal types other than cattle from information in USDA's *Agricultural Waste Management Field Handbook* (USDA 1996), the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and others (Meagher 1986, EPA 1992, Safley 2000, ERG 2003b, IPCC 2006, and ERG 2010a). For a description of the TAM used for cattle, please see Section 5.1.

- WMS usage was estimated for swine and dairy cattle for different farm size categories using data from USDA (USDA, APHIS 1996, Bush 1998, Ott 2000, USDA 2014a) and EPA (ERG 2000a, EPA 2002a, 2002b). For beef cattle and poultry, manure management system usage data were not tied to farm size but were based on other data sources (ERG 2000a, USDA, APHIS 2000, UEP 1999). For other animal types, manure management system usage was based on previous estimates (EPA 1992). American bison WMS usage was assumed to be the same as not on feed (NOF) cattle, while mules and asses were assumed to be the same as horses.

- VS production rates for all cattle except for calves were calculated by head for each state and animal type in the CEFM. VS production rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996, 2008 and ERG 2010b and 2010c) and data that was not available in the most recent *Handbook* were obtained from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) or the *2006 IPCC Guidelines*. American bison VS production was assumed to be the same as NOF bulls.

- The maximum CH_4-producing capacity of the VS (B_o) was determined for each animal type based on literature values (Morris 1976, Bryant et al. 1976, Hashimoto 1981, Hashimoto 1984, EPA 1992, Hill 1982, Hill 1984).

- MCFs for dry systems were set equal to default IPCC factors based on state climate for each year (IPCC 2006). MCFs for liquid/slurry, anaerobic lagoon, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted in the van't Hoff-Arrhenius equation which is consistent with IPCC (2006) Tier 2 methodology.

- Data from anaerobic digestion systems with CH_4 capture and combustion were obtained from the EPA AgSTAR Program, including information presented in the *AgSTAR Digest* (EPA 2000, 2003, 2006) and the AgSTAR project database (EPA 2012). Anaerobic digester emissions were calculated based on estimated methane production and collection and destruction efficiency assumptions (ERG 2008).
- For all cattle except for calves, the estimated amount of VS (kg per animal-year) managed in each WMS for each animal type, state, and year were taken from the CEFM, assuming American bison VS production to be the same as NOF bulls. For animals other than cattle, the annual amount of VS (kg per year) from manure excreted in each WMS was calculated for each animal type, state, and year. This calculation multiplied the animal population (head) by the VS excretion rate (kg VS per 1,000 kg animal mass per day), the TAM (kg animal mass per head) divided by 1,000, the WMS distribution (percent), and the number of days per year (365.25).

The estimated amount of VS managed in each WMS was used to estimate the CH_4 emissions (kg CH_4 per year) from each WMS. The amount of VS (kg per year) were multiplied by the maximum CH_4 producing capacity of the VS (B_o) (m^3 CH_4 per kg VS), the MCF for that WMS (percent), and the density of CH_4 (kg CH_4 per m^3 CH_4). The CH_4 emissions for each WMS, state, and animal type were summed to determine the total U.S. CH_4 emissions.

Nitrous Oxide Calculation Methods

The following inputs were used in the calculation of direct and indirect N_2O emissions:

- Animal population data (by animal type and state);
- TAM data (by animal type);
- Portion of manure managed in each WMS (by state and animal type);
- Total Kjeldahl N excretion rate (Nex);
- Direct N_2O emission factor (EF_{WMS});
- Indirect N_2O emission factor for volatilization ($EF_{volatilization}$);
- Indirect N_2O emission factor for runoff and leaching ($EF_{runoff/leach}$);
- Fraction of N loss from volatilization of NH_3 and NO_x ($Frac_{gas}$); and
- Fraction of N loss from runoff and leaching ($Frac_{runoff/leach}$).

N_2O emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources (except for population, TAM, and WMS, which were described above) are described below:

- Nex rates for all cattle except for calves were calculated by head for each state and animal type in the CEFM. Nex rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996, 2008 and ERG 2010b and 2010c) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and IPCC (2006). American bison Nex rates were assumed to be the same as NOF bulls.
- All N_2O emission factors (direct and indirect) were taken from IPCC (2006). These data are appropriate because they were developed using U.S. data.
- Country-specific estimates for the fraction of N loss from volatilization ($Frac_{gas}$) and runoff and leaching ($Frac_{runoff/leach}$) were developed. $Frac_{gas}$ values were based on WMS-specific volatilization values as estimated from EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). $Frac_{runoff/leaching}$ values were based on regional cattle runoff data from EPA's Office of Water (EPA 2002b; see Annex 3.11).

To estimate N_2O emissions for cattle (except for calves) and American bison, the estimated amount of N excreted (kg per animal-year) managed in each WMS for each animal type, state, and year were taken from the CEFM. For calves and other animals, the amount of N excreted (kg per year) in manure in each WMS for each animal type, state, and year was calculated. The population (head) for each state and animal was multiplied by TAM (kg animal mass per head) divided by 1,000, the nitrogen excretion rate (Nex, in kg N per 1,000 kg animal mass per day), WMS distribution (percent), and the number of days per year.

Direct N_2O emissions were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the N_2O direct emission factor for that WMS (EF_{WMS}, in kg N_2O-N per kg N) and the conversion factor of N_2O-N to

N_2O. These emissions were summed over state, animal, and WMS to determine the total direct N_2O emissions (kg of N_2O per year).

Next, indirect N_2O emissions from volatilization (kg N_2O per year) were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through volatilization ($Frac_{tas}$) divided by 100, and the emission factor for volatilization ($EF_{volatilization}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. Indirect N_2O emissions from runoff and leaching (kg N_2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through runoff and leaching ($Frac_{runoff/leach}$) divided by 100, and the emission factor for runoff and leaching ($EF_{runoff/leach}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. The indirect N_2O emissions from volatilization and runoff and leaching were summed to determine the total indirect N_2O emissions.

The direct and indirect N_2O emissions were summed to determine total N_2O emissions (kg N_2O per year).

Uncertainty and Time-Series Consistency

An analysis (ERG 2003a) was conducted for the manure management emission estimates presented in the 1990 through 2001 Inventory report (i.e., 2003 submission to the UNFCCC) to determine the uncertainty associated with estimating CH_4 and N_2O emissions from livestock manure management. The quantitative uncertainty analysis for this source category was performed in 2002 through the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The uncertainty analysis was developed based on the methods used to estimate CH_4 and N_2O emissions from manure management systems. A normal probability distribution was assumed for each source data category. The series of equations used were condensed into a single equation for each animal type and state. The equations for each animal group contained four to five variables around which the uncertainty analysis was performed for each state. These uncertainty estimates were directly applied to the 2014 emission estimates as there have not been significant changes in the methodology since that time.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-8. Manure management CH_4 emissions in 2014 were estimated to be between 50.2 and 73.4 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2014 emission estimate of 61.2 MMT CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 14.7 and 21.7 MMT CO_2 Eq. (or approximately 16 percent below and 24 percent above the actual 2014 emission estimate of 17.5 MMT CO_2 Eq.).

Table 5-8: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O (Direct and Indirect) Emissions from Manure Management (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Manure Management	CH_4	61.2	50.2	73.4	-18%	20%
Manure Management	N_2O	17.5	14.7	21.7	-16%	24%

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

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Tier 2 activities focused on comparing estimates for the previous and current Inventories for N_2O emissions from managed systems and CH_4 emissions from livestock manure. All errors identified were corrected. Order of magnitude checks were also conducted, and corrections made where needed. Manure N data were checked by comparing state-level data with bottom up estimates derived at the county level and summed to the state level. Similarly, a comparison was made by animal and WMS type for the full time series, between national level estimates for N excreted and the sum of county estimates for the full time series.

Any updated data, including population, are validated by experts to ensure the changes are representative of the best available U.S.-specific data. The U.S.-specific values for TAM, Nex, VS, B_o, and MCF were also compared to the IPCC default values and validated by experts. Although significant differences exist in some instances, these differences are due to the use of U.S.-specific data and the differences in U.S. agriculture as compared to other countries. The U.S. manure management emission estimates use the most reliable country-specific data, which are more representative of U.S. animals and systems than the 2006 IPCC default values.

For additional verification, the implied CH_4 emission factors for manure management (kg of CH_4 per head per year) were compared against the default 2006 IPCC values. Table 5-9 presents the implied emission factors of kg of CH_4 per head per year used for the manure management emission estimates as well as the IPCC default emission factors. The U.S. implied emission factors fall within the range of the 2006 IPCC default values, except in the case of sheep, goats, and some years for horses and dairy cattle. The U.S. implied emission factors are greater than the 2006 IPCC default value for those animals due to the use of U.S.-specific data for typical animal mass and VS excretion. There is an increase in implied emission factors for dairy and swine across the time series. This increase reflects the dairy and swine industry trend towards larger farm sizes; large farms are more likely to manage manure as a liquid and therefore produce more CH_4 emissions.

Table 5-9: 2006 IPCC Implied Emission Factor Default Values Compared with Calculated Values for CH_4 from Manure Management (kg/head/year)

Animal Type	IPCC Default CH_4 Emission Factors (kg/head/year)	Implied CH_4 Emission Factors (kg/head/year)						
		1990	2005	2010	2011	2012	2013	2014
Dairy Cattle	48-112	30.2	59.4	66.5	67.5	70.3	68.7	69.7
Beef Cattle	1-2	1.5	1.6	1.6	1.7	1.7	1.6	1.6
Swine	10-45	11.5	15.0	14.6	14.4	14.6	14.1	14.0
Sheep	0.19-0.37	0.6	0.6	0.5	0.5	0.5	0.5	0.5
Goats	0.13-0.26	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Poultry	0.02-1.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Horses	1.56-3.13	4.3	3.1	2.6	2.6	2.7	2.5	2.5
Mules and Asses	0.76-1.14	0.9	1.0	0.9	1.0	1.0	0.9	0.9
American Bison	NA	1.8	2.0	2.1	2.1	2.1	2.0	2.0

NA – Not applicable

In addition, 2006 default IPCC emission factors for N_2O were compared to the U.S. Inventory implied N_2O emission factors. Default N_2O emission factors from the *2006 IPCC Guidelines* were used to estimate N_2O emission from each WMS in conjunction with U.S.-specific Nex values. The implied emission factors differed from the U.S. Inventory values due to the use of U.S.-specific Nex values and differences in populations present in each WMS throughout the time series.

Recalculations Discussion

The CEFM produces population, VS and Nex data for cattle, excepting calves, that are used in the manure management inventory. As a result, all changes to the CEFM described in Section 5.1 contributed to changes in the population, VS and Nex data used for calculating CH_4 and N_2O cattle emissions from Manure Management. In addition, the Manure Management emission estimates included the following recalculations relative to the previous Inventory:

- State animal populations were updated to reflect updated USDA NASS datasets, which resulted in population changes for poultry in 2013, both beef and dairy calves from 2009 through 2013, sheep in 2011 and 2012, and swine from 2008 through 2013.
- Indirect N_2O emissions for daily spread were added, as they are not accounted for in the Agricultural Soil Management category. This inclusion increased indirect and total N_2O emissions for dairy cows and dairy heifers. Indirect N_2O emissions increased between 0.9 and 5.2 percent per year, while total N_2O emissions increased between 0.6 to 1.4 percent per year.

Planned Improvements

The uncertainty analysis for Manure Management will be updated in future Inventories to more accurately assess uncertainty of emission calculations. This update is necessary due to the extensive changes in emission calculation methodology, including estimation of emissions at the WMS level and the use of new calculations and variables for indirect N_2O emissions.

In the next Inventory report, updated AgSTAR anaerobic digester data will be incorporated. In addition, potential data sources (such as the USDA Agricultural Resource Management Survey) for updated WMS distribution estimates will be reviewed and discussed with USDA. Further, future Inventories may present emissions on a monthly basis to show seasonal emission changes for each WMS; this update would help compare these Inventory data to other data and models.

5.3 Rice Cultivation (IPCC Source Category 3C) (TO BE UPDATED)

Most of the world's rice, and all rice in the United States, is grown on flooded fields (Baicich 2013). When fields are flooded, aerobic decomposition of organic material gradually depletes most of the oxygen in the soil. Once depleted, soil conditions become anaerobic, and CH_4 is produced by the decomposition of soil organic matter by anaerobic methanogenic bacteria. Most of the CH_4 produced does not reach the atmosphere. Up to 60 to 90 percent is oxidized by aerobic methanotrophic bacteria in the soil (some oxygen remains at the interfaces of soil and water, and soil and root systems) (Holzapfel-Pschorn et al. 1985, Sass et al. 1990) and some is leached away as dissolved CH_4 in floodwater that percolates from the field. The remaining un-oxidized CH_4 is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants. Minor amounts of CH_4 also escape from the soil via diffusion and bubbling through floodwaters.

The water management systems used to cultivate rice are one of the most important factors affecting CH_4 emissions. Upland rice fields are not flooded, and therefore are not believed to produce much CH_4. In deepwater rice fields (i.e., fields with flooding depths greater than one meter), the lower stems and roots of the rice plants die, thus blocking the primary CH_4 transport pathway to the atmosphere. The quantities of CH_4 released from deepwater fields are therefore believed to be significantly less than rice fields with shallower flooding depths (Sass 2001). Some flooded rice fields are drained periodically during the growing season, either intentionally or accidentally. If water is drained and soils are allowed to dry sufficiently, CH_4 emissions decrease or stop entirely due to soil aeration. Aeration not only causes existing soil CH_4 to oxidize, but also inhibits further CH_4 production in soils. In the United States, rice is grown under continuously flooded, shallow water conditions (USDA 2012) and mid-season drainage does not occur except by accident (e.g., due to levee breach).

Other factors that influence CH_4 emissions from flooded rice fields include fertilization practices (i.e., the use of urea and organic fertilizers), soil temperature, soil type, rice variety, and cultivation practices (e.g., tillage, seeding, and weeding practices). Factors that influence the amount of organic material available for anaerobic decomposition (i.e., fertilizer use, soil type, rice variety,[4] and cultivation practices) are the most important variables influencing the amount of CH_4 emitted over the growing season. Soil temperature is an important factor regulating the activity of methanogenic bacteria which in turn affects the rate of CH_4 production. However, although temperature influences the time required to convert organic material to CH_4, the impact of soil temperature on CH_4 emissions is minor over the length of the growing season. The application of synthetic fertilizers also influences CH_4 emissions; in particular, both nitrate and sulfate fertilizers (e.g., ammonium nitrate and ammonium sulfate) appear to inhibit CH_4 formation. Nitrate and sulfate fertilizers are not commonly used in rice cultivation in the United States.

Rice is currently cultivated in seven states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, and Texas.[5] Soil types, rice varieties, and cultivation practices for rice vary from state to state, and even from farm to farm. Most rice farmers recycle crop residues from the previous rice or rotational crop, either by leaving them standing, disking them, or rolling them into fields. Most farmers also apply synthetic fertilizer (usually urea) to their fields. In addition, the climatic conditions of Arkansas, Florida, southwest Louisiana, and Texas often allow for a second, or ratoon, rice crop. Ratoon crops are produced from regrowth of the stubble remaining after the harvest of the first rice crop. Ratoon crops are infrequent to non-existent in California, Mississippi, and Missouri. In 2012, Arkansas reported a larger-than-usual ratoon crop (10 percent) due to an early rice harvest followed by warm weather and heavy rains (ideal conditions for secondary growth and ratoon crops) (Hardke 2014). CH_4 emissions from ratoon crops are considerably higher than those from the primary crops due to the lack of a delay between cropping seasons (which would allow the stubble to decay aerobically) (Wang et al. 2013). Specifically, the amount of organic material available for anaerobic decomposition during ratoon crop production is considerably higher than the amount available with the first (i.e., primary) crop production.

Rice cultivation is a minor source of CH_4 emissions in the United States (see Table 5-10 and Table 5-11). In 2013, CH_4 emissions from rice cultivation were 8.3 MMT CO_2 Eq. (332 kt). Annual emissions have fluctuated unevenly between 1990 and 2013, ranging from an annual decrease of 24 percent from 2010 and 2011 to an annual increase of 18 percent from 2009 to 2010. There was an overall decrease of 16 percent between 1990 and 2006, due to an overall decrease in primary crop area. However, between 2006 and 2013 emission levels have increased by 8 percent due to increased ratooning and changes in production areas. California, Louisiana and Texas reported an increase in rice crop area from 2012 to 2013. All other states reported a decrease in rice crop area from 2012 to 2013. The factors that affect the rice acreage in any year vary from state to state and are typically the result of weather phenomena (Baldwin et al. 2010).

Table 5-10: CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq.)

State	1990		2005		2010	2011	2012	2013	2014
Arkansas	4.0		5.7		6.2	6.2	6.2	6.2	6.2
California	1.0		2.3		1.6	1.6	1.6	1.6	1.6
Florida	+		+		+	+	+	+	+
Illinois	+		+		+	+	+	+	+
Louisiana	3.0		3.1		2.6	2.6	2.6	2.6	2.6
Minnesota	+		+		+	+	+	+	+
Mississippi	0.7		0.8		0.4	0.4	0.4	0.4	0.4
Missouri	0.3		0.5		0.8	0.8	0.8	0.8	0.8
New York	+		+		+	+	+	+	+
South Carolina	+		+		+	+	+	+	+
Tennessee	+		+		+	+	+	+	+
Texas	2.4		1.7		0.6	0.6	0.6	0.6	0.6
Total	**11.3**		**14.2**		**12.2**	**12.2**	**12.2**	**12.2**	**12.2**

+ Less than 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

---

[4] The roots of rice plants shed organic material, which is referred to as "root exudate." The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

[5] Oklahoma has also historically produced rice. 2007 was the most recent production year reported (77 hectares).

Table 5-11: CH_4 Emissions from Rice Cultivation (kt)

State	1990	2005	2010	2011	2012	2013	2014
Arkansas	160.0	229.4	246.5	246.8	247.1	247.1	246.4
California	38.1	90.3	64.2	64.4	64.2	64.3	64.5
Florida	+	0.8	+	+	+	+	+
Illinois	+	0.3	+	+	+	+	+
Louisiana	118.1	124.9	103.8	103.5	104.6	104.5	105.7
Minnesota	0.8	0.8	0.2	0.2	0.2	0.2	0.2
Mississippi	27.5	32.5	16.5	16.7	16.7	16.6	16.5
Missouri	11.3	20.6	31.4	31.5	31.5	31.5	31.4
New York	+	+	+	+	+	+	+
South Carolina	+	+	+	+	+	+	+
Tennessee	+	0.7	+	+	+	+	+
Texas	95.5	66.8	23.6	23.7	23.6	23.7	23.4
Total	**451**	**567**	**486**	**487**	**488**	**488**	**488**

+ Less than 0.5 kt

Note: Totals may not sum due to independent rounding.

Methodology

IPCC (2006) recommends using harvested rice areas, and seasonally integrated emission factors (i.e., country specific emission factors that have been developed from standardized field measurements (representing the mix of different conditions that influence CH_4 emissions in the area) for each commonly occurring rice production system). To that end, the recommended GPG methodology and Tier 2 U.S.-specific seasonally integrated emission factors derived from U.S. based rice field measurements are used.

Regional emission factors were derived based on a literature review of recent research on CH_4 emissions from U.S. rice production. In California, some rice fields are flooded during the winter to prepare the fields for the next growing season, and to create waterfowl habitat (Young 2013). Winter flooded rice crops generate CH_4 year round due to the anaerobic conditions the winter flooding creates (Environmental Defense Fund 2011), and up to 50 percent of the CH_4 emissions occur in the winter (Fitzgerald et al. 2000). Thus for winter flooded rice crops in California, an annual CH_4 emission factor is used. For non-winter flooded California rice crops, a seasonal emission factor is applied as almost all of the CH_4 emissions occur during the growing season (Fitzgerald et al. 2000). California-specific winter flooded and non-winter flooded emission factors were applied to rice area harvested in California. Average U.S. seasonal emission factors were applied to Arkansas, Florida, Louisiana, Missouri, Mississippi, and Texas as there was not sufficient data to develop state-specific, or daily emission factors, or both. As described above, seasonal emissions are much higher for ratooned crops than for primary crops. Therefore, emissions from ratooned and primary areas are estimated separately using the appropriate representative emission factors. This approach is consistent with IPCC (2006).

To determine what CH_4 emission factors should be used for the primary and ratoon crops, CH_4 flux information from rice field measurements in the United States was collected. Experiments that involved atypical or non-representative management practices (e.g., the application of nitrate or sulfate fertilizers, or other substances believed to suppress CH_4 formation, or floodwaters were drained mid-season), as well as experiments in which measurements were not made over an entire flooding season were excluded from the analysis. The remaining experimental results were then sorted by state, season (i.e., primary and ratoon), flooding practices, and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added).

Eleven California-specific primary crop experimental results were added for California rice emissions starting with the 1990-2012 Inventory. These California-specific studies were selected because they met the criteria of experiments on primary crops with added synthetic and organic fertilizer, without residue burning, and without winter flooding (Bossio et al. 1999; Fitzgerald et al. 2000). The seasonal emission rates estimated in these studies were averaged to derive a seasonal emission factor for California's primary, non-winter flooded rice crop. Similarly, separate California-specific studies meeting the same criteria, (i.e., primary crops with added synthetic and organic fertilizer, without residue burning) but with winter flooding (Bossio et al. 1999; Fitzgerald et al. 2000; McMillan et al. 2007) were averaged to derive an annual emission factor for California's primary, winter-flooded rice crop. Approximately 60 percent of California's rice crop is winter-flooded (Environmental Defense Fund 2011), therefore the California-specific, winter flooded emission factor was applied to 60 percent of the California rice area harvested and the California-specific, non-winter flooded emission factor was applied to the 40 percent of the California rice area harvested. The resultant seasonal emission factor for the California, non-winter flooded crop is 133 kg CH_4/hectare/season, and the annual emission factor for the California, winter-flooded crop is 266 kg CH_4/hectare/season.

For the remaining states, a non-California U.S. seasonal emission factor was derived by averaging seasonal emissions rates from primary crops with added synthetic and organic fertilizer (Byrd 2000; Kongchum 2005; Rogers et al. 2011; Sass et al. 1991a, 1991b, 2002a, 2002b; Yao 2001). The seasonal emissions rates from ratoon crops with added synthetic fertilizer (Lindau and Bollich 1993; Lindau et al. 1995) were averaged to derive a seasonal emission factor for the ratoon crop. The resultant seasonal emission factor for the primary crop is 237 kg CH_4/hectare/season, and the resultant emission factor for the ratoon crop is 780 kg CH_4/hectare/season.

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 5-12, and the ratooned crop area as a percent of primary crop area is shown in Table 5-13. Primary crop areas for 1990 through 2013 for all states except Florida and Oklahoma were taken from U.S. Department of Agriculture's *Field Crops Final Estimates 1987–1992* (USDA 1994), *Field Crops Final Estimates 1992–1997* (USDA 1998), *Field Crops Final Estimates 1997–2002* (USDA 2003), and *Crop Production Summary* (USDA 2005 through 2014). Source data for non-USDA sources of primary and ratoon harvest areas are shown in Table 5-14. California, Mississippi, Missouri, and Oklahoma have not ratooned rice over the period 1990 through 2013 (Anderson 2008 through 2014; Beighley 2011 through 2012; Buehring 2009 through 2011; Guethle 1999 through 2010; Lee 2003 through 2007; Mutters 2001 through 2005; Street 1999 through 2003; Walker 2005, 2007 through 2008).

Table 5-12: Rice Area Harvested (Hectare)

State/Crop	1990	2005	2009	2010	2011	2012	2013
Arkansas							
Primary	485,633	661,675	594,901	722,380	467,017	520,032	433,023
Ratoon[a]	-	662	6	7	5	52,003	21,651
California	159,854	212,869	225,010	223,796	234,723	225,415	227,034
Florida							
Primary	4,978	4,565	5,664	5,330	8,212	6,244	6,739
Ratoon	2,489	-	2,266	2,275	2,311	2,748	2,159
Louisiana							
Primary	220,558	212,465	187,778	216,512	169,162	160,664	167,139
Ratoon	66,168	27,620	65,722	86,605	59,207	64,265	63,513
Mississippi	101,174	106,435	98,341	122,622	63,537	52,206	50,182
Missouri	32,376	86,605	80,939	101,578	51,801	71,631	63,132
Oklahoma	617	271	-	-	-	-	-
Texas							
Primary	142,857	81,344	68,798	76,083	72,845	54,229	58,276
Ratoon	57,143	21,963	39,903	41,085	56,091	33,080	39,628
Total Primary	**1,148,047**	**1,366,228**	**1,261,431**	**1,468,300**	**1,067,298**	**1,090,421**	**1,005,525**
Total Ratoon	**125,799**	**50,245**	**107,897**	**129,971**	**117,613**	**152,096**	**126,951**
Total	**1,273,847**	**1,416,473**	**1,369,328**	**1,598,271**	**1,184,911**	**1,242,517**	**1,132,476**

[a] Arkansas ratooning occurred only in 1998, 1999, and 2005 through 2013, with particularly high ratoon rates in 2012 and 2013.

"-" No reported value

Note: Totals may not sum due to independent rounding.

Table 5-13: Ratooned Area as Percent of Primary Growth Area

State	1990	2005	2009	2010	2011	2012	2013
Arkansas	+	0.1%	+	+	+	10%	5%
Florida	50%	+	40%	43%	28%	44%	32%
Louisiana	30%	13%	35%	40%	35%	40%	38%

Texas	40%	27%	58%	54%	77%	61%	68%

+ Indicates ratooning less than 0.05 percent of primary growth area.

Table 5-14: Non-USDA Data Sources for Rice Harvest Information

State/Crop	1990	2005	2009	2010	2011	2012	2013
Arkansas – Ratoon[a]	Slaton	Wilson	Wilson (2009 – 2011)			Hardke (2012 – 2013)	
Florida – Primary[b]	Schueneman	Gonzalez	Gonzalez (2009 – 2013)				
Florida – Ratoon[c]	Schueneman	Gonzalez	Gonzalez (2009 – 2013)				
Louisiana – Ratoon[d]	Linscombe	Linscombe	Linscombe (2009 -2013)				
Oklahoma – Primary[e]	Lee	Lee	Anderson (2009 – 2013)				
Texas – Ratoon[f]	Klosterboer	TAES	Texas Agricultural Experiment Station (TAES) (2009 – 2013)				

[a] Arkansas: *1990 – 2000* (Slaton 1999 through 2001); *2001 – 2011* (Wilson 2002 through 2007, 2009 through 2012). *2012 – 2013* (Hardke 2013, 2014).

[b] Florida - Primary: *1990 – 2000* (Schueneman 1997, 1999 through 2001); *2001* (Deren 2002); *2002 – 2004* (Kirstein 2003 through 2004, 2006); *2005 – 2013* (Gonzalez 2007 through 2014)

[c] Florida - Ratoon: *1990 – 2000* (Schueneman 1997, 1999 through 2001); *2001* (Deren 2002); *2002 – 2003* (Kirstein 2003 through 2004, 2006); *2004* (Cantens 2004- 2005); *2005 – 2013* (Gonzalez 2007 through 2014)

[d] Louisiana: *1990 - 2013* (Linscombe 1999, 2001 through 2014).

[e] Oklahoma: *1990 – 2006* (Lee 2003 through 2007); *2007 – 2013* (Anderson 2008 through 2014).

[f] Texas: *1990 – 2002* (Klosterboer 1997, 1999 through 2003); *2003 – 2004* (Stansel 2004 through 2005); *2005* (Texas Agricultural Experiment Station 2006); *2006 – 2013* (Texas Agricultural Experiment Station 2007 – 2014).

Box 5-1: Comparison of the U.S. Inventory Seasonal Emission Factors and IPCC (1996) Default Emission Factors

Emissions from rice production were estimated using a Tier 2 methodology consistent with IPCC (2006). Representative emission factors using experimentally determined seasonal CH_4 emissions from U.S. rice fields for both primary and ratoon crops were derived from a literature review. Emissions are compared with the *1996 IPCC Guidelines* default U.S. seasonal emission factor, and not the more recent *2006 IPCC Guidelines* global daily emission factor. The rationale for this comparison is that the evaluated studies were specific to the U.S., were regional specific seasonal emission factors, and did not include daily emission factors or season length. As explained above, four different emission factors were calculated: (1) a seasonal, California-specific factor without winter flooding (133 kg CH_4/hectare/season), (2) an annual, California specific-factor with winter flooding (266 kg CH_4/hectare/year), (3) a seasonal, non-California primary crop factor (237 kg CH_4/hectare/season), and (4) a seasonal, non-California ratoon crop factor (780 kg CH_4/hectare/season). These emission factors represent averages across rice field measurements representing typical water management practices and synthetic and organic amendment application practices in the United States according to regional experts (Anderson 2013; Beighly 2012; Fife 2011; Gonzalez 2013; Linscombe 2013; Vayssières 2013; Wilson 2012). The IPCC (1996) default factor for U.S. (i.e., Texas) rice production for both primary and ratoon crops is 250 kg CH_4/hectare/season. This default value is based on a study by Sass and Fisher (1995) which reflects a growing season in Texas of approximately 275 days. Data results in the evaluated studies were provided as seasonal emission factors; therefore, neither daily emission factors nor growing season length was estimated. Some variability within season lengths in the evaluated studies is assumed. The Tier 2 emission factors used here represent rice cultivation practices specific to the United States. For comparison, the 2013 U.S. emissions from rice cultivation are 8.3 MMT CO_2 Eq. using the four U.S.-specific emission factors for both primary and ratoon crops and 7.2 MMT CO_2 Eq. using the IPCC (1996) emission factor.

Table 5-15: Non-California Seasonal Emission Factors (kg CH_4/hectare/season)

Primary		Ratoon	
Minimum	61	Minimum	481

Maximum	500	Maximum	1490
Mean	237	Mean	780

Table 5-16: California Emission Factors (kg CH_4/hectare/year or season)

Winter Flooded (Annual)[b]		Non-Winter Flooded (Seasonal)[c]	
Minimum	131	Minimum	62
Maximum	369	Maximum	221
Mean	266	Mean	133

Note: See methodology text for why the emission factor is annual for winter flooded and seasonal for non-winter flooded California rice production.

[b] Percentage of California rice crop winter flooded: 60 percent.

[c] Percentage of California rice crop not winter flooded: 40 percent.

Uncertainty and Time-Series Consistency

The largest uncertainty in the calculation of CH_4 emissions from rice cultivation is associated with the emission factors. Seasonal emissions, derived from field measurements in the United States, vary by more than one order of magnitude. This inherent variability is due to differences in cultivation practices, particularly fertilizer type, amount, and mode of application; differences in cultivar type; and differences in soil and climatic conditions. A portion of this variability is accounted for by separating primary from ratooned areas. However, even within a cropping season or a given management regime, measured emissions may vary significantly. Of the experiments used to derive the emission factors applied here, primary emissions ranged from 61 to 500 kg CH_4/hectare/season and ratoon emissions ranged from 481 to 1,490 kg CH_4/hectare/season. The uncertainty distributions around the California winter flooding, California non-winter flooding, non-California primary, and ratoon emission factors were derived using the distributions of the relevant emission factors available in the literature and described above. Variability around the rice emission factor means was not normally distributed for any crop system, but rather skewed, with a tail trailing to the right of the mean. A lognormal statistical distribution was, therefore, applied in the uncertainty analysis.

Other sources of uncertainty include the primary rice-cropped area for each state, percent of rice-cropped area that is ratooned, the length of the growing season, and the extent to which flooding outside of the normal rice season is practiced. Expert judgment was used to estimate the uncertainty associated with primary rice-cropped area for each state at 1 to 5 percent, and a normal distribution was assumed. Uncertainties were applied to ratooned area by state, based on the level of reporting performed by the state. Within California, the uncertainty associated with the percentage of rice fields that are winter flooded was estimated at plus and minus 20 percent. No uncertainty estimates were calculated for the practice of flooding outside of the normal rice season outside of California because CH_4 flux measurements have not been undertaken over a sufficient geographic range or under a broad enough range of representative conditions to account for this source in the emission estimates or its associated uncertainty.

To quantify the uncertainties for emissions from rice cultivation, a Monte Carlo (Approach 2) uncertainty analysis was performed using the information provided above. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-17. Rice cultivation CH_4 emissions in 2013 were estimated to be between 4.2 and 15.9 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 50 percent below to 91 percent above the actual 2013 emission estimate of 8.3 MMT CO_2 Eq.

Table 5-17: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq. and Percent)

Source	Gas	2013 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Rice Cultivation	CH_4	8.3	4.2	15.9	-50%	91%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for rice cultivation was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing trends across years, states, and cropping seasons to attempt to identify any outliers or inconsistencies. No problems were found.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most Inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for these greenhouse gases. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations Chapter. As a result of the updated GWP value for CH_4, emissions estimates for each year from 1990 to 2012 increased by 19 percent relative to the emissions estimates in previous Inventory reports.

Additionally, the 2012 emission estimates were updated to reflect an increase in previously-reported ratooning in Arkansas. Rice was harvested early in 2012, after which a high percentage of “secondary growth” occurred. Estimated percent ratooning of secondary growth in 2012 increased from 5 to 10 percent (Hardke 2014), resulting in a 0.4 MMT CO_2 eq. (21 kt C) increase in emissions.

Planned Improvements

A planned improvement for the 1990 through 2014 Inventory will be the expansion of the California-specific rice emission factors to include an emission factor for the period prior to the passage of the Air Resources Board (ARB) Mandate phasing out rice residue burning. This non-flooded residue burned emission factor will take into account the phase down of rice straw burning that occurred in California from 1990 to 2002. During this time period, the percentage of acres burned annually decreased from 75 percent in 1992 to 13 percent in 2002 (California Air Resources Board 2003). California studies that include rice burning on non-flooded lands will be used to develop the pre-2002 rice burning emission factor, and further research will be conducted to determine the percentage of winter flooded area to which the current California winter flooded emission factor will be applied. This new time series dependent emission factor will be applied to non-flooded burned area during the 1990 through 2002 time period to capture the significant change in the percentage of rice area burned due to the California ARB Mandate. Following 2002, the current methodology and emission factors will be applied.

Another possible future improvement is to create additional state- or region-specific emission factors for rice cultivation. This prospective improvement would likely not take place for another two to three years, because the analyses needed for it are currently taking place.

5.4 Agricultural Soil Management (IPCC Source Category 3D)

Nitrous oxide (N_2O) is naturally produced in soils through the microbial processes of nitrification and denitrification that is driven by the availability of mineral N (Firestone and Davidson 1989).[6] Mineral N is made available in soils through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere.[7] A number of agricultural activities increase mineral nitrogen (N) availability in soils that lead to direct N_2O emissions from nitrification and denitrification at the site of a management activity (see Figure 5-2) (Mosier et al. 1998), including fertilization; application of managed livestock manure and other organic materials such as sewage sludge; deposition of manure on soils by domesticated animals in pastures, rangelands, and paddocks (PRP) (i.e., by grazing animals and other animals whose manure is not managed); production of N-fixing crops and forages; retention of crop residues; and drainage of organic soils (i.e., soils with a high organic matter content, otherwise known as Histosols[8]) in croplands and grasslands (IPCC 2006). Additionally, agricultural soil management activities, including irrigation, drainage, tillage practices, and fallowing of land, can influence N mineralization by impacting moisture and temperature regimes in soils. Indirect emissions of N_2O occur when N is transported from a site and is subsequently converted to N_2O; there are two pathways for indirect emissions: (1) volatilization and subsequent atmospheric deposition of applied/mineralized N, and (2) surface runoff and leaching of applied/mineralized N into groundwater and surface water.[9]

Direct and indirect emissions from agricultural lands are included in this section (i.e., cropland and grassland as defined in Chapter 6.1 Representation of the U.S. Land Base). The U.S. Inventory includes all greenhouse gas emissions from managed land based on guidance in IPCC (2006), and consequently N mineralization from decomposition of soil organic matter and asymbiotic N fixation are also included in this section to fully address emissions from the managed land base (see Methodology section for more information).

---

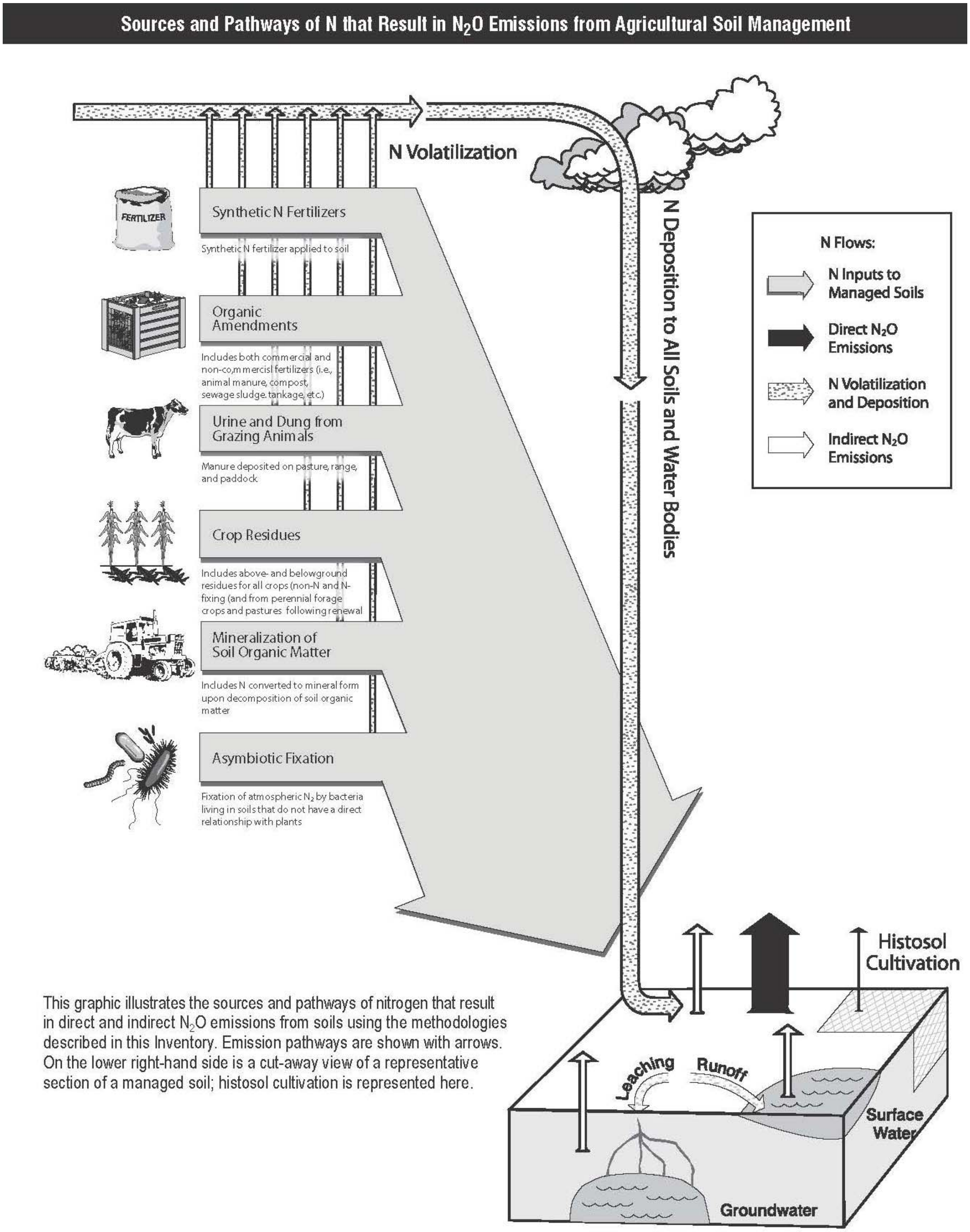
[6] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product in the reaction sequence of denitrification, which leaks from microbial cells into the soil and then into the atmosphere. Nitrous oxide is also produced during nitrification, although by a less well-understood mechanism (Nevison 2000).

[7] Asymbiotic N fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[8] Drainage of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby increasing N_2O emissions from these soils.

[9] These processes entail volatilization of applied or mineralized N as NH_3 and NO_x, transformation of these gases within the atmosphere (or upon deposition), and deposition of the N primarily in the form of particulate NH_4^+, nitric acid (HNO_3), and NO_x.

Figure 5-2: Sources and Pathways of N that Result in N_2O Emissions from Agricultural Soil Management



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from soils using the methodologies described in this Inventory. Emission pathways are shown with arrows. On the lower right-hand side is a cut-away view of a representative section of a managed soil; histosol cultivation is represented here.

Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions from this source in 2014 are 318.5 MMT CO_2 Eq. (1,069 kt) (see Table 5-18 and Table 5-19) Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2014, although overall emissions are 5 percent higher in 2014 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production. From 1990 to 2014, on average cropland accounted for approximately 70 percent of total direct emissions, while grassland accounted for approximately 30 percent. The percentages for indirect emissions on average are approximately 66 percent for croplands, 34 percent for grasslands. Estimated direct and indirect N_2O emissions by sub-source category are shown in Table 5-20 and Table 5-21.

Table 5-18: N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990	2005	2010	2011	2012	2013	2014
Direct	**245.0**	**248.3**	**263.8**	**264.5**	**264.5**	**261.2**	**261.3**
Cropland	171.9	174.4	185.7	186.9	187.9	185.2	185.3
Grassland	73.2	73.9	78.1	77.6	76.6	76.0	76.0
Indirect	**57.9**	**48.4**	**56.6**	**58.4**	**58.3**	**57.2**	**57.2**
Cropland	36.2	34.0	39.7	40.6	41.1	40.3	40.3
Grassland	21.7	14.5	16.9	17.7	17.3	17.0	17.0
Total	**302.9**	**296.7**	**320.4**	**322.9**	**322.9**	**318.4**	**318.5**

Table 5-19: N_2O Emissions from Agricultural Soils (kt)

Activity	1990	2005	2010	2011	2012	2013	2014
Direct	**822**	**833**	**885**	**888**	**888**	**877**	**877**
Cropland	577	585	623	627	630	621	622
Grassland	246	248	262	260	257	255	255
Indirect	**194**	**163**	**190**	**196**	**196**	**192**	**192**
Cropland	121	114	133	136	138	135	135
Grassland	73	49	57	60	58	57	57
Total	**1,017**	**996**	**1,075**	**1,084**	**1,083**	**1,069**	**1,069**

Table 5-20: Direct N_2O Emissions from Agricultural Soils by Land Use Type and N Input Type (MMT CO_2 Eq.)

Activity	1990	2005	2010	2011	2012	2013	2014
Cropland	**171.9**	**174.4**	**185.7**	**186.9**	**187.9**	**185.2**	**185.3**
Mineral Soils	**168.6**	**171.2**	**182.6**	**183.9**	**184.9**	**182.2**	**182.2**
Synthetic Fertilizer	59.2	61.4	59.3	61.0	61.8	59.5	59.5
Organic Amendment[a]	11.9	12.9	13.4	13.5	13.6	13.5	13.5
Residue N[b]	25.9	26.6	27.8	27.6	27.5	27.5	27.6
Mineralization and Asymbiotic Fixation	71.6	70.3	82.2	81.8	82.0	81.6	81.6
Organic Soils	**3.2**	**3.2**	**3.0**	**3.0**	**3.0**	**3.0**	**3.0**
Grassland	**73.2**	**73.9**	**78.1**	**77.6**	**76.6**	**76.0**	**76.0**
Mineral Soils	**70.3**	**71.0**	**75.5**	**74.9**	**74.0**	**73.3**	**73.3**
Synthetic Fertilizer	1.1	1.3	1.3	1.2	1.2	1.2	1.2
PRP Manure	13.4	12.3	12.5	11.9	11.0	10.3	10.3
Managed Manure[c]	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Sewage Sludge	0.2	0.5	0.5	0.5	0.6	0.6	0.6
Residue N[d]	19.7	21.0	21.8	21.7	21.7	21.7	21.7
Mineralization and Asymbiotic Fixation	35.8	35.8	39.1	39.4	39.4	39.4	39.4
Organic Soils	2.9	2.9	2.7	2.7	2.7	2.7	2.7
Total	**245.0**	**248.3**	**263.8**	**264.5**	**264.5**	**261.2**	**261.3**

[a] Organic amendment inputs include managed manure, daily spread manure, and commercial organic fertilizers (i.e., dried blood, dried manure, tankage, compost, and other).

[b] Cropland residue N inputs include N in unharvested legumes as well as crop residue N.

[c] Managed manure inputs include managed manure and daily spread manure amendments that are applied to grassland soils.

[d] Grassland residue N inputs include N in ungrazed legumes as well as ungrazed grass residue N

Table 5-21: Indirect N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990	2005	2010	2011	2012	2013	2014
Cropland	**36.2**	**34.0**	**39.7**	**40.6**	**41.1**	**40.3**	**40.3**
Volatilization & Atm. Deposition	13.0	13.8	13.9	14.3	14.5	14.2	14.2
Surface Leaching & Run-Off	23.2	20.2	25.8	26.4	26.6	26.0	26.0
Grassland	**21.7**	**14.5**	**16.9**	**17.7**	**17.3**	**17.0**	**17.0**
Volatilization & Atm. Deposition	4.4	4.7	4.8	4.7	4.6	4.5	4.5
Surface Leaching & Run-Off	17.4	9.8	12.1	13.0	12.7	12.4	12.4
Total	**57.9**	**48.4**	**56.6**	**58.4**	**58.3**	**57.2**	**57.2**

Figure 5-3 and Figure 5-4 show regional patterns for direct N_2O emissions for croplands and grasslands, and Figure 5-5 and Figure 5-6 show N losses from volatilization, leaching, and runoff that lead to indirect N_2O emissions. Annual emissions and N losses in 2014 are shown for the Tier 3 Approach only.

Direct N_2O emissions from croplands tend to be high in the Corn Belt (Illinois, Iowa, Indiana, Ohio, southern and western Minnesota, and eastern Nebraska), where a large portion of the land is used for growing highly fertilized corn and N-fixing soybean crops (Figure 5-3). Kansas has high direct emissions associated with N management in wheat production systems. Hay production in Missouri and irrigated cropping systems in California also contribute relatively large amounts of direct N_2O emissions, along with a combination of irrigated cropping in the west Texas and hay production in east Texas. Direct emissions are low in many parts of the eastern United States because only a small portion of land is cultivated and in many western states where rainfall and access to irrigation water are limited.

Direct emissions from grasslands are highest in the central and western United States (Figure 5-4) where a high proportion of the land is used for cattle grazing. In contrast, most areas in the Great Lake states, the Northeast, and Southeast have moderate to low emissions due to less land dedicated to livestock grazing. However, emissions from the Northeast and Great Lake states tend to be higher on a per unit area basis compared to other areas in the country. This effect is likely due to a larger impact of freeze-thaw cycles in these regions, and possibly greater water-filled pore space in the soil, which is key driver of N_2O emissions (Kessavalou et al. 1998, Bateman and Baggs 2005).

Indirect emissions from croplands and grasslands (Figure 5-5 and Figure 5-6) show similar emission patterns to those of direct emissions because the same driving variables (N inputs, weather patterns, soil characteristics) are controlling both types of emissions. There are some exceptions to the similarity in patterns, however, because the processes that contribute to indirect emissions (NO_3^- leaching, N volatilization) do not respond in exactly the same manner to the driving variables as the processes that contribute to direct emissions (nitrification and denitrification).

Figure 5-3: Crops, Annual Direct N_2O Emissions Estimated Using the Tier 3 DAYCENT Model, 1990-2014 (MMT CO_2 Eq./year) (TO BE UPDATED)

Figure 5-4: Grasslands, Annual Direct N_2O Emissions Estimated Using the Tier 3 DAYCENT Model, 1990-2014 (MMT CO_2 Eq./year) (TO BE UPDATED)

Figure 5-5: Crops, Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the Tier 3 DAYCENT Model, 1990-2014 (kt N/year) (TO BE UPDATED)

Figure 5-6: Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the Tier 3 DAYCENT Model, 1990-2014 (kt N/year) (TO BE UPDATED)

Methodology

The *2006 IPCC Guidelines* (IPCC 2006) divide emissions from the Agricultural Soil Management source category into five components, including (1) direct emissions from N additions to cropland and grassland mineral soils from synthetic fertilizers, sewage sludge applications, crop residues, organic amendments, and biological N fixation associated with planting of legumes on cropland and grassland soils; (2) direct emissions from soil organic matter mineralization due to land use and management change, (3) direct emissions from drainage of organic soils in croplands and grasslands; (4) direct emissions from soils due to manure deposited by livestock on PRP grasslands; and (5) indirect emissions from soils and water from N additions and manure deposition to soils that lead to volatilization, leaching, or runoff of N and subsequent conversion to N_2O.

The United States has adopted methods in the IPCC (2006) for agricultural soil management. These methods include (1) estimating the contribution of N in crop residues to indirect soil N_2O emissions; (2) adopting the revised emission factor for direct N_2O emissions for Tier 1 methods used in the Inventory (described later in this section); (3) removing double counting of emissions from N-fixing crops associated with biological N fixation and crop residue N input categories; (4) using revised crop residue statistics to compute N inputs to soils from harvest yield data; and (5) estimating emissions associated with land use and management change (which can significantly change the N mineralization rates from soil organic matter).[10] The Inventory also reports on total emissions from all managed land, which is a proxy for anthropogenic impacts on greenhouse gas emissions (IPCC 2006), including direct and indirect N_2O emissions from asymbiotic fixation and mineralization of soil organic matter and litter. One recommendation from IPCC (2006) that has not been completely adopted is the estimation of emissions from grassland pasture renewal, which involves occasional plowing to improve forage production in pastures. Currently no data are available to address pasture renewal.

Direct N_2O Emissions

The methodology used to estimate direct N_2O emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches (IPCC 2006, Del Grosso et al. 2010). A Tier 3 process-based model (DAYCENT) is used to estimate direct emissions from a variety of crops that are grown on mineral (i.e., non-organic) soils, including alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat; as well as the direct emissions from non-federal grasslands with the exception of sewage sludge amendments (Del Grosso et al. 2010). The Tier 3 approach has been specifically designed and tested to estimate N_2O emissions in the United States, accounting for more of the environmental and management influences on soil N_2O emissions than the IPCC Tier 1 method (see Box 5-2 for further elaboration). Moreover, the Tier 3 approach allows for the Inventory to address direct N_2O emissions and soil C stock changes from mineral cropland soils in a single analysis. 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 two source categories (i.e., agricultural soil C and N_2O) in a single inventory analysis ensures that there is consistent activity data and treatment of the processes, and interactions are taken into account between C and N cycling in soils.

The Tier 3 approach is based on the cropping and land use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2013). The NRI is a statistically-based sample of all non-federal land, and includes 380,956 points in agricultural land for the conterminous United States that are included in the Tier 3 method. The Tier 1 approach is used to estimate the emissions from the remaining 92,013 in the NRI survey that are designated as cropland or grassland (discussed later in this section). Each point is associated with an "expansion factor" that allows scaling of N_2O emissions from NRI points to the entire country (i.e., each expansion factor

---

[10] N inputs from asymbiotic N fixation are not directly addressed in *2006 IPCC Guidelines*, but are a component of the total emissions from managed lands and are included in the Tier 3 approach developed for this source.

represents the amount of area with the same land-use/management history as the sample point). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. For cropland, data were collected in 4 out of 5 years in the cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, the annual data are currently available through 2012 (USDA-NRCS 2015) although this Inventory only uses NRI data through 2010 because newer data were not made available in time to incorporate the additional years into this Inventory.

Box 5-2: Tier 1 vs. Tier 3 Approach for Estimating N_2O Emissions

The IPCC (2006) Tier 1 approach is based on multiplying activity data on different N inputs (e.g., synthetic fertilizer, manure, N fixation, etc.) by the appropriate default IPCC emission factors to estimate N_2O emissions on an input-by-input basis. The Tier 1 approach requires a minimal amount of activity data, readily available in most countries (e.g., total N applied to crops); calculations are simple; and the methodology is highly transparent. In contrast, the Tier 3 approach developed for this Inventory employs a process-based model (i.e., DAYCENT) that represents the interaction of N inputs and the environmental conditions at specific locations. Consequently, the Tier 3 approach produces more accurate estimates; it accounts more comprehensively for land-use and management impacts and their interaction with environmental factors (i.e., weather patterns and soil characteristics), which will enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more detailed activity data (e.g., crop-specific N amendment rates), additional data inputs (e.g., daily weather, soil types, etc.), and considerable computational resources and programming expertise. The Tier 3 methodology is less transparent, and thus it is critical to evaluate the output of Tier 3 methods against measured data in order to demonstrate the adequacy of the method for estimating emissions (IPCC 2006). Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding N cycling. Tier 1 assumes that N added to a system is subject to N_2O emissions only during that year and cannot be stored in soils and contribute to N_2O emissions in subsequent years. This is a simplifying assumption that is likely to create bias in estimated N_2O emissions for a specific year. In contrast, the process-based model used in the Tier 3 approach includes the legacy effect of N added to soils in previous years that is re-mineralized from soil organic matter and emitted as N_2O during subsequent years.

DAYCENT is used to estimate N_2O emissions associated with production of alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat, but is not applied to estimate N_2O emissions from other crops or rotations with other crops,[11] such as sugarcane, some vegetables, tobacco, and perennial/horticultural crops. Areas that are converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland and settlements, is not simulated with DAYCENT. DAYCENT is also not used to estimate emissions from land areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume), or to estimate emissions from organic soils (Histosols). The Tier 3 method has not been fully tested for estimating N_2O emissions associated with these crops and rotations, land uses, as well as organic soils or cobbly, gravelly, and shaley mineral soils. In addition, federal grassland areas are not simulated with DAYCENT due to limited activity on land use histories. For areas that are not included in the DAYCENT simulations, the Tier 1 IPCC (2006) methodology is used to estimate (1) direct emissions from crops on mineral soils that are not simulated by DAYCENT; (2) direct emissions from Pasture/Range/Paddock (PRP) on federal grasslands; and (3) direct emissions from drainage of organic soils in croplands and grasslands.

Tier 3 Approach for Mineral Cropland Soils

The DAYCENT biogeochemical model (Parton et al. 1998, and Del Grosso et al. 2001, 2011) is used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of a wide variety of crops based on the cropping histories in the 2010 NRI (USDA-NRCS 2013). The crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets,

---

[11] A small proportion of the major commodity crop production, such as corn and wheat, is included in the Tier 1 analysis because these crops are rotated with other crops or land uses (e.g., forest lands) that are not simulated by DAYCENT.

sunflowers, tomatoes, and wheat. Crops simulated by DAYCENT are grown on approximately 91 percent of total cropland area in the United States. For agricultural systems in the central region of the United States, crop production for key crops (i.e., corn, soybeans, sorghum, cotton and wheat) is simulated in DAYCENT with a NASA-CASA production algorithm (Potter et al.1993, Potter et al. 2007) using the MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, with a pixel resolution of 250m.[12]

DAYCENT is used to estimate direct N_2O emissions due to mineral N available from the following sources: (1) the application of synthetic fertilizers; (2) the application of livestock manure; (3) the retention of crop residues and subsequent mineralization of N during microbial decomposition (i.e., leaving residues in the field after harvest instead of burning or collecting residues); and (4) mineralization of soil organic matter, in addition to asymbiotic fixation. Note that commercial organic fertilizers (TVA 1991 through 1994 and AAPFCO 1995 through 2011) are addressed with the Tier 1 method because county-level application data would be needed to simulate applications in DAYCENT, and currently data are only available at the national scale. The third and fourth sources are generated internally by the DAYCENT model.

Synthetic fertilizer data are based on fertilizer use and rates by crop type for different regions of the United States that are obtained primarily from the USDA Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of livestock manure application to cropland during 1997 are estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. The adjustments are based on county-scale ratios of manure available for application to soils in other years relative to 1997 (see Annex 3.12 for further details). Greater availability of managed manure N relative to 1997 is assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 is assumed to reduce the amended area. Data on the county-level N available for application is estimated for managed systems based on the total amount of N excreted in manure minus N losses during storage and transport, and including the addition of N from bedding materials. N losses include direct N_2O emissions, volatilization of ammonia and NO_x, runoff and leaching, and poultry manure used as a feed supplement. For unmanaged systems, it is assumed that no N losses or additions occur prior to the application of manure to the soil. More information on livestock manure production is available in the Manure Management Section 5.2 and Annex 3.11.

The IPCC approach considers crop residue N and N mineralized from soil organic matter as activity data. However, they are not treated as activity data in DAYCENT simulations because residue production, symbiotic N fixation (e.g., legumes), mineralization of N from soil organic matter, and asymbiotic N fixation are internally generated by the model as part of the simulation. In other words, DAYCENT accounts for the influence of symbiotic N fixation, mineralization of N from soil organic matter and crop residue retained in the field, and asymbiotic N fixation on N_2O emissions, but these are not model inputs. The N_2O emissions from crop residues are reduced by approximately 3 percent to avoid double-counting associated with non-CO_2 greenhouse gas emissions from agricultural residue burning. The estimate of residue burning is based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, Cibrowski 1996).

Additional sources of data are used to supplement the mineral N (USDA ERS 1997, 2011), livestock manure (Edmonds et al. 2003), and land-use information (USDA-NRCS 2013). The Conservation Technology Information Center (CTIC 2004) provided annual data on tillage activity with adjustments for long-term adoption of no-till agriculture (Towery 2001). Tillage data has an influence on soil organic matter decomposition and subsequent soil N_2O emissions. The time series of tillage data began in 1989 and ended in 2004, so further changes in tillage practices since 2004 are not currently captured in the Inventory. Daily weather data are used as an input in the model simulations, based on gridded weather data at a 32 km scale from the North America Regional Reanalysis Product (NARR) (Mesinger et al. 2006). Soil attributes are obtained from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011).

Each 2010 NRI point is run 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulations for the analysis. Soil N_2O emission estimates from DAYCENT are adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). Soil N_2O emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2010, but

---

[12] See <https://lpdaac.usgs.gov/products/modis_products_table>.

emissions from 2011 to 2014 are assumed to be similar to 2010. Annual data are currently available through 2012 (USDA-NRCS 2015). However, this Inventory only uses NRI data through 2010 because newer data were not available in time to incorporate the additional years into this Inventory.

Nitrous oxide emissions from managed agricultural lands are the result of interactions among anthropogenic activities (e.g., N fertilization, manure application, tillage) and other driving variables, such as weather and soil characteristics. These factors influence key processes associated with N dynamics in the soil profile, including immobilization of N by soil microbial organisms, decomposition of organic matter, plant uptake, leaching, runoff, and volatilization, as well as the processes leading to N_2O production (nitrification and denitrification). It is not possible to partition N_2O emissions into each anthropogenic activity directly from model outputs due to the complexity of the interactions (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). To approximate emissions by activity, the amount of mineral N added to the soil for each of these sources is determined and then divided by the total amount of mineral N that is made available in the soil according to the DAYCENT model. The percentages are then multiplied by the total of direct N_2O emissions in order to approximate the portion attributed to key practices. This approach is only an approximation because it assumes that all N made available in soil has an equal probability of being released as N_2O, regardless of its source, which is unlikely to be the case (Delgado et al. 2009). However, this approach allows for further disaggregation of emissions by source of N, which is valuable for reporting purposes and is analogous to the reporting associated with the IPCC (2006) Tier 1 method, in that it associates portions of the total soil N_2O emissions with individual sources of N.

Tier 1 Approach for Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology is used to estimate direct N_2O emissions for mineral cropland soils that are not simulated by DAYCENT. For the Tier 1 Approach, estimates of direct N_2O emissions from N applications are based on mineral soil N that is made available from the following practices: (1) the application of synthetic commercial fertilizers; (2) application of managed manure and non-manure commercial organic fertilizers; and (3) the retention of above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure, commercial organic amendments is not included in the DAYCENT simulations because county-level data are not available.[13] Consequently, commercial organic fertilizer, as well as additional manure that is not added to crops in the DAYCENT simulations, are included in the Tier 1 analysis. The following sources are used to derive activity data:

- A process-of-elimination approach is used to estimate synthetic N fertilizer additions for crop areas not simulated by DAYCENT. The total amount of fertilizer used on farms has been estimated at the county-level by the USGS from sales records (Ruddy et al. 2006), and these data are aggregated to obtain state-level N additions to farms. For 2002 through 2014, state-level fertilizer for on-farm use is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 1995 through 2007, AAPFCO 2008 through 2014).[14] After subtracting the portion of fertilizer applied to crops and grasslands simulated by DAYCENT (see Tier 3 Approach for Cropland Mineral Soils Section and Grasslands Section for information on data sources), the remainder of the total fertilizer used on farms is assumed to be applied to crops that are not simulated by DAYCENT.
- Similarly, a process-of-elimination approach is used to estimate manure N additions for crops that are not simulated by DAYCENT. The amount of manure N applied in the Tier 3 approach to crops and grasslands is subtracted from total manure N available for land application (see Tier 3 Approach for Cropland Mineral Soils Section and Grasslands Section for information on data sources), and this difference is assumed to be applied to crops that are not simulated by DAYCENT.

---

[13] Commercial organic fertilizers include dried blood, tankage, compost, and other, but the dried manure and sewage sludge is removed from the dataset in order to avoid double counting with other datasets that are used for manure N and sewage sludge.

[14] Values are not available for 2013 so a "least squares line" statistical extrapolation using the previous 5 years of data is used to arrive at an approximate value for 2014.

- Commercial organic fertilizer additions are based on organic fertilizer consumption statistics, which are converted to units of N using average organic fertilizer N content (TVA 1991 through 1994, AAPFCO 1995 through 2011). Commercial fertilizers do include some manure and sewage sludge, but the amounts are removed from the commercial fertilizer data to avoid double counting with the manure N dataset described above and the sewage sludge amendment data discussed later in this section.
- Crop residue N is derived by combining amounts of above- and below-ground biomass, which are determined based on NRI crop area data (USDA-NRCS 2013), crop production yield statistics (USDA-NASS 2014), dry matter fractions (IPCC 2006), linear equations to estimate above-ground biomass given dry matter crop yields from harvest (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and N contents of the residues (IPCC 2006).

The total increase in soil mineral N from applied fertilizers and crop residues is multiplied by the IPCC (2006) default emission factor to derive an estimate of direct N_2O emissions using the Tier 1 Approach.

Drainage of Organic Soils in Croplands and Grasslands

The IPCC (2006) Tier 1 methods are used to estimate direct N_2O emissions due to drainage of organic soils in croplands or grasslands at a state scale. State-scale estimates of the total area of drained organic soils are obtained from the 2010 NRI (USDA-NRCS 2013) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). Temperature data from Daly et al. (1994, 1998) are used to subdivide areas into temperate and tropical climates using the climate classification from IPCC (2006). Annual data are available between 1990 and 2010. Emissions are assumed to be similar to 2010 from 2011 to 2014 because no additional activity data are currently available from the NRI for the latter years. To estimate annual emissions, the total temperate area is multiplied by the IPCC default emission factor for temperate regions, and the total tropical area is multiplied by the IPCC default emission factor for tropical regions (IPCC 2006).

Direct N_2O Emissions from Grassland Soils

As with N_2O from croplands, the Tier 3 process-based DAYCENT model and Tier 1 method described in IPCC (2006) are combined to estimate emissions from non-federal grasslands and PRP manure N additions for federal grasslands, respectively. Grassland includes pasture and rangeland that produce grass forage primarily for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have addition management, such as irrigation or interseeding legumes. DAYCENT is used to simulate N_2O emissions from NRI survey locations (USDA-NRCS 2013) on non-federal grasslands resulting from manure deposited by livestock directly onto pastures and rangelands (i.e., PRP manure), N fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure such as Daily Spread), and synthetic fertilizer application. Other N inputs are simulated within the DAYCENT framework, including N input from mineralization due to decomposition of soil organic matter and N inputs from senesced grass litter, as well as asymbiotic fixation of N from the atmosphere. The simulations used the same weather, soil, and synthetic N fertilizer data as discussed under the Tier 3 Approach for Mineral Cropland Soils section. Managed manure N amendments to grasslands are estimated from Edmonds et al. (2003) and adjusted for annual variation using data on the availability of managed manure N for application to soils, according to methods described in the Manure Management section (5.2 Manure Management (IPCC Source Category 3B)) and Annex 3.11. Biological N fixation is simulated within DAYCENT, and therefore is not an input to the model.

Manure N deposition from grazing animals in PRP systems (i.e., PRP manure) is another key input of N to grasslands. The amounts of PRP manure N applied on non-federal grasslands for each NRI point are based on amount of N excreted by livestock in PRP systems. The total amount of N excreted in each county is divided by the grassland area to estimate the N input rate associated with PRP manure. The resulting input rates are used in the DAYCENT simulations. DAYCENT simulations of non-federal grasslands accounted for approximately 72 percent of total PRP manure N in aggregate across the country. The remainder of the PRP manure N in each state is assumed to be excreted on federal grasslands, and the N_2O emissions are estimated using the IPCC (2006) Tier 1 method with IPCC default emission factors. Sewage sludge is assumed to be applied on grasslands because of the heavy metal content and other pollutants in human waste that limit its use as an amendment to croplands. Sewage sludge application is estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007). Sewage sludge data on soil amendments to agricultural lands are only available at the national scale, and it is not possible to associate application with specific soil conditions and weather at the county scale. Therefore, DAYCENT could not be used to simulate the influence of sewage sludge amendments on N_2O emissions from grassland soils, and consequently, emissions from sewage sludge are estimated using the IPCC (2006) Tier 1 method.

Grassland area data are consistent with the Land Representation reported in the LULUCF chapter. Data are obtained from the U.S. Department of Agriculture NRI (Nusser and Goebel 1998) and the U.S. Geological Survey (USGS) National Land Cover Dataset (Vogelman et al. 2001), which are reconciled with the Forest Inventory and Analysis Data. The area data for pastures and rangeland are aggregated to the county level to estimate non-federal and federal grassland areas.

N_2O emissions for the PRP manure N deposited on federal grasslands and applied sewage sludge N are estimated using the Tier 1 method by multiplying the N input by the appropriate emission factor. Emissions from manure N are estimated at the state level and aggregated to the entire country, but emissions from sewage sludge N are calculated exclusively at the national scale.

As previously mentioned, each NRI point is simulated 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulation runs for the analysis. Soil N_2O emission estimates from DAYCENT are adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). Soil N_2O emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2010, but emissions from 2011 to 2014 are assumed to be similar to 2010. The annual data are currently available through 2012 (USDA-NRCS 2015). However, this Inventory only uses NRI data through 2010 because newer data are not made available in time to incorporate the additional years into this Inventory.

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from the Tier 1 and 3 approaches for cropland mineral soils, from drainage and cultivation of organic cropland soils, and from grassland soils are summed to obtain the total direct N_2O emissions from agricultural soil management (see Table 5-18 and Table 5-19).

Indirect N_2O Emissions

This section describes the methods used for estimating indirect soil N_2O emissions from croplands and grasslands. Indirect N_2O emissions occur when mineral N made available through anthropogenic activity is transported from the soil either in gaseous or aqueous forms and later converted into N_2O. There are two pathways leading to indirect emissions. The first pathway results from volatilization of N as NO_x and NH_3 following application of synthetic fertilizer, organic amendments (e.g., manure, sewage sludge), and deposition of PRP manure. N made available from mineralization of soil organic matter and residue, including N incorporated into crops and forage from symbiotic N fixation, and input of N from asymbiotic fixation also contributes to volatilized N emissions. Volatilized N can be returned to soils through atmospheric deposition, and a portion of the deposited N is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil N (primarily in the form of NO_3) that is made available through anthropogenic activity on managed lands, mineralization of soil organic matter and residue, including N incorporated into crops and forage from symbiotic N fixation, and inputs of N into the soil from asymbiotic fixation. The NO_3^- is subject to denitrification in water bodies, which leads to N_2O emissions. Regardless of the eventual location of the indirect N_2O emissions, the emissions are assigned to the original source of the N for reporting purposes, which here includes croplands and grasslands.

Indirect N_2O Emissions from Atmospheric Deposition of Volatilized N

The Tier 3 DAYCENT model and IPCC (2006) Tier 1 methods are combined to estimate the amount of N that is volatilized and eventually emitted as N_2O. DAYCENT is used to estimate N volatilization for land areas whose direct emissions are simulated with DAYCENT (i.e., most commodity and some specialty crops and most grasslands). The N inputs included are the same as described for direct N_2O emissions in the Tier 3 Approach for Cropland Mineral Soils Section and Grasslands Section. N volatilization for all other areas is estimated using the Tier 1 method and default IPCC fractions for N subject to volatilization (i.e., N inputs on croplands not simulated by DAYCENT, PRP manure N excreted on federal grasslands, sewage sludge application on grasslands). For the volatilization data generated from both the DAYCENT and Tier 1 approaches, the IPCC (2006) default emission factor is used to estimate indirect N_2O emissions occurring due to re-deposition of the volatilized N (Table 5-21).

Indirect N_2O Emissions from Leaching/Runoff

As with the calculations of indirect emissions from volatilized N, the Tier 3 DAYCENT model and IPCC (2006) Tier 1 method are combined to estimate the amount of N that is subject to leaching and surface runoff into water bodies, and eventually emitted as N_2O. DAYCENT is used to simulate the amount of N transported from lands in the Tier 3 Approach. N transport from all other areas is estimated using the Tier 1 method and the IPCC (2006) default factor for the proportion of N subject to leaching and runoff. This N transport estimate includes N applications on croplands that are not simulated by DAYCENT, sewage sludge amendments on grasslands, and PRP manure N excreted on federal grasslands. For both the DAYCENT Tier 3 and IPCC (2006) Tier 1 methods, nitrate leaching is assumed to be an insignificant source of indirect N_2O in cropland and grassland systems in arid regions as discussed in IPCC (2006). In the United States, the threshold for significant nitrate leaching is based on the potential evapotranspiration (PET) and rainfall amount, similar to IPCC (2006), and is assumed to be negligible in regions where the amount of precipitation plus irrigation does not exceed 80 percent of PET. For leaching and runoff data estimated by the Tier 3 and Tier 1 approaches, the IPCC (2006) default emission factor is used to estimate indirect N_2O emissions that occur in groundwater and waterways (Table 5-21).

Uncertainty and Time-Series Consistency

Uncertainty is estimated for each of the following five components of N_2O emissions from agricultural soil management: (1) direct emissions simulated by DAYCENT; (2) the components of indirect emissions (N volatilized and leached or runoff) simulated by DAYCENT; (3) direct emissions approximated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) approximated with the IPCC (2006) Tier 1 method; and (5) indirect emissions estimated with the IPCC (2006) Tier 1 method. Uncertainty in direct emissions, which account for the majority of N_2O emissions from agricultural management, as well as the components of indirect emissions calculated by DAYCENT are estimated with a Monte Carlo Analysis, addressing uncertainties in model inputs and structure (i.e., algorithms and parameterization) (Del Grosso et al. 2010). Uncertainties in direct emissions calculated with the IPCC (2006) Approach 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Approach 1 method, and indirect N_2O emissions are estimated with a simple error propagation approach (IPCC 2006). Uncertainties from the Approach 1 and Approach 3 (i.e., DAYCENT) estimates are combined using simple error propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.12. The combined uncertainty for direct soil N_2O emissions ranged from 16 percent below to 24 percent above the 2014 emissions estimate of 261.3 MMT CO_2 Eq., and the combined uncertainty for indirect soil N_2O emissions range from 46 percent below to 139 percent above the 2014 estimate of 57.2 MMT CO_2 Eq.

Table 5-22: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2014 (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N_2O Emissions	N_2O	261.3	220.6	324.9	-16%	24%
Indirect Soil N_2O Emissions	N_2O	57.2	30.8	136.6	-46%	139%

Notes: Due to lack of data, uncertainties in managed manure N production, PRP manure N production, other organic fertilizer amendments, and sewage sludge amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventories.

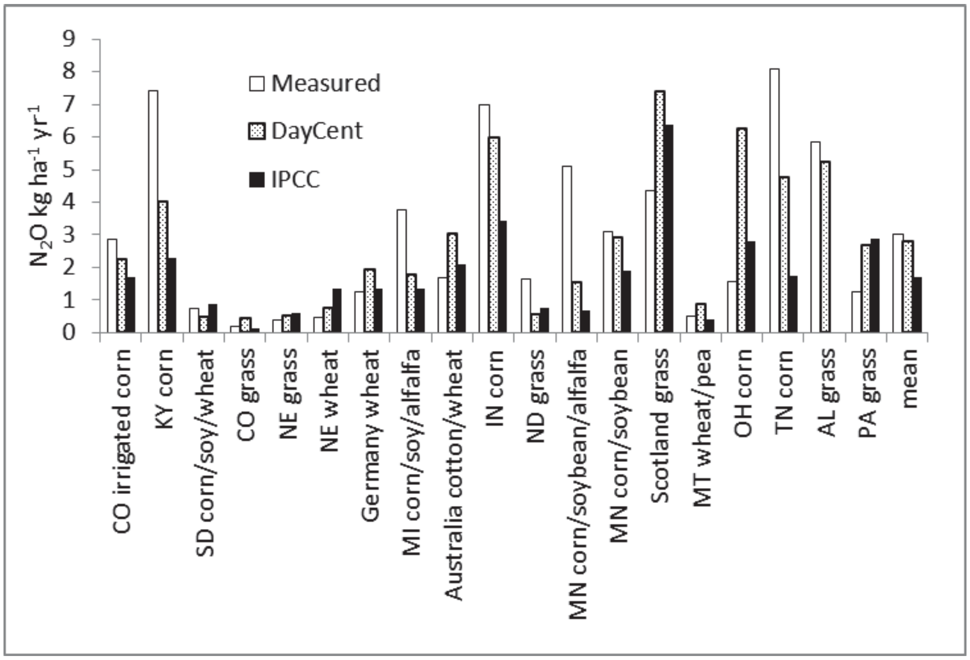
Additional uncertainty is associated with the lack of an estimation of N_2O emissions for croplands and grasslands in Hawaii and Alaska, with the exception of drainage for organic soils in Hawaii. Agriculture is not extensive in either state, so the emissions are likely to be small compared to the conterminous United States.

Methodological recalculations are applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends are described in more detail in the Methodology section above.

QA/QC and Verification

DAYCENT results for N_2O emissions and NO_3^- leaching are compared with field data representing various cropland and grassland systems, soil types, and climate patterns (Del Grosso et al. 2005, Del Grosso et al. 2008), and further evaluated by comparing the model results to emission estimates produced using the IPCC (2006) Tier 1 method for the same sites. N_2O measurement data are available for 26 sites in the United States, 4 in Europe, and one in Australia, representing over 75 different combinations of fertilizer treatments and cultivation practices. DAYCENT estimates of N_2O emissions are closer to measured values at most sites compared to the IPCC Tier 1 estimate (Figure 5-7). In general, IPCC Tier 1 methodology tends to over-estimate emissions when observed values are low and under-estimate emissions when observed values are high, while DAYCENT estimates have less bias. DAYCENT accounts for key site-level factors (weather, soil characteristics, and management) that are not addressed in the IPCC Tier 1 Method, and thus the model is better able to represent the variability in N_2O emissions. Nitrate leaching data are available for four sites in the United States, representing 12 different combinations of fertilizer amendments/tillage practices. DAYCENT does have a tendency to under-estimate very high N_2O emission rates; and estimates are adjusted using the statistical model derived from the comparison of model estimates to measurements (See Annex 3.12 for more information). Regardless, the comparison demonstrates that DAYCENT provides relatively high predictive capability for N_2O emissions and NO_3^- leaching, and is an improvement over the IPCC Tier 1 method.

Figure 5-7: Comparison of Measured Emissions at Field Sites and Modeled Emissions Using the DAYCENT Simulation Model and IPCC Tier 1 Approach.



Spreadsheets containing input data and probability distribution functions required for DAYCENT simulations of croplands and grasslands and unit conversion factors have been checked, in addition to the program scripts that are used to run the Monte Carlo uncertainty analysis. Links between spreadsheets have been checked, updated, and corrected when necessary. Spreadsheets containing input data, emission factors, and calculations required for the Tier 1 approach have been checked and updated as needed. Quality control is still underway and may lead to further changes in the next Inventory report.

Recalculations Discussion

Methodological recalculations in the current Inventory are associated with the following improvements: (1) Driving the DAYCENT simulations with updated input data for land management from the National Resources Inventory extending the time series through 2010; (2) accounting for N inputs from residues associated with additional crops not simulated by DAYCENT including most vegetable crops; (3) modifying the number of experimental study sites used to quantify model uncertainty for direct N_2O emissions; and (4) using DAYCENT for direct N_2O emissions from most flooded rice lands, instead of using the Tier 1 approach for all rice lands. These changes resulted in an increase in emissions of approximately 24 percent on average relative to the previous Inventory and a decrease in the upper bound of the 95 percent confidence interval for direct N_2O emissions from 26 to 24 percent. The differences are mainly due to increasing the number of study sites used to quantify model uncertainty and correct bias.

Planned Improvements

Several planned improvements are underway:

(1) Improvements are underway to update the time series of land use and management data from the 2012 USDA NRI so that the time series of activity data are extended through 2012. Fertilization and tillage activity data will also be updated as part of this improvement. In addition, the remote-sensing based data on the Enhanced Vegetation Index will be extended through 2012 in order to use the EVI data to drive crop production in DAYCENT.

(2) Improvements in the DAYCENT biogeochemical model are underway. Model structure will be improved with a better representation of plant phenology, particularly senescence events following grain filling in crops, such as wheat. In addition, crop parameters associated with temperature effects on plant production will be further improved in DAYCENT with additional model calibration. An improved representation of drainage is also under development. Experimental study sites will continue to be added for quantifying model structural uncertainty, and studies that have continuous (daily) measurements of N_2O (e.g., Scheer et al. 2013) will be given priority because they provide more robust estimates of annual emissions compared to studies that sample trace gas emissions weekly or less frequently.

(3) Improvements are also underway to account for the influence of nitrification inhibitors and slow-release fertilizers (e.g., polymer-coated fertilizers). Field data suggests that nitrification inhibitors and slow-release fertilizers reduce N_2O emissions significantly. The DAYCENT model can represent nitrification inhibitors and slow-release fertilizers, but accounting for these in national simulations is contingent on testing the model with a sufficient number of field studies and collection of activity data about the use of these fertilizers;

(4) Improvements are underway to simulate crop residue burning in the DAYCENT model based on the amount of crop residues burned according to the data that is used in the Field Burning of Agricultural Residues source category (Section 5.5). See the Planned Improvement section in the Field Burning of Agricultural Residues for more information.

(5) Alaska and Hawaii are not included in the current Inventory for agricultural soil management, with the exception of N_2O emissions from drained organic soils in croplands and grasslands for Hawaii. A planned improvement over the next two years is to add these states into the Inventory analysis.

5.5 Field Burning of Agricultural Residues (IPCC Source Category 3F)

Crop production creates large quantities of agricultural crop residues, which farmers manage in a variety of ways. For example, crop residues can be left in the field and possibly incorporated into the soil with tillage; collected and used as fuel, animal bedding material, supplemental animal feed, or construction material; composted and applied to soils; transported to landfills; or burned in the field. Field burning of crop residues is not considered a net source of CO_2 emissions because the C released to the atmosphere as CO_2 during burning is reabsorbed during the next growing season for the crop. However, crop residue burning is a net source of CH_4, N_2O, CO, and NO_x, which are released during combustion.

In the United States, field burning of agricultural residues commonly occurs in southeastern states, the Great Plains, and the Pacific Northwest (McCarty 2011). The primary crops that are managed with residue burning include corn, cotton, lentils, rice, soybeans, sugarcane, and wheat (McCarty 2009). Rice, sugarcane, and wheat residues account for approximately 70 percent of all crop residue burning and emissions (McCarty 2011). In 2014, CH_4 and N_2O emissions from Field Burning of Agricultural Residues were 0.3 MMT CO_2 Eq. (11 kt) and 0.1 MMT. CO_2 Eq. (0.3 kt), respectively. Furthermore, annual emissions from this source from 1990 to 2014 have remained relatively constant, averaging approximately 0.3 MMT CO_2 Eq. (10 kt) of CH_4 and 0.1 MMT CO_2 Eq. (0.3 kt) of N_2O (see Table 5-23 and Table 5-24).

Table 5-23: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq.)

Gas/Crop Type	1990	2005	2010	2011	2012	2013	2014
CH_4	**0.2**	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Wheat	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	+	0.1	0.1	0.1	0.1	0.1
Sugarcane	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Lentil	+	+	+	+	+	+	+
N_2O	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Wheat	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Lentil	+	+	+	+	+	+	+
Total	**0.3**	**0.3**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**

\+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 5-24: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (kt)

Gas/Crop Type	1990	2005	2010	2011	2012	2013	2014
CH_4	**10**	**8**	**11**	**11**	**11**	**11**	**11**
Wheat	5	4	5	5	5	5	5
Rice	2	2	2	2	2	2	2
Sugarcane	1	1	1	1	1	1	2
Corn	1	1	1	1	1	1	2
Soybeans	1	1	1	1	1	1	1
Lentil	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+

N_2O	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Wheat	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Lentil	+	+	+	+	+	+	+
CO	**201**	**177**	**229**	**232**	**233**	**237**	**238**
NO_x	**6**	**6**	**7**	**7**	**8**	**8**	**8**

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding

Methodology

A U.S.-specific Tier 2 method was used to estimate greenhouse gas emissions from Field Burning of Agricultural Residues (for more details, see Box 5-3). In order to estimate the amounts of C and N released during burning, the following equation was used:

$$\text{C or N released} = \Sigma \text{ for all crop types and states} \left[\frac{AB}{CAH \times CP \times RCR \times DMF \times BE \times CE \times (FC \text{ or } FN)}\right]$$

where,

Area Burned (AB) = Total area of crop burned, by state
Crop Area Harvested (CAH) = Total area of crop harvested, by state
Crop Production (CP) = Annual production of crop in kt, by state
Residue: Crop Ratio (RCR) = Amount of residue produced per unit of crop production
Dry Matter Fraction (DMF) = Amount of dry matter per unit of biomass for a crop
Fraction of C or N (FC or FN) = Amount of C or N per unit of dry matter for a crop
Burning Efficiency (BE) = The proportion of prefire fuel biomass consumed[15]
Combustion Efficiency (CE) = The proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively

Crop Production and Crop Area Harvested were available by state and year from USDA (2014) for all crops (except rice in Florida and Oklahoma, as detailed below). The amount C or N released was used in the following equation to determine the CH_4, CO, N_2O and NO_x emissions from the field burning of agricultural residues:

$$CH_4 \text{ and CO, or } N_2O \text{ and } NO_x \text{ Emissions from Field Burning of Agricultural Residues} =$$

$$\text{C or N Released} \times ER \times CF$$

where,

Emissions Ratio (ER) = g CH_4-C or CO-C/g C released, or g N_2O-N or NO_x-N/g N released
Conversion Factor (CF) = conversion, by molecular weight ratio, of CH_4-C to C (16/12), or CO-C to C (28/12), or N_2O-N to N (44/28), or NO_x-N to N (30/14)

Box 5-3: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from Field Burning of Agricultural Residues were calculated using a Tier 2 methodology that is based on method developed by the IPCC/UNEP/OECD/IEA (1997) and incorporates crop- and country-specific emission factors and variables. The rationale for using the IPCC/UNEP/OECD/IEA (1997) approach rather than the method

---

[15] In IPCC/UNEP/OECD/IEA (1997), the equation for C or N released contains the variable 'fraction oxidized in burning'. This variable is equivalent to (burning efficiency × combustion efficiency).

provided in the *2006 IPCC Guidelines* is as follows: (1) the equations from both guidelines rely on the same underlying variables (though the formats differ); (2) the IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues; and (3) the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this Inventory includes emissions from seven crops (corn, cotton, lentils, rice, soybeans, sugarcane, and wheat).

A comparison of the methods and factors used in: (1) The current Inventory and (2) the default IPCC (2006) approach was undertaken in the 1990 through 2014 Inventory report to determine the difference in overall estimates between the two approaches. To estimate greenhouse gas emissions from Field Burning of Agricultural Residue using the IPCC (2006) methodology, the following equation—cf. IPCC (2006) Equation 2.27—was used:

$$\text{Emissions (kt)} = AB \times (M_B \times C_f) \times G_{ef} \times 10^{-6}$$

where,

Area Burned (AB) = Total area of crop burned (ha)
Mass Burned ($M_B \times C_f$) = IPCC (2006) default fuel biomass consumption (metric tons dry matter burnt ha^{-1})
Emission Factor (G_{ef}) = IPCC (2006) emission factor (g kg^{-1} dry matter burnt)

The IPCC (2006) default approach resulted in 5 percent higher emissions of CH_4 and 21 percent higher emissions of N_2O compared to this Inventory (and are within the uncertainty ranges estimated for this source category). The IPCC/UNEP/OECD/IEA (1997) is considered a more appropriate method for U.S. conditions because it is more flexible for incorporating country-specific data compared to IPCC (2006) approach for Tier 1 and 2 methods.

Crop yield data (except rice in Florida) were based on USDA's QuickStats (USDA 2015), and crop area data were based on the 2010 National Resources Inventory (NRI) (USDA 2013). In order to estimate total crop production, the crop yield data from USDA Quick Stats crop yields was multiplied by the NRI crop areas. Rice yield data for Florida was estimated separately because yield data were not collected by USDA. Total rice production for Florida was determined using NRI crop areas and total yields were based on average primary and ratoon rice yields from Schueneman and Deren (2002). Relative proportions of ratoon crops were derived from information in several publications (Schueneman 1999, 2000, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007 through 2014). The production data for the crop types whose residues are burned are presented in Table 5-25. Crop weight by bushel was obtained from Murphy (1993).

The fraction of crop area burned was calculated using data on area burned by crop type and state[16] from McCarty (2010) for corn, cotton, lentils, rice, soybeans, sugarcane, and wheat.[17] McCarty (2010) used remote sensing data from Moderate Resolution Imaging Spectroradiometer (MODIS) to estimate area burned by crop. State-level area burned data were divided by state-level crop area harvested data to estimate the percent of crop area burned by crop type for each state. The average percentage of crop area burned at the national scale is shown in Table 5-26. Data on fraction of crop area burned were only available from McCarty (2010) for the years 2003 through 2007. For other years in the time series, the percent area burned was set equal to the average over the five-year period from 2003 to 2007. Table 5-26 shows the resulting percentage of crop residue burned at the national scale by crop type. State-level estimates are also available upon request.

All residue: crop product mass ratios except sugarcane and cotton were obtained from Strehler and Stützle (1987). The ratio for sugarcane is from Kinoshita (1988) and the ratio for cotton is from Huang et al. (2007). The residue: crop ratio for lentils was assumed to be equal to the average of the values for peas and beans. Residue dry matter fractions for all crops except soybeans, lentils, and cotton were obtained from Turn et al. (1997). Soybean and lentil dry matter fractions were obtained from Strehler and Stützle (1987); the value for lentil residue was assumed to

---

[16] Alaska and Hawaii were excluded.

[17] McCarty (2009) also examined emissions from burning of Kentucky bluegrass and a general "other crops/fallow" category, but USDA crop area and production data were insufficient to estimate emissions from these crops using the methodology employed in the Inventory. McCarty (2009) estimates that approximately 18 percent of crop residue emissions result from burning of the Kentucky bluegrass and "other crops" categories.

equal the value for bean straw. The cotton dry matter fraction was taken from Huang et al. (2007). The residue C contents and N contents for all crops except soybeans and cotton are from Turn et al. (1997). The residue C content for soybeans is the IPCC default (IPCC/UNEP/OECD/IEA 1997), and the N content of soybeans is from Barnard and Kristoferson (1985). The C and N contents of lentils were assumed to equal those of soybeans. The C and N contents of cotton are from Lachnicht et al. (2004). The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent, for all crop types, except sugarcane (EPA 1994). For sugarcane, the burning efficiency was assumed to be 81 percent (Kinoshita 1988) and the combustion efficiency was assumed to be 68 percent (Turn et al. 1997). See Table 5-27 for a summary of the crop-specific conversion factors. Emission ratios and mole ratio conversion factors for all gases were based on the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) (see Table 5-28).

Table 5-25: Agricultural Crop Production (kt of Product)

Crop	1990	2005	2010	2011	2012	2013	2014
Corn[a]	229,152	300,826	335,526	321,791	270,180	350,338	378,432
Cotton	4,446	6,811	4,814	4,369	5,156	4,841	5,104
Lentils	38	248	406	234	251	271	156
Rice	8,903	12,577	11,372	11,791	12,543	12,928	12,869
Soybeans	55,129	86,903	94,445	90,746	86,910	95,454	103,570
Sugarcane	31,827	32,496	30,333	32,469	34,925	34,186	34,160
Wheat	79,011	70,074	71,017	62,131	71,094	68,772	64,748

[a] Corn for grain (i.e., excludes corn for silage).

Table 5-26: U.S. Average Percent Crop Area Burned by Crop (Percent)

State	1990	2005	2010	2011	2012	2013	2014
Corn	+	+	+	+	+	+	+
Cotton	1 %	1 %	1 %	1 %	1 %	1 %	1 %
Lentils	2 %	+	+	1 %	1 %	1 %	1 %
Rice	9 %	5 %	7 %	7 %	7 %	7 %	7 %
Soybeans	+	+	+	+	+	+	+
Sugarcane	10 %	14 %	23 %	25 %	23 %	22 %	24 %
Wheat	2 %	2 %	2 %	3 %	2 %	2 %	2 %

+ Does not exceed 0.5 percent

Table 5-27: Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue: Crop Ratio	Dry Matter Fraction	C Fraction	N Fraction	Burning Efficiency (Fraction)	Combustion Efficiency (Fraction)
Corn	1.0	0.91	0.448	0.006	0.93	0.88
Cotton	1.6	0.90	0.445	0.012	0.93	0.88
Lentils	2.0	0.85	0.450	0.023	0.93	0.88
Rice	1.4	0.91	0.381	0.007	0.93	0.88
Soybeans	2.1	0.87	0.450	0.023	0.93	0.88
Sugarcane	0.2	0.62	0.424	0.004	0.81	0.68
Wheat	1.3	0.93	0.443	0.006	0.93	0.88

Table 5-28: Greenhouse Gas Emission Ratios and Conversion Factors

Gas	Emission Ratio	Conversion Factor
CH_4:C	0.005[a]	16/12
CO:C	0.060[a]	28/12
N_2O:N	0.007[b]	44/28
NO_x:N	0.121[b]	30/14

[a] Mass of C compound released (units of C) relative to mass of total C released from burning (units of C).

[b] Mass of N compound released (units of N) relative to mass of total N released from burning (units of N).

Uncertainty and Time-Series Consistency

The results of the Approach 2 Monte Carlo uncertainty analysis are summarized in Table 5-29. CH_4 emissions from Field Burning of Agricultural Residues in 2014 were estimated to be between 0.18 and 0.44 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 41 percent below and 42 percent above the 2014 emission estimate of 0.3 MMT CO_2 Eq. Also at the 95 percent confidence level, N_2O emissions were estimated to be between 0.07 and 0.14 MMT CO_2 Eq., or approximately 30 percent below and 31 percent above the 2014 emission estimate of 0.1 MMT CO_2 Eq.

Table 5-29: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH_4	0.3	0.18	0.44	-41%	42%
Field Burning of Agricultural Residues	N_2O	0.1	0.07	0.14	-30%	31%

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

Due to data limitations, there are additional uncertainties in agricultural residue burning due to the omission of burning associated with Kentucky bluegrass and "other crop" residues.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above

QA/QC and Verification

A source-specific QA/QC plan for Field Burning of Agricultural Residues was implemented with Tier 1 and 2 analyses. The Tier 1 analysis conducted this year uncovered a data transcription error in the corn production data for 1990. No other errors were found.

Recalculations Discussion

The source data for crop areas was changed from USDA NASS QuickStats to the 2010 National Resources Inventory (NRI). This change ensures greater consistency across cropland source categories, including direct and indirect soil nitrous oxide emissions in Section 5.4 Agricultural Soil Management, and soil carbon stock changes in the *Cropland Remaining Cropland* and *Land Converted to Cropland* sections, which also rely on the NRI data as the basis for crop areas. The NRI data were used to recalculate percent crop area burned and total crop production. This change resulted in higher crop production estimates (ranging from 4 to 40 percent) and lower burned area percentages (ranging from -2 to -42 percent) relative to the previous method. However, the overall impact on the recalculated emissions was relatively small, with CH_4 and N_2O emissions decreasing by 13 and 8 percent respectively. In addition, correcting a transcription error in crop production for corn in 1990 (Table 5-25) led to a larger recalculation in emissions for 1990 relative to the other years.

Planned Improvements

A new method is in development that will directly link agricultural residue burning with the Tier 3 methods that are used in the Agricultural Soil Management, *Cropland Remaining Cropland*, and *Land Converted to Cropland* chapters of the Inventory. The method is based on the DAYCENT model, and burning events will be simulated directly within the process-based model framework using information derived from remote sensing fire products. This improvement will lead to greater consistency in the methods for these sources, and better ensure mass balance of C and N in the inventory analysis.

6. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the net greenhouse gas flux resulting from the use and conversion of land-use categories in the United States.[1] The Intergovernmental Panel on Climate Change *2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) recommends reporting fluxes according to changes within and conversions between certain land-use types termed: Forest Land, Cropland, Grassland, Settlements, Wetlands (as well as Other Land). The greenhouse gas flux from *Forest Land Remaining Forest Land* is reported using estimates of changes in forest ecosystem carbon (C) stocks, harvested wood pools, non-carbon dioxide (non-CO_2) emissions from forest fires, and the application of synthetic fertilizers to forest soils. Fluxes are also included for forest ecosystem pools for *Land Converted to Forest Land*. [2] The greenhouse gas flux from agricultural lands (i.e., Cropland and Grassland) that is reported in this chapter includes changes in organic C stocks in mineral and organic soils due to land use and management, and emissions of CO_2 due to the application of crushed limestone and dolomite to managed land (i.e., soil liming) and urea fertilization.[3] Fluxes are reported for four agricultural land use/land-use change categories: *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland,* and *Land Converted to Grassland*. Fluxes from *Wetlands Remaining Wetlands* include CO_2, CH_4 and N_2O emissions from managed peatlands; estimates for *Land Converted to Wetlands* are currently not available. Fluxes resulting from *Settlements Remaining Settlements* include those from urban trees and soil fertilization; fluxes from *Land Converted to Settlement* are currently not available. Landfilled yard trimmings and food scraps are accounted for separately under *Other*.

Land use, land-use change, and forestry activities in 2014 resulted in a C sequestration (i.e., total sinks) of 685.8 MMT CO_2 Eq.[4] (187.0 MMT C).[5] This represents an offset of approximately 10.0 percent of total (i.e., gross) greenhouse gas emissions in 2014. Emissions from land use, land-use change, and forestry activities in 2014 represent 0.4 percent of total greenhouse gas emissions.[6]

Total land use, land-use change, and forestry C sequestration decreased by approximately 2.6 percent between 1990 and 2014. This increase was primarily due to a decrease in the rate of net C accumulation in agricultural soil carbon

---

[1] The term "flux" is used to describe the net emissions of greenhouse gases to the atmosphere 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".

[2] Estimates from *Land Converted to Forest Land* are currently under development.

[3] Direct and indirect emissions of N_2O from inputs of N to cropland and grassland soils are included in the Agriculture Chapter.

[4] Following the revised reporting requirements under the UNFCCC, this Inventory report presents CO_2 equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

[5] Net flux from LULUCF includes the positive C sequestration reported for *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Other Land* plus the loss in C sequestration reported for *Land Converted to Cropland* and *Grassland Remaining Grassland*.

[6] LULUCF emissions include the CO_2, CH_4, and N_2O emissions reported for *Forest Fires, Forest Soils, Liming, Urea Fertilization, Settlement Soils,* and *Peatlands Remaining Peatlands*.

stocks.[7] Net C accumulation in *Forest Land Remaining Forest Land*, *Land Converted to Grassland*, and *Settlements Remaining Settlements* increased, while net C accumulation in *Cropland Remaining Cropland, Grassland Remaining Grassland*, and *Landfilled Yard Trimmings and Food Scraps* slowed over this period. Emissions from *Land Converted to Cropland* and *Wetlands Remaining Wetlands* decreased. Emissions and removals for Land Use, Land-Use Change, and Forestry are summarized in Table 6-1 by land-use and category.

Table 6-1: Emissions and Removals (Flux) from Land Use, Land-Use Change, and Forestry by Land Use and Land-Use Change Category (MMT CO_2 Eq.)

Land-Use/Source Category	1990	2005	2010	2011	2012	2013	2014
Forest Land Remaining Forest Land	**(570.5)**	**(515.5)**	**(579.1)**	**(566.6)**	**(558.0)**	**(567.5)**	**(570.7)**
Changes in Forest Carbon Stock[a]	(576.0)	(532.4)	(585.0)	(578.1)	(576.7)	(580.1)	(583.4)
Forest Fires	5.4	16.5	5.4	11.0	18.3	12.2	12.2
Forest Soils[b]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Land Converted to Forest Land							
Changes in Forest Carbon Stock							
Cropland Remaining Cropland	**(36.1)**	**(8.7)**	**3.9**	**(12.1)**	**(8.5)**	**(8.6)**	**(7.3)**
Changes in Agricultural Soil Carbon Stock	(43.2)	(16.5)	(4.7)	(20.0)	(18.7)	(16.8)	(16.0)
Liming	4.7	4.3	4.8	3.9	6.0	3.9	4.1
Urea Fertilization	2.4	3.5	3.8	4.1	4.2	4.3	4.5
Land Converted to Cropland	**22.8**	**14.6**	**15.6**	**14.2**	**14.5**	**14.8**	**14.7**
Changes in Agricultural Soil Carbon Stock	22.8	14.6	15.6	14.2	14.5	14.8	14.7
Grassland Remaining Grassland	**(12.9)**	**2.9**	**2.6**	**11.3**	**11.7**	**11.9**	**11.9**
Changes in Agricultural Soil Carbon Stock	(12.9)	2.9	2.6	11.3	11.7	11.9	11.9
Land Converted to Grassland	**(8.5)**	**(12.8)**	**(12.3)**	**(11.0)**	**(10.9)**	**(10.9)**	**(10.9)**
Changes in Agricultural Soil Carbon Stock	(8.5)	(12.8)	(12.3)	(11.0)	(10.9)	(10.9)	(10.9)
Settlements Remaining Settlements	**(59.0)**	**(78.2)**	**(83.8)**	**(84.8)**	**(85.8)**	**(87.1)**	**(88.2)**
Changes in Urban Tree Carbon Stock[c]	(60.4)	(80.5)	(86.1)	(87.3)	(88.4)	(89.5)	(90.6)
Settlement Soils[d]	1.4	2.3	2.4	2.5	2.5	2.4	2.4
Wetlands Remaining Wetlands	**1.1**	**1.1**	**1.0**	**0.9**	**0.8**	**0.8**	**0.8**
Peatlands Remaining Peatlands	1.1	1.1	1.0	0.9	0.8	0.8	0.8
Other	**(26.0)**	**(11.4)**	**(13.2)**	**(12.7)**	**(12.2)**	**(11.7)**	**(11.6)**
Landfilled Yard Trimmings and Food Scraps	(26.0)	(11.4)	(13.2)	(12.7)	(12.2)	(11.7)	(11.6)
LULUCF Emissions[e]	**15.0**	**28.2**	**17.8**	**22.9**	**32.3**	**24.1**	**24.6**
LULUCF Total Net Flux[f]	**(704.2)**	**(636.1)**	**(683.2)**	**(683.6)**	**(680.8)**	**(682.4)**	**(685.8)**
LULUCF Sector Total[g]	**(689.1)**	**(607.9)**	**(665.3)**	**(660.7)**	**(648.5)**	**(658.3)**	**(661.3)**

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

[a] Includes the effects of net additions to stocks of carbon stored in forest ecosystem pools and harvested wood products.

[b] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land*, and *Land Converted to Forest Land*, but not from land-use conversion.

[c] Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[d] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*, but not from land-use conversion.

[e] LULUCF emissions include the CO_2, CH_4, and N_2O emissions reported for *Forest Fires, Forest Soils, Liming, Urea Fertilization, Settlement Soils,* and *Peatlands Remaining Peatlands.*

[f] Total net flux from LULUCF are only included in the Net Emissions total. Net flux from LULUCF includes the positive C sequestration reported for *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Other Land* plus the loss in C sequestration reported for *Land Converted to Cropland* and *Grassland Remaining Grassland*.

[g] The LULUCF Sector Total is sum of positive emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO_2 (i.e., sinks or negative emissions) from the atmosphere.

Carbon dioxide removals are presented in Table 6-2 along with CO_2, CH_4, and N_2O emissions from Land use, Land-Use Change, and Forestry source categories. Liming and urea fertilization in 2014 resulted in CO_2 emissions of 8.7 MMT CO_2 Eq. (8,653 kt of CO_2). Lands undergoing peat extraction (i.e., *Peatlands Remaining Peatlands*) resulted

---

[7] Carbon sequestration estimates are net figures. The C stock in a given pool fluctuates due to both gains and losses. When losses exceed gains, the C stock decreases, and the pool acts as a source. When gains exceed losses, the C stock increases, and the pool acts as a sink; also referred to as net C sequestration or removal.

in CO_2 emissions of 0.8 MMT CO_2 Eq. (842 kt of CO_2), methane (CH_4) emissions of less than 0.05 MMT CO_2 Eq., and nitrous oxide (N_2O) emissions of less than 0.05 MMT CO_2 Eq. The application of synthetic fertilizers to forest soils in 2014 resulted in N_2O emissions of 0.5 MMT CO_2 Eq. (2 kt of N_2O). Nitrous oxide emissions from fertilizer application to forest soils have increased by 455 percent since 1990, but still account for a relatively small portion of overall emissions. Additionally, N_2O emissions from fertilizer application to settlement soils in 2014 accounted for 2.4 MMT CO_2 Eq. (8 kt of N_2O). This represents an increase of 78 percent since 1990. Forest fires in 2014 resulted in CH_4 emissions of 7.3 MMT CO_2 Eq. (294 kt of N_2O), and in N_2O emissions of 4.8 MMT CO_2 Eq. (16 kt of N_2O). Emissions and removals for Land Use, Land-Use Change, and Forestry are shown in Table 6-2 and Table 6-3.

Table 6-2: Emissions and Removals (Flux) from Land Use, Land-Use Change, and Forestry by Gas (MMT CO_2 Eq.)

Gas/Land-Use Category	1990	2005	2010	2011	2012	2013	2014
Net CO_2 Flux[a]	**(704.2)**	**(636.1)**	**(683.2)**	**(683.6)**	**(680.8)**	**(682.4)**	**(685.8)**
Forest Land Remaining Forest Land[b]	(576.0)	(532.4)	(585.0)	(578.1)	(576.7)	(580.1)	(583.4)
Land Converted to Forest Land							
Cropland Remaining Cropland	(43.2)	(16.5)	(4.7)	(20.0)	(18.7)	(16.8)	(16.0)
Land Converted to Cropland[a]	22.8	14.6	15.6	14.2	14.5	14.8	14.7
Grassland Remaining Grassland[a]	(12.9)	2.9	2.6	11.3	11.7	11.9	11.9
Land Converted to Grassland	(8.5)	(12.8)	(12.3)	(11.0)	(10.9)	(10.9)	(10.9)
Settlements Remaining Settlements[c]	(60.4)	(80.5)	(86.1)	(87.3)	(88.4)	(89.5)	(90.6)
Other: Landfilled Yard Trimmings and Food Scraps	(26.0)	(11.4)	(13.2)	(12.7)	(12.2)	(11.7)	(11.6)
CO_2	**8.1**	**9.0**	**9.6**	**8.9**	**11.0**	**9.0**	**9.5**
Cropland Remaining Cropland: Liming	4.7	4.3	4.8	3.9	6.0	3.9	4.1
Cropland Remaining Cropland: Urea Fertilization	2.4	3.5	3.8	4.1	4.2	4.3	4.5
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.1	1.1	1.0	0.9	0.8	0.8	0.8
CH_4	**3.3**	**9.9**	**3.3**	**6.6**	**11.1**	**7.3**	**7.4**
Forest Land Remaining Forest Land: Forest Fires	3.3	9.9	3.3	6.6	11.1	7.3	7.3
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N_2O	**3.6**	**9.3**	**5.0**	**7.3**	**10.3**	**7.7**	**7.7**
Forest Land Remaining Forest Land: Forest Fires	2.2	6.5	2.2	4.4	7.3	4.8	4.8
Forest Land Remaining Forest Land: Forest Soils[d]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Settlements Remaining Settlements: Settlement Soils[e]	1.4	2.3	2.4	2.5	2.5	2.4	2.4
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
LULUCF Emissions[f]	**15.0**	**28.2**	**17.8**	**22.9**	**32.3**	**24.1**	**24.6**
LULUCF Total Net Flux[a]	**(704.2)**	**(636.1)**	**(683.2)**	**(683.6)**	**(680.8)**	**(682.4)**	**(685.8)**
LULUCF Sector Total[g]	**(689.1)**	**(607.9)**	**(665.3)**	**(660.7)**	**(648.5)**	**(658.3)**	**(661.3)**

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

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Total net flux from LULUCF is only included in the Net Emissions total. Net flux from LULUCF includes the positive C sequestration reported for *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Other Land* plus the loss in C sequestration reported for *Land Converted to Cropland* and *Grassland Remaining Grassland*.

[b] Includes the effects of net additions to stocks of carbon stored in forest ecosystem pools and harvested wood products.

[c] Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[d] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land*, and *Land Converted to Forest Land*, but not from land-use conversion.

[e] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*, but not from land-use conversion.

[f] LULUCF emissions include the CO_2, CH_4, and N_2O emissions reported for *Forest Fires, Forest Soils, Liming, Urea Fertilization, Settlement Soils,* and *Peatlands Remaining Peatlands.*

[g] The LULUCF Sector Total is the sum of positive emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO_2 (i.e., sinks or negative emissions) from the atmosphere.

Table 6-3: Emissions and Removals (Flux) from Land Use, Land-Use Change, and Forestry by Gas (kt)

Gas/Land-Use Category	1990	2005	2010	2011	2012	2013	2014
Net CO_2 Flux[a]	**(704,191)**	**(636,143)**	**(683,157)**	**(683,557)**	**(680,812)**	**(682,365)**	**(685,827)**
Forest Land Remaining Forest Land[b]	(576,023)	(532,408)	(584,984)	(578,060)	(576,738)	(580,109)	(583,385)
Land Converted to Forest Land							
Cropland Remaining Cropland	(43,199)	(16,547)	(4,699)	(20,042)	(18,739)	(16,833)	(15,988)
Land Converted to Cropland[a]	22,812	14,646	15,621	14,160	14,505	14,754	14,726
Grassland Remaining Grassland[a]	(12,906)	2,888	2,580	11,259	11,706	11,924	11,926
Land Converted to Grassland	(8,491)	(12,838)	(12,346)	(10,964)	(10,932)	(10,909)	(10,907)
Settlements Remaining Settlements[c]	(60,408)	(80,523)	(86,129)	(87,250)	(88,372)	(89,493)	(90,614)
Other: Landfilled Yard Trimmings and Food Scraps	(25,975)	(11,360)	(13,200)	(12,659)	(12,242)	(11,698)	(11,585)
CO_2	**8,139**	**8,955**	**9,584**	**8,898**	**11,015**	**9,021**	**9,495**
Cropland Remaining Cropland: Liming	4,667	4,349	4,784	3,873	5,978	3,909	4,139
Cropland Remaining Cropland: Urea Fertilization	2,417	3,504	3,778	4,099	4,225	4,342	4,514
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1,055	1,101	1,022	926	812	770	842
CH_4	**131**	**397**	**131**	**265**	**443**	**294**	**294**
Forest Land Remaining Forest Land: Forest Fires	131	397	131	265	443	294	294
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N_2O	**12**	**31**	**17**	**25**	**34**	**26**	**26**
Forest Land Remaining Forest Land: Forest Fires	7	22	7	15	24	16	16
Forest Land Remaining Forest Land: Forest Soils[d]	+	2	2	2	2	2	2
Settlements Remaining Settlements: Settlement Soils[e]	5	8	8	8	9	8	8
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt

[a] Net flux from LULUCF includes the positive C sequestration reported for *Forest Land Remaining Forest Land, Land Converted to Forest Land Cropland Remaining Cropland, Land Converted to Grassland, Settlements Remaining Settlements*, and *Other Land* plus the loss in C sequestration reported for *Land Converted to Cropland* and *Grassland Remaining Grassland*.

[b] Includes the effects of net additions to stocks of carbon stored in forest ecosystem pools and harvested wood products.

[c] Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[d] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land*, and *Land Converted to Forest Land*, but not from land-use conversion.

[e] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*, but not from land-use conversion.

Box 6-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emissions inventories, the emissions and sinks presented in this report are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change

(IPCC).[8] Additionally, the calculated emissions and sinks in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[9] The use of consistent methods to calculate emissions and sinks by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard, U.S. emissions and sinks reported in this Inventory report are comparable to emissions and sinks reported by other countries. The manner that emissions and sinks are provided in this Inventory is one of many ways U.S. emissions and sinks could be examined; this Inventory report presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. The report itself follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted.

6.1 Representation of the U.S. Land Base

A national land-use categorization system that is consistent and complete, both temporally and spatially, is needed in order to assess land use and land-use change status and the associated greenhouse gas fluxes over the Inventory time series. This system should be consistent with IPCC (2006), such that all countries reporting on national greenhouse gas fluxes to the UNFCCC should: (1) describe the methods and definitions used to determine areas of managed and unmanaged lands in the country (Table 6-4), (2) describe and apply a consistent set of definitions for land-use categories over the entire national land base and time series (i.e., such that increases in the land areas within particular land-use categories are balanced by decreases in the land areas of other categories unless the national land base is changing) (Table 6-5), and (3) account for greenhouse gas fluxes on all managed lands. The IPCC (2006, Vol. IV, Chapter 1) considers all anthropogenic greenhouse gas emissions and removals associated with land use and management to occur on managed land, and all emissions and removals on managed land should be reported based on this guidance (see IPCC 2010 for further discussion). Consequently, managed land serves as a proxy for anthropogenic emissions and removals. This proxy is intended to provide a practical framework for conducting an inventory, even though some of the greenhouse gas emissions and removals on managed land are influenced by natural processes that may or may not be interacting with the anthropogenic drivers. Guidelines for factoring out natural emissions and removals may be developed in the future, but currently the managed land proxy is considered the most practical approach for conducting an inventory in this sector (IPCC 2010). The implementation of such a system helps to ensure that estimates of greenhouse gas fluxes are as accurate as possible, and does allow for potentially subjective decisions in regards to subdividing natural and anthropogenic driven emissions. This section of the Inventory has been developed in order to comply with this guidance.

Three databases are used to track land management in the United States and are used as the basis to classify U.S. land area into the thirty-six IPCC land-use and land-use change categories (Table 6-5) (IPCC 2006). The primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI)[10] and the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)[11] Database. The Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Dataset (NLCD)[12] is also used to identify land uses in regions that were not included in the NRI or FIA.

The total land area included in the U.S. Inventory is 936 million hectares across the 50 states.[13] Approximately 890 million hectares of this land base is considered managed and 46 million hectares is unmanaged, which has not

---

[8] See <http://www.ipcc-nggip.iges.or.jp/public/index.html>.

[9] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

[10] NRI data is available at <http://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home>.

[11] FIA data is available at <http://www.fia.fs.fed.us/tools-data/default.asp>.

[12] NLCD data is available at <http://www.mrlc.gov/> and MRLC is a consortium of several U.S. government agencies.

[13] The current land representation does not include areas from U.S. Territories, but there are planned improvements to include these regions in future reports.

changed by much over the time series of the Inventory (Table 6-5). In 2014, the United States had a total of 295 million hectares of managed Forest Land (3.2 percent increase since 1990), 164 million hectares of Cropland (6.3 percent decrease since 1990), 321 million hectares of managed Grassland (1.7 percent decrease since 1990), 42 million hectares of managed Wetlands (7.2 percent decrease since 1990), 43 million hectares of Settlements (28 percent increase since 1990), and 25 million hectares of managed Other Land (Table 6-5). Wetlands are not differentiated between managed and unmanaged, and are reported solely as managed. In addition, C stock changes are not currently estimated for the entire land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the Inventory (e.g., *Grassland Remaining Grassland*, interior Alaska).[14] Planned improvements are under development to account for C stock changes on all managed land (e.g., grasslands and forest lands in Alaska) and ensure consistency between the total area of managed land in the land-representation description and the remainder of the Inventory.

Dominant land uses vary by region, largely due to climate patterns, soil types, geology, proximity to coastal regions, and historical settlement patterns, although all land uses occur within each of the 50 states (Table 6-4). Forest Land tends to be more common in the eastern states, mountainous regions of the western United States, and Alaska. Cropland is concentrated in the mid-continent region of the United States, and Grassland is more common in the western United States and Alaska. Wetlands are fairly ubiquitous throughout the United States, though they are more common in the upper Midwest and eastern portions of the country. Settlements are more concentrated along the coastal margins and in the eastern states.

Table 6-4: Managed and Unmanaged Land Area by Land-Use Categories for All 50 States (Thousands of Hectares)

Land-Use Categories	1990	2005	2010	2011	2012	2013	2014
Managed Lands	**890,019**	**890,016**	**890,017**	**890,017**	**890,017**	**890,017**	**890,017**
Forest Land	285,837	292,106	294,175	294,585	294,988	294,988	294,988
Croplands	174,678	166,064	163,745	163,745	163,752	163,752	163,752
Grasslands	326,526	323,239	321,717	321,421	321,118	321,118	321,118
Settlements	33,420	40,450	42,645	42,645	42,648	42,648	42,648
Wetlands	45,361	43,004	42,336	42,223	42,113	42,112	42,113
Other Land	24,197	25,154	25,398	25,398	25,399	25,399	25,399
Unmanaged Lands	**46,211**	**46,214**	**46,213**	**46,213**	**46,213**	**46,213**	**46,213**
Forest Land	9,634	9,634	9,634	9,634	9,634	9,634	9,634
Croplands	0	0	0	0	0	0	0
Grasslands	25,782	25,782	25,782	25,782	25,782	25,782	25,782
Settlements	0	0	0	0	0	0	0
Wetlands	0	0	0	0	0	0	0
Other Land	10,795	10,797	10,797	10,797	10,797	10,797	10,797
Total Land Areas	**936,230**	**936,230**	**936,230**	**936,230**	**936,230**	**936,230**	**936,230**
Forest Land	295,471	301,740	303,810	304,219	304,622	304,622	304,622
Croplands	174,678	166,064	163,745	163,745	163,752	163,752	163,752
Grasslands	352,308	349,021	347,499	347,203	346,900	346,900	346,900
Settlements	33,420	40,450	42,645	42,645	42,648	42,648	42,648
Wetlands	45,361	43,004	42,336	42,223	42,113	42,112	42,113
Other Land	34,992	35,951	36,195	36,195	36,196	36,196	36,196

Table 6-5: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States (Thousands of Hectares)

Land-Use & Land-Use Change Categories[a]	1990	2005	2010	2011	2012	2013	2014
Total Forest Land	**285,837**	**292,106**	**294,175**	**294,585**	**294,988**	**294,988**	**294,988**
FF	284,642	291,098	293,234	293,644	294,051	294,051	294,051

---

[14] These "managed area" discrepancies also occur in the Common Reporting Format (CRF) tables submitted to the UNFCCC.

CF	233	215	189	189	183	183	183
GF	841	635	637	637	638	638	638
WF	20	23	23	23	23	23	23
SF	15	15	16	16	15	15	15
OF	86	120	77	77	77	77	77
Total Cropland	**174,678**	**166,064**	**163,745**	**163,745**	**163,752**	**163,752**	**163,752**
CC	161,960	151,903	152,079	152,079	152,084	152,084	152,084
FC	252	91	48	48	49	49	49
GC	12,066	13,581	11,215	11,215	11,215	11,215	11,215
WC	141	166	114	114	114	114	114
SC	77	78	72	72	72	72	72
OC	182	245	217	217	217	217	217
Total Grassland	**326,526**	**323,239**	**321,717**	**321,421**	**321,118**	**321,118**	**321,118**
GG	316,489	303,987	303,284	302,989	302,687	302,688	302,687
FG	899	1,538	1,481	1,481	1,479	1,479	1,479
CG	8,396	16,335	15,776	15,776	15,776	15,776	15,776
WG	283	437	250	250	250	250	250
SG	53	115	119	119	119	119	119
OG	406	827	806	806	806	806	806
Total Wetlands	**45,361**	**43,004**	**42,336**	**42,223**	**42,113**	**42,112**	**42,113**
WW	44,649	41,785	41,280	41,167	41,056	41,056	41,056
FW	38	41	35	35	35	35	35
CW	214	362	321	321	321	321	321
GW	396	770	661	661	661	661	661
SW	2	1	2	2	2	2	2
OW	63	45	38	38	38	38	38
Total Settlements	**33,420**	**40,450**	**42,645**	**42,645**	**42,648**	**42,648**	**42,648**
SS	30,632	32,188	34,870	34,870	34,870	34,870	34,870
FS	232	339	362	362	365	365	365
CS	1,227	3,530	3,205	3,205	3,205	3,205	3,205
GS	1,268	4,164	3,981	3,981	3,981	3,981	3,981
WS	6	26	24	24	24	24	24
OS	55	201	204	204	204	204	204
Total Other Land	**24,197**	**25,154**	**25,398**	**25,398**	**25,399**	**25,399**	**25,399**
OO	23,162	23,312	23,475	23,475	23,476	23,476	23,476
FO	37	54	61	61	61	61	61
CO	328	706	812	812	812	812	812
GO	531	966	969	969	969	969	969
WO	135	109	70	70	70	70	70
SO	4	7	12	12	12	12	12
Grand Total	**890,019**	**890,016**	**890,017**	**890,017**	**890,017**	**890,017**	**890,017**

[a] The abbreviations are "F" for Forest Land, "C" for Cropland, "G" for Grassland, "W" for Wetlands, "S" for Settlements, and "O" for Other Lands. Lands remaining in the same land-use category are identified with the land-use abbreviation given twice (e.g., "FF" is Forest Land Remaining Forest Land), and land-use change categories are identified with the previous land use abbreviation followed by the new land-use abbreviation (e.g., "CF" is Cropland Converted to Forest Land).

Note: All land areas reported in this table are considered managed. A planned improvement is underway to deal with an exception for wetlands, which based on the definitions for the current U.S. Land Representation Assessment includes both managed and unmanaged lands. U.S. Territories have not been classified into land uses and are not included in the U.S. Land Representation Assessment. See the Planned Improvements section for discussion on plans to include territories in future inventories. In addition, C stock changes are not currently estimated for the entire land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the Inventory.

Figure 6-1: Percent of Total Land Area for Each State in the General Land-Use Categories for 2014 (TO BE UPDATED)

Methodology

IPCC Approaches for Representing Land Areas

IPCC (2006) describes three approaches for representing land areas. Approach 1 provides data on the total area for each individual land-use category, but does not provide detailed information on changes of area between categories and is not spatially explicit other than at the national or regional level. With Approach 1, total net conversions between categories can be detected, but not the individual changes (i.e., additions and/or losses) between the land-use categories that led to those net changes. Approach 2 introduces tracking of individual land-use changes between the categories (e.g., Forest Land to Cropland, Cropland to Forest Land, and Grassland to Cropland), using survey samples or other forms of data, but does not provide location data on all parcels of land. Approach 3 extends Approach 2 by providing location data on all parcels of land, such as maps, along with the land-use history. The three approaches are not presented as hierarchical tiers and are not mutually exclusive.

According to IPCC (2006), the approach or mix of approaches selected by an inventory agency should reflect calculation needs and national circumstances. For this analysis, the NRI, FIA, and the NLCD have been combined to provide a complete representation of land use for managed lands. These data sources are described in more detail later in this section. NRI and FIA are Approach 2 data sources that do not provide spatially-explicit representations of land use and land-use conversions, even though land use and land-use conversions are tracked explicitly at the survey locations. NRI and FIA data are aggregated and used to develop a land-use conversion matrix for a political or ecologically-defined region. NLCD is a spatially-explicit time series of land-cover data that is used to inform the classification of land use, and is therefore Approach 3 data. Lands are treated as remaining in the same category (e.g., *Cropland Remaining Cropland*) if a land-use change has not occurred in the last 20 years. Otherwise, the land is classified in a land-use change category based on the current use and most recent use before conversion to the current use (e.g., *Cropland Converted to Forest Land*).

Definitions of Land Use in the United States

Managed and Unmanaged Land

The United States definition of managed land is similar to the basic IPCC (2006) definition of managed land, but with some additional elaboration to reflect national circumstances. Based on the following definitions, most lands in the United States are classified as managed:

- *Managed Land*: Land is considered managed if direct human intervention has influenced its condition. Direct intervention occurs mostly in areas accessible to human activity and includes altering or maintaining the condition of the land to produce commercial or non-commercial products or services; to serve as transportation corridors or locations for buildings, landfills, or other developed areas for commercial or non-commercial purposes; to extract resources or facilitate acquisition of resources; or to provide social functions for personal, community, or societal objectives where these areas are readily accessible to society.[15]
- *Unmanaged Land*: All other land is considered unmanaged. Unmanaged land is largely comprised of areas inaccessible to society due to the remoteness of the locations. Though these lands may be influenced

---

[15] Wetlands are an exception to this general definition, because these lands, as specified by IPCC (2006), are only considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the United States is difficult due to limited data availability. Wetlands are not characterized by use within the NRI. Therefore, unless wetlands are managed for cropland or grassland, it is not possible to know if they are artificially created or if the water table is managed based on the use of NRI data. As a result, all wetlands are reported as managed. See the Planned Improvements section of the Inventory for work being done to refine the Wetland area estimates.

indirectly by human actions such as atmospheric deposition of chemical species produced in industry or CO_2 fertilization, they are not influenced by a direct human intervention.[16]

In addition, land that is previously managed remains in the managed land base for 20 years before re-classifying the land as unmanaged in order to account for legacy effects of management on C stocks.

Land-Use Categories

As with the definition of managed lands, IPCC (2006) provides general non-prescriptive definitions for the six main land-use categories: Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land. In order to reflect national circumstances, country-specific definitions have been developed, based predominantly on criteria used in the land-use surveys for the United States. Specifically, the definition of Forest Land is based on the FIA definition of forest,[17] while definitions of Cropland, Grassland, and Settlements are based on the NRI.[18] The definitions for Other Land and Wetlands are based on the IPCC (2006) definitions for these categories.

- *Forest Land*: A land-use category that includes areas at least 120 feet (36.6 meters) wide and at least one 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. Forest Land 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. However, land is not classified as Forest Land if completely surrounded by urban or developed lands, even if the criteria are consistent with the tree area and cover requirements for Forest Land. These areas are classified as Settlements. In addition, Forest Land does not include land that is predominantly under an agricultural land use (Oswalt et al. 2014).

- *Cropland*: A land-use category that includes areas used for the production of adapted crops for harvest; this category includes both cultivated and non-cultivated lands. Cultivated crops include row crops or close-grown crops and also hay or pasture in rotation with cultivated crops. Non-cultivated cropland includes continuous hay, perennial crops (e.g., orchards) and horticultural cropland. Cropland also includes land with agroforestry, such as alley cropping and windbreaks,[19] if the dominant use is crop production, assuming the stand or woodlot does not meet the criteria for Forest Land. Lands in temporary fallow or enrolled in conservation reserve programs (i.e., set-asides[20]) are also classified as Cropland, as long as these areas do not meet the Forest Land criteria. Roads through Cropland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Cropland area estimates and are, instead, classified as Settlements.

- *Grassland*: A land-use category on which the plant cover is composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing, and includes both pastures and native rangelands. This includes areas where practices such as clearing, burning, chaining, and/or chemicals are applied to maintain the grass vegetation. Grassland may have three or fewer years of

---

[16] There are some areas, such as Forest Land and Grassland in Alaska that are classified as unmanaged land due to the remoteness of their location.

[17] See <http://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2015/Core-FIA-FG-7.pdf>, page 22.

[18] See <http://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home>.

[19] Currently, there is no data source to account for biomass C stock change associated with woody plant growth and losses in alley cropping systems and windbreaks in cropping systems, although these areas are included in the cropland land base.

[20] A set-aside is cropland that has been taken out of active cropping and converted to some type of vegetative cover, including, for example, native grasses or trees.

hay production[21] that is otherwise pasture or rangelands. Savannas, deserts, and tundra are considered Grassland.[22] Drained wetlands are considered Grassland if the dominant vegetation meets the plant cover criteria for Grassland. Woody plant communities of low forbs and shrubs, such as mesquite, chaparral, mountain shrub, and pinyon-juniper, are also classified as Grassland if they do not meet the criteria for Forest Land. Grassland includes land managed with agroforestry practices, such as silvipasture and windbreaks, if the land is principally grasses, grass-like plants, forbs, and shrubs suitable for grazing and browsing, and assuming the stand or woodlot does not meet the criteria for Forest Land. Roads through Grassland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Grassland and are, instead, classified as Settlements.

- *Wetlands*: A land-use category that includes land covered or saturated by water for all or part of the year, in addition to the areas of lakes, reservoirs, and rivers. Managed Wetlands are those where the water level is artificially changed, or were created by human activity. Certain areas that fall under the managed Wetlands definition are included in other land uses based on the IPCC guidance, including Cropland (drained wetlands for crop production and also systems that are flooded for most or just part of the year, such as rice cultivation and cranberry production), Grassland (drained wetlands dominated by grass cover), and Forest Land (including drained or un-drained forested wetlands).
- *Settlements*: A land-use category representing developed areas consisting of units of 0.25 acres (0.1 ha) or more that includes residential, industrial, commercial, and institutional land; construction sites; public administrative sites; railroad yards; cemeteries; airports; golf courses; sanitary landfills; sewage treatment plants; water control structures and spillways; parks within urban and built-up areas; and highways, railroads, and other transportation facilities. Also included are tracts of less than 10 acres (4.05 ha) that may meet the definitions for Forest Land, Cropland, Grassland, or Other Land but are completely surrounded by urban or built-up land, and so are included in the Settlements category. Rural transportation corridors located within other land uses (e.g., Forest Land, Cropland, and Grassland) are also included in Settlements.
- *Other Land*: A land-use category that includes bare soil, rock, ice, and all land areas that do not fall into any of the other five land-use categories, which allows the total of identified land areas to match the managed land base. Following the guidance provided by the IPCC (2006), C stock changes and non-CO_2 emissions are not estimated for Other Lands because these areas are largely devoid of biomass, litter and soil C pools. However, C stock changes and non-CO_2 emissions are estimated for *Land Converted to Other Land* during the first 20 years following conversion to account for legacy effects.

Land-Use Data Sources: Description and Application to U.S. Land Area Classification

U.S. Land-Use Data Sources

The three main sources for land-use data in the United States are the NRI, FIA, and the NLCD (Table 6-6). These data sources are combined to account for land use in all 50 states. FIA and NRI data are used when available for an area because the surveys contain additional information on management, site conditions, crop types, biometric measurements, and other data from which to estimate C stock changes on those lands. If NRI and FIA data are not available for an area, however, then the NLCD product is used to represent the land use.

---

[21] Areas with four or more years of continuous hay production are Cropland because the land is typically more intensively managed with cultivation, greater amounts of inputs, and other practices.

[22] *2006 IPCC Guidelines* do not include provisions to separate desert and tundra as land use categories.

Table 6-6: Data Sources Used to Determine Land Use and Land Area for the Conterminous United States, Hawaii, and Alaska

	NRI	FIA	NLCD
Forest Land			
Conterminous United States			
Non-Federal		•	
Federal		•	
Hawaii			
Non-Federal	•		
Federal			•
Alaska			
Non-Federal			•
Federal			•
Croplands, Grasslands, Other Lands, Settlements, and Wetlands			
Conterminous United States			
Non-Federal	•		
Federal			•
Hawaii			
Non-Federal	•		
Federal			•
Alaska			
Non-Federal			•
Federal			•

National Resources Inventory

For the Inventory, the NRI is the official source of data on all land uses on non-federal lands in the conterminous United States and Hawaii (except Forest Land), and is also used as the resource to determine the total land base for the conterminous United States and Hawaii. The NRI is a statistically-based survey conducted by the USDA Natural Resources Conservation Service and is designed to assess soil, water, and related environmental resources on non-federal lands. The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the United States Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit (typically a 160 acre [64.75 hectare] square quarter-section), three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land-use information (Nusser and Goebel 1997). The NRI survey utilizes data derived from remote sensing imagery and site visits in order to provide detailed information on land use and management, particularly for croplands and grasslands, and is used as the basis to account for C stock changes in agricultural lands (except federal Grasslands). The NRI survey was conducted every 5 years between 1982 and 1997, but shifted to annualized data collection in 1998. The land use between five-year periods from 1982 and 1997 are assumed to be the same for a five-year time period if the land use is the same at the beginning and end of the five-year period. (Note: most of the data has the same land use at the beginning and end of the five-year periods.) If the land use had changed during a five-year period, then the change is assigned at random to one of the five years. For crop histories, years with missing data are estimated based on the sequence of crops grown during years preceding and succeeding a missing year in the NRI history. This gap-filling approach allows for development of a full time series of land-use data for non-federal lands in the conterminous United States and Hawaii. This Inventory incorporates data through 2010 from the NRI. The land use patterns are assumed to remain the same from 2010 through 2014 for this Inventory, but the time series will be updated when new data are released.

Forest Inventory and Analysis

The FIA program, conducted by the USFS, is another statistically-based survey for the conterminous United States, and the official source of data on Forest Land area and management data for the Inventory in this region of the country. FIA engages in a hierarchical system of sampling, with sampling categorized as Phases 1 through 3, in which sample points for phases are subsets of the previous phase. Phase 1 refers to collection of remotely-sensed data (either aerial photographs or satellite imagery) primarily to classify land into forest or non-forest and to identify landscape patterns like fragmentation and urbanization. Phase 2 is the collection of field data on a network of ground plots that enable classification and summarization of area, tree, and other attributes associated with forest-land uses. Phase 3 plots are a subset of Phase 2 plots where data on indicators of forest health are measured. Data from all three phases are also used to estimate C stock changes for Forest Land. Historically, FIA inventory surveys have been conducted periodically, with all plots in a state being measured at a frequency of every five to 14 years. A new national plot design and annual sampling design was introduced by FIA about ten years ago. Most states, though, have only recently been brought into this system. Annualized sampling means that a portion of plots throughout each state is sampled each year, with the goal of measuring all plots once every five years. See Annex 3.13 to see the specific survey data available by state. The most recent year of available data varies state by state (range of most recent data is from 2012 through 2014; see Table A-246).

National Land Cover Dataset

While the NRI survey sample covers the conterminous United States and Hawaii, land use data are only collected on non-federal lands. In addition, FIA only records data for forest land across the land base in the conterminous United States and a portion of Alaska.[23] Consequently, major gaps exist in the land use classification when the datasets are combined, such as federal grassland operated by Bureau of Land Management (BLM), USDA, and National Park Service, as well as Alaska.[24] The NLCD is used as a supplementary database to account for land use on federal lands in the conterminous United States and Hawaii, in addition to federal and non-federal lands in Alaska.

NLCD products provide land-cover for 1992, 2001, 2006, and 2011 in the conterminous United States (Homer et al. 2007), and also for Alaska and Hawaii in 2001. For the conterminous United States, the NLCD data have been further processed to derive Land Cover Change Products for 2001, 2006, and 2011 (Fry et al. 2011, Homer et al. 2007, Jin et al. 2013). A change product is not available for Alaska and Hawaii because the data are only available for one year, i.e., 2001). The NLCD products are based primarily on Landsat Thematic Mapper imagery at a 30 meter resolution, and contain 21 categories of land-cover information, which have been aggregated into the thirty-six IPCC land-use categories for the conterminous United States and into the six IPCC land use categories for Hawaii and Alaska.

The aggregated maps of IPCC land use categories were used in combination with the NRI database to represent land use and land-use change for federal lands, as well as federal and non-federal lands in Alaska. Specifically, NRI survey locations designated as federal lands were assigned a land use/land use change category based on the NLCD maps that had been aggregated into the IPCC categories. This analysis addressed shifts in land ownership across years between federal or non-federal classes as represented in the NRI survey (i.e., the ownership is classified for each survey location is the NRI). NLCD is strictly a source of land-cover information, however, and does not provide the necessary site conditions, crop types, and management information from which to estimate C stock changes on those lands. The sources of these additional data are discussed in subsequent sections of the NIR.

Managed Land Designation

Lands are designated as managed in the United States based on the definition provided earlier in this section. In order to apply the definition in an analysis of managed land, the following criteria are used:

- All Croplands and Settlements are designated as managed so only Grassland, Forest Land or Other Lands may be designated as unmanaged land;
- All Forest Lands with active fire protection are considered managed;
- All Grassland is considered managed at a county scale if there are livestock in the county;[25]
- Other areas are considered managed if accessible based on the proximity to roads and other transportation corridors, and/or infrastructure;

---

[23] FIA does collect some data on non-forest land use, but these are held in regional databases versus the national database. The status of these data is being investigated.

[24] The FIA and NRI survey programs also do not include U.S. Territories with the exception of non-federal lands in Puerto Rico, which are included in the NRI survey. Furthermore, NLCD does not include coverage for all U.S. Territories.

[25] Assuming all grasslands are grazed in a county with even very small livestock populations is a conservative assumption about human impacts on grasslands. Currently, detailed information on grazing at sub-county scales is not available for the United States to make a finer delineation of managed land.

- Protected lands maintained for recreational and conservation purposes are considered managed (i.e., managed by public and private organizations);
- Lands with active and/or past resource extraction are considered managed; and
- Lands that were previously managed but subsequently classified as unmanaged remain in the managed land base for 20 years following the conversion to account for legacy effects of management on C stocks.

The analysis of managed lands is conducted using a geographic information system. Lands that are used for crop production or settlements are determined from the NLCD (Fry et al. 2011, Homer et al. 2007, Jin et al. 2013). Forest Lands with active fire management are determined from maps of federal and state management plans from the National Atlas (U.S. Department of Interior 2005) and Alaska Interagency Fire Management Council (1998). It is noteworthy that all forest lands in the conterminous United States have active fire protection, and are therefore designated as managed regardless of accessibility or other criteria. The designation of grasslands as managed is based on livestock population data at the county scale from the USDA National Agricultural Statistics Service (U.S. Department of Agriculture 2014). Accessibility is evaluated based on a 10-km buffer surrounding road and train transportation networks using the ESRI Data and Maps product (ESRI 2008), and a 10-km buffer surrounding settlements using NLCD. Lands maintained for recreational purposes are determined from analysis of the Protected Areas Database (U.S. Geological Survey 2012). The Protected Areas Database includes lands protected from conversion of natural habitats to anthropogenic uses and describes the protection status of these lands. Lands are considered managed that are protected from development if the regulations permit extractive or recreational uses or suppression of natural disturbance. Lands that are protected from development and not accessible to human intervention, including no suppression of disturbances or extraction of resources, are not included in the managed land base. Multiple data sources are used to determine lands with active resource extraction: Alaska Oil and Gas Information System (Alaska Oil and Gas Conservation Commission 2009), Alaska Resource Data File (U.S. Geological Survey 2012), Active Mines and Mineral Processing Plants (U.S. Geological Survey 2005), and Coal Production and Preparation Report (U.S. Energy Information Administration 2011). A buffer of 3,300 and 4,000 meters is established around petroleum extraction and mine locations, respectively, to account for the footprint of operation and impacts of activities on the surrounding landscape. The buffer size is based on visual analysis of approximately 130 petroleum extraction sites and 223 mines. The resulting managed land area is overlaid on the NLCD to estimate the area of managed land by land use for both federal and non-federal lands. The remaining land represents the unmanaged land base. The resulting spatial product is used to identify NRI survey locations that are considered managed and unmanaged for the conterminous United States and Hawaii, in addition to determining which areas in the NLCD for Alaska are included in the managed land base.

Approach for Combining Data Sources

The managed land base in the United States has been classified into the thirty-six IPCC land-use/land-use conversion categories using definitions developed to meet national circumstances, while adhering to IPCC (2006).[26] In practice, the land was initially classified into a variety of land-use categories within the NRI, FIA, and NLCD datasets, and then aggregated into the thirty-six broad land use and land-use change categories identified in IPCC (2006). All three datasets provide information on forest land areas in the conterminous United States, but the area data from FIA serve as the official dataset for estimating Forest Land in the conterminous United States.

Therefore, another step in the analysis is to address the inconsistencies in the representation of the forest land among the three databases. NRI and FIA have different criteria for classifying Forest Land in addition to different sampling designs, leading to discrepancies in the resulting estimates of Forest Land area on non-federal land in the conterminous United States. Similarly, there are discrepancies between the NLCD and FIA data for defining and classifying Forest Land on federal lands. Any change in Forest Land Area in the NRI and NLCD also requires a corresponding change in other land use areas because of the dependence between the Forest Land area and the amount of land designated as other land uses, such as the amount of Grassland, Cropland, and Wetlands (i.e., areas for the individual land uses must sum to the total area of the country).

FIA is the main database for forest statistics, and consequently, the NRI and NLCD are adjusted to achieve consistency with FIA estimates of Forest Land in the conterminous United States. Adjustments are made in the

---

[26] Definitions are provided in the previous section.

Forest Land Remaining Forest Land, *Land Converted to Forest Land*, and Forest Land converted to other uses (i.e., grassland, cropland and wetlands). All adjustments are made at the state scale to address the differences in forest land definitions and the resulting discrepancies in areas among the land use and land-use change categories. There are three steps in this process. The first step involves adjustments for *Land Converted to Forest Land* (Grassland, Cropland and Wetlands), followed by adjustments in Forest Land converted to another land use (i.e., Grassland, Cropland and Wetlands), and finally adjustments to *Forest Land Remaining Forest Land*.

In the first step, *Land Converted to Forest Land* in the NRI and NLCD are adjusted to match the state-level estimates in the FIA data for non-federal and federal *Land Converted to Forest Land*, respectively. FIA data do not provide specific land use categories that are converted to Forest Land, but rather a sum of all *Land Converted to Forest Land*. The NRI and NLCD provide information on specific land use conversions, however, such as *Grassland Converted to Forest Land*. Therefore, adjustments at the state level to NRI and NLCD are made proportional to the amount of land use change into Forest Land for the state, prior to any adjustments. For example, if 50 percent of land use change to Forest Land is associated with *Grassland Converted to Forest Land* in a state according to NRI or NLCD, then half of the discrepancy with FIA data in the area of *Land Converted to Forest Land* is addressed by increasing or decreasing the area in *Grassland Converted to Forest Land*. Moreover, any increase or decrease in *Grassland Converted to Forest Land* in NRI or NLCD is addressed by a corresponding change in the area of *Grassland Remaining Grassland*, so that the total amount of managed area is not changed within an individual state.

In the second step, state-level areas are adjusted in the NRI and NLCD to address discrepancies with FIA data for Forest Land converted to other uses. Similar to *Land Converted to Forest Land*, FIA does not provide information on the specific land use changes, and so areas associated with Forest Land conversion to other land uses in NRI and NLCD are adjusted proportional to the amount area in each conversion class in these datasets.

In the final step, the area of *Forest Land Remaining Forest Land* in a given state according to the NRI and NLCD is adjusted to match the FIA estimates for non-federal and federal land, respectively. It is assumed that the majority of the discrepancy in *Forest Land Remaining Forest Land* is associated with an under- or over-prediction of *Grassland Remaining Grassland* and *Wetland Remaining Wetland* in the NRI and NLCD. This step also assumes that there are no changes in the land use conversion categories. Therefore, corresponding increases or decreases are made in the area estimates of *Grasslands Remaining Grasslands* and *Wetlands Remaining Wetlands* from the NRI and NLCD, in order to balance the change in *Forest Land Remaining Forest Land* area, and ensure no change in the overall amount of managed land within an individual state. The adjustments are based on the proportion of land within each of these land-use categories at the state level. (i.e., a higher proportion of Grassland led to a larger adjustment in Grassland area).

The modified NRI data are then aggregated to provide the land-use and land-use change data for non-federal lands in the conterminous United States, and the modified NLCD data are aggregated to provide the land use and land-use change data for federal lands. Data for all land uses in Hawaii are based on NRI for non-federal lands and on NLCD for federal lands. Land use data in Alaska are based solely on the NLCD data (Table 6-6). The result is land use and land-use change data for the conterminous United States, Hawaii, and Alaska.[27]

A summary of the details on the approach used to combine data sources for each land use are described below.

- *Forest Land*: Both non-federal and federal forest lands in the conterminous United States and coastal Alaska are covered by FIA. FIA is used as the basis for both Forest Land area data as well as to estimate C stocks and fluxes on Forest Land in the conterminous United States. FIA does have survey plots in coastal Alaska that are used to determine the C stock changes, but the area data for this region are based on the 2001 NLCD. In addition, interior Alaska is not currently surveyed by FIA so forest land in this region are also based on the 2001 NLCD. NRI is being used in the current report to provide Forest Land areas on non-federal lands in Hawaii and NLCD is used for federal lands. FIA data will be collected in Hawaii in the future.

- *Cropland*: Cropland is classified using the NRI, which covers all non-federal lands within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Cropland area data as well as to estimate soil C stocks and fluxes on Cropland. NLCD

---

[27] Only one year of data are currently available for Alaska so there is no information on land-use change for this state.

is used to determine Cropland area and soil C stock changes on federal lands in the conterminous United States and Hawaii. NLCD is also used to determine croplands in Alaska, but C stock changes are not estimated for this region in the current Inventory.

- *Grassland*: Grassland on non-federal lands is classified using the NRI within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Grassland area data as well as to estimate soil C stocks and fluxes on Grassland. Grassland area and soil C stock changes are determined using the classification provided in the NLCD for federal land within the conterminous United States. NLCD is also used to estimate the areas of federal and non-federal grasslands in Alaska, and the federal lands in Hawaii, but the current Inventory does not include C stock changes in these areas.
- *Wetlands*: NRI captures wetlands on non-federal lands within 49 states (excluding Alaska), while federal wetlands and wetlands in Alaska are covered by the NLCD.[28]
- *Settlements*: NRI captures non-federal settlement area in 49 states (excluding Alaska). If areas of Forest Land or Grassland under 10 acres (4.05 ha) are contained within settlements or urban areas, they are classified as Settlements (urban) in the NRI database. If these parcels exceed the 10 acre (4.05 ha) threshold and are Grassland, they will be classified as such by NRI. Regardless of size, a forested area is classified as non-forest by FIA if it is located within an urban area. Settlements on federal lands and in Alaska are covered by NLCD.
- *Other Land*: Any land that is not classified into one of the previous five land-use categories, is categorized as Other Land using the NRI for non-federal areas in the conterminous United States and Hawaii and using the NLCD for the federal lands in all regions of the United States and for non-federal lands in Alaska.

Some lands can be classified into one or more categories due to multiple uses that meet the criteria of more than one definition. However, a ranking has been developed for assignment priority in these cases. The ranking process is from highest to lowest priority, in the following manner:

Settlements > Cropland > Forest Land > Grassland > Wetlands > Other Land

Settlements are given the highest assignment priority because they are extremely heterogeneous with a mosaic of patches that include buildings, infrastructure, and travel corridors, but also open grass areas, forest patches, riparian areas, and gardens. The latter examples could be classified as Grassland, Forest Land, Wetlands, and Cropland, respectively, but when located in close proximity to settlement areas they tend to be managed in a unique manner compared to non-settlement areas. Consequently, these areas are assigned to the Settlements land-use category. Cropland is given the second assignment priority, because cropping practices tend to dominate management activities on areas used to produce food, forage, or fiber. The consequence of this ranking is that crops in rotation with pasture will be classified as Cropland, and land with woody plant cover that is used to produce crops (e.g., orchards) is classified as Cropland, even though these areas may meet the definitions of Grassland or Forest Land, respectively. Similarly, Wetlands are considered Croplands if they are used for crop production, such as rice or cranberries. Forest Land occurs next in the priority assignment because traditional forestry practices tend to be the focus of the management activity in areas with woody plant cover that are not croplands (e.g., orchards) or settlements (e.g., housing subdivisions with significant tree cover). Grassland occurs next in the ranking, while Wetlands then Other Land complete the list.

The assignment priority does not reflect the level of importance for reporting greenhouse gas emissions and removals on managed land, but is intended to classify all areas into a discrete land use. Currently, the IPCC does not make provisions in the guidelines for assigning land to multiple uses. For example, a wetland is classified as Forest Land if the area has sufficient tree cover to meet the stocking and stand size requirements. Similarly, wetlands are classified as Cropland if they are used for crop production, such as rice or cranberries, or as Grassland if they are composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing. Regardless of the classification, emissions from these areas are included in the Inventory if

---

[28] This analysis does not distinguish between managed and unmanaged wetlands, which is a planned improvement for the Inventory.

the land is considered managed and presumably impacted by anthropogenic activity in accordance with the guidance provided in IPCC (2006).

QA/QC and Verification

The land base derived from the NRI, FIA, and NLCD was compared to the Topologically Integrated Geographic Encoding and Referencing (TIGER) survey (U.S. Census Bureau 2010). The U.S. Census Bureau gathers data on the U.S. population and economy, and has a database of land areas for the country. The land area estimates from the U.S. Census Bureau differ from those provided by the land-use surveys used in the Inventory because of discrepancies in the reporting approach for the Census and the methods used in the NRI, FIA, and NLCD. The area estimates of land-use categories, based on NRI, FIA, and NLCD, are derived from remote sensing data instead of the land survey approach used by the U.S. Census Survey. More importantly, the U.S. Census Survey does not provide a time series of land-use change data or land management information. Consequently, the U.S. Census Survey was not adopted as the official land area estimate for the Inventory. Rather, the NRI, FIA, and NLCD datasets were adopted because these databases provide full coverage of land area and land use for the conterminous United States, Alaska, and Hawaii, in addition to management and other data relevant for the Inventory. Regardless, the total difference between the U.S. Census Survey and the combined NRI, FIA, and NLCD data is about 46 million hectares for the total U.S. land base of about 936 million hectares currently included in the Inventory, or a 5 percent difference. Much of this difference is associated with open waters in coastal regions and the Great Lakes, which is included in the TIGER Survey of the U.S. Census, but not included in the land representation using the NRI, FIA and NLCD. There is only a 0.4 percent difference when open water in coastal regions is removed from the TIGER data.

Recalculations Discussion

In previous years, FIA did not separate Forest Land into land use and land use change categories, reporting all areas as *Forest Land Remaining Forest Land* for the purpose of estimating forest carbon stock changes. In this Inventory, forest carbon stock changes are reported for *Land Converted to Forest*, *Forest Converted to other Land Uses*, in addition to *Forest Land Remaining Forest Land*. As such, adjustments to NRI and NLCD accounted for land use changes associated with Forest Land, which led to minor adjustments to the time series. Other small changes occurred in the areas of Grassland, Wetland, and Cropland due to the modifications to the Forest Land data in FIA and the process of combining the NRI, NLCD and FIA products into a harmonized dataset.

In addition to the changes in the FIA data, a new NRI dataset was incorporated into the current Inventory extending the time series from 2007 to 2010. The NRI program also recalculated the previous time series based on changes to the classification and imputation procedures for filling gaps.

The definition of Grassland also changed so that a land use history that includes three or fewer years within a sequence of grass pasture or rangeland is considered Grassland, rather than converting these areas into Cropland. Land use remains virtually unchanged in these cases with harvesting of the existing grass vegetation, with no impact on carbon stocks. In contrast, longer term adoption of continuous hay tends to change the management to a more intensive set of practices that influences the carbon stocks. This exception is only applied to hay. Any change in land management that involves cultivation of other crops, such as corn, wheat, or soybeans, is still considered a land use change.

The revisions in land representation led to the following changes in land use areas for the managed land base: on average over the time series, Forest Land area decreased by 0.2 percent, Cropland area increased by 3.1 percent, Grassland area increased by 0.7 percent, Wetland area decreased by 0.8 percent, Settlements decreased by 16.6 percent, and Other Lands increased by 5.8 percent.

Planned Improvements

A key planned improvement is to fully incorporate area data by land-use type for U.S. Territories into the Inventory. Fortunately, most of the managed land in the United States is included in the current land-use statistics, but a complete accounting is a key goal for the near future. Preliminary land-use area data for U.S. Territories by land-use category are provided in Box 6-2: Preliminary Estimates of Land Use in U.S. Territories.

Box 6-2: Preliminary Estimates of Land Use in U.S. Territories

Several programs have developed land cover maps for U.S. Territories using remote sensing imagery, including the Gap Analysis program, Caribbean Land Cover project, National Land Cover Dataset, USFS Pacific Islands Imagery Project, and the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program. Land-cover data can be used to inform a land-use classification if there is a time series to evaluate the dominate practices. For example, land that is principally used for timber production with tree cover over most of the time series is classified as forest land even if there are a few years of grass dominance following timber harvest. These products were reviewed and evaluated for use in the national Inventory as a step towards implementing a planned improvement to include U.S. Territories in the land representation for the Inventory. Recommendations are to use the NOAA Coastal Change Analysis Program (C-CAP) Regional Land Cover Database for the smaller island Territories (U.S. Virgin Islands, Guam, Northern Marianas Islands, and American Samoa) because this program is ongoing and therefore will be continually updated. The C-CAP product does not cover the entire territory of Puerto Rico so the NLCD was used for this area. The final selection of a land-cover product for these territories is still under discussion. Results are presented below (in hectares). The total land area of all U.S. Territories is 1.05 million hectares, representing 0.1 percent of the total land base for the United States.

Table 6-7: Total Land Area (Hectares) by Land-Use Category for U.S. Territories

	Puerto Rico	**U.S. Virgin Islands**	**Guam**	**Northern Marianas Islands**	**American Samoa**	**Total**
Cropland	19,712	138	236	289	389	20,764
Forest Land	404,004	13,107	24,650	25,761	15,440	482,962
Grasslands	299,714	12,148	15,449	13,636	1,830	342,777
Other Land	5,502	1,006	1,141	5,186	298	13,133
Settlements	130,330	7,650	11,146	3,637	1,734	154,496
Wetlands	24,525	4,748	1,633	260	87	31,252
Total	**883,788**	**38,796**	**54,255**	**48,769**	**19,777**	**1,045,385**

Additional work will be conducted to reconcile differences in Forest Land estimates between the NRI and FIA. This improvement will include an analysis designed to develop finer scale adjustments at the survey locations. Harmonization is planned at the survey location scale using ancillary data, such as the NLCD, which is expected to better capture the differences in Forest Land classification between the two surveys, as well as the conversions of land to other uses that involve Forest Land.

NLCD data for Alaska were recently released for 2011, and will be used to analyze land use change for this state in the next inventory. There are also other databases that may need to be reconciled with the NRI and NLCD datasets, particularly for Settlements. Urban area estimates, used to produce C stock and flux estimates from urban trees, are currently based on population data (1990, 2000, and 2010 U.S. Census data). Using the population statistics, “urban clusters” are defined as areas with more than 500 people per square mile. The USFS is currently moving ahead with an urban forest inventory program so that urban forest area estimates will be consistent with FIA forest area estimates outside of urban areas, which would be expected to reduce omissions and overlap of forest area estimates along urban boundary areas.

As adopted by the UNFCCC, new guidance in the *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands* will be implemented in the Inventory. This will likely have implications for the classification of managed and unmanaged wetlands in the Inventory report. More detailed wetlands datasets will also be evaluated and integrated into the analysis in order to implement the new guidance.

6.2 Forest Land Remaining Forest Land

Changes in Forest Carbon Stocks (IPCC Source Category 4A1)

Delineation of Carbon Pools

For estimating carbon (C) stocks or stock change (flux), C in forest ecosystems can be divided into the following five storage pools (IPCC 2006):

- Aboveground biomass, which includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This category includes live understory.
- Belowground biomass, which includes all living biomass of coarse living roots greater than 2 mm diameter.
- Dead wood, which includes all non-living woody biomass either standing, lying on the ground (but not including litter), or in the soil.
- Litter, which includes the litter, fumic, and humic layers, and all non-living biomass with a diameter less than 7.5 cm at transect intersection, lying on the ground.
- Soil organic C (SOC), including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools.

In addition, there are two harvested wood pools to account for when estimating C flux:

- Harvested wood products (HWP) in use.
- HWP in solid waste disposal sites (SWDS).

Forest Carbon Cycle

Carbon is continuously cycled among the previously defined C storage pools and the atmosphere as a result of biological processes in forests (e.g., photosynthesis, respiration, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, and replanting). As trees photosynthesize and grow, C is removed from the atmosphere and stored in living tree biomass. As trees die and otherwise deposit litter and debris on the forest floor, C is released to the atmosphere and is also transferred to the soil pool by organisms that facilitate decomposition.

The net change in forest C is not equivalent to the net flux between forests and the atmosphere because timber harvests do not cause an immediate flux of all harvested biomass C to the atmosphere. Instead, harvesting transfers a portion of the C stored in wood to a "product pool." Once in a product pool, the C is emitted over time as CO_2 when the wood product combusts or decays. The rate of emission varies considerably among different product pools. For example, if timber is harvested to produce energy, combustion releases C immediately, and these emissions are reported for information purposes in the Energy sector with the harvest (i.e., the associated reduction in forest C stocks) and subsequent combustion implicitly accounted for under the Land Use, Land-Use Change, and Forestry (LULUCF) sector (i.e., the harvested timber does not enter the HWP pools). Conversely, if timber is harvested and used as lumber in a house, it may be many decades or even centuries before the lumber decays and C is released to the atmosphere. If wood products are disposed of in SWDS, the C contained in the wood may be released many years or decades later, or may be stored almost permanently in the SWDS. These latter fluxes are also accounted for under the LULUCF sector.

Quantification of the U.S. Forest Carbon Cycle

This section describes the general method for quantifying the net changes in C stocks in the five forest C pools and two harvested wood pools. The basic methodology for determining C stock and stock-change relies on data from the annual forest inventory system that is implemented across all U.S. forest lands (except for interior Alaska) with continual improvements in this monitoring system and associated forest C estimation techniques reflected in the C estimates (Woodall et al. 2015a). The net change in stocks for each pool is estimated, and then the changes in stocks are summed for all pools to estimate total net flux. The focus on C implies that all C-based greenhouse gases are included, and the focus on stock change suggests that specific ecosystem fluxes do not need to be separately itemized in this report. Changes in C stocks from disturbances, such as forest fires or harvesting, are included in the net changes. For instance, an inventory conducted after fire counts only the trees that are left. Therefore, changes in C stocks from natural disturbances, such as wildfires, pest outbreaks, and storms, are accounted for in the forest inventory approach; however, they are highly variable from year to year. The IPCC (2006) recommends estimating changes in C stocks from forest lands according to several land-use types and conversions, specifically *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. This is the first report to delineate forest C stock changes by the two land-use types as specifically requested by a UNFCCC in country review (UNFCCC 2012). In order to facilitate the delineation between the two land use classes, a new approach to forest C accounting was developed in the United States: The Forest Carbon Accounting Framework (FCAF; Woodall et al. 2015a).

Forest Area Status in the United States

Approximately 34 percent of the U.S. land area is estimated to be forested (Oswalt et al. 2014). The most recent forest inventories from each of the conterminous 48 states (USDA Forest Service 2014a, 2014b) include an estimated 266 million hectares of forest land that are considered managed and are included in this inventory. An additional 6 million hectares of forest land in southeast and south central Alaska are inventoried and are included here. Some differences exist in forest land defined in Oswalt et al. (2014) and the forest land included in this report, which is based on the USDA Forest Service (2015b) forest inventory. Survey data are not yet available for Hawaii and interior Alaska, but estimates of these areas are included in Oswalt et al. (2014). Updated survey data for central and western forest land in both Oklahoma and Texas have only recently become available, and these forests contribute to overall C stocks reported below. While Hawaii and U.S. Territories have relatively small areas of forest land and thus may not substantially influence the overall C budget, these regions will be added to the C budget as sufficient data become available. Agroforestry systems that meet the definition of forest land are also not currently accounted for in the Inventory, since they are not explicitly inventoried by either the Forest Inventory and Analysis (FIA) program of the USDA Forest Service or the Natural Resources Inventory (NRI) of the USDA Natural Resources Conservation Service (Perry et al. 2005).

An estimated 77 percent (211 million hectares) of U.S. forests in Alaska and the conterminous U.S. are classified as timberland, meaning they meet minimum levels of productivity and have not been removed from production. Ten percent of Alaska forest land and 80 percent of forest land in the conterminous U.S. are classified as timberland. Of the remaining non-timberland, 30 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 69 million hectares are lower productivity forest lands (Oswalt et al. 2014). Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than other forest land.

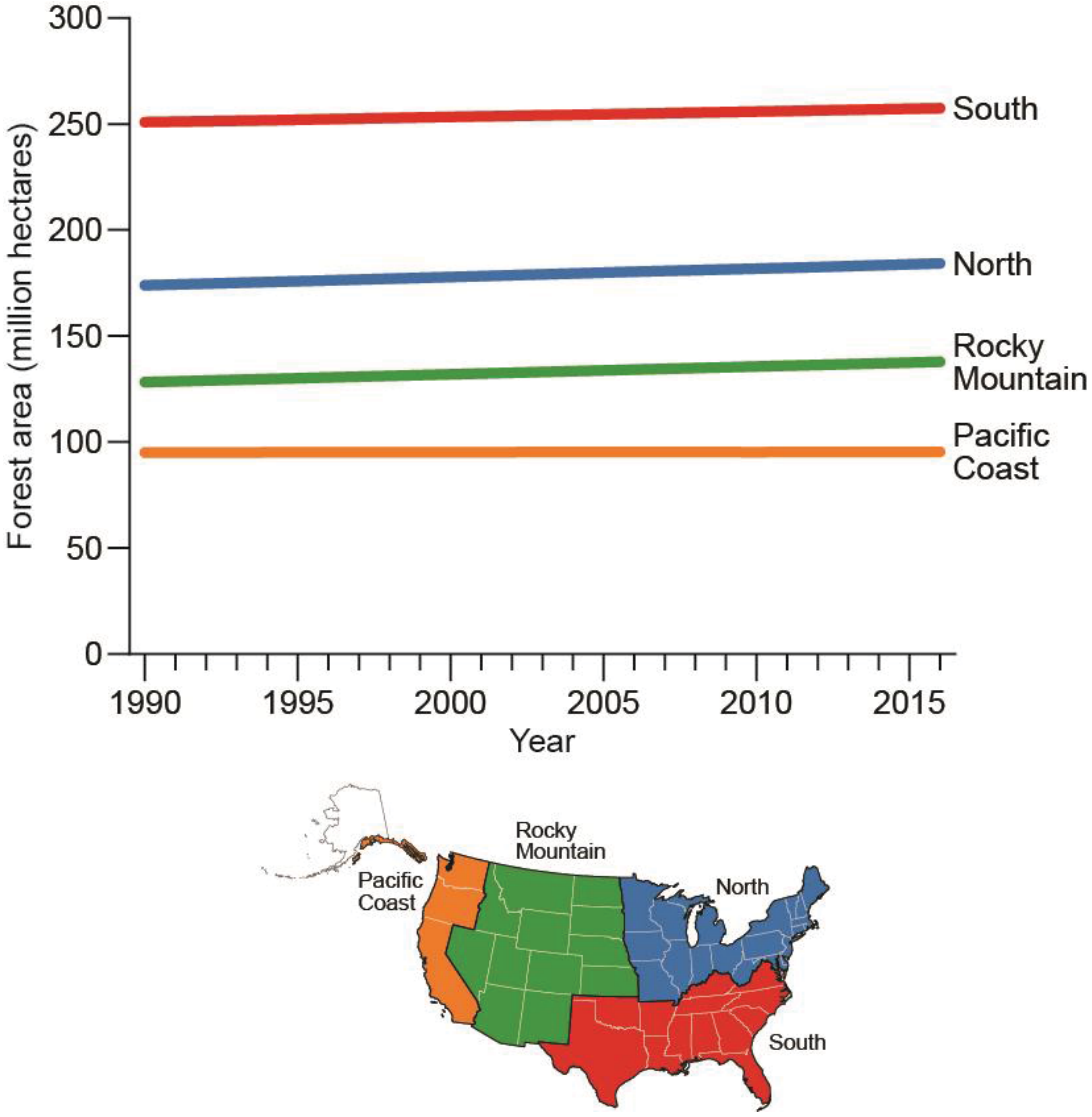
Since the late 1980s, forest land area has increased by about 14 million hectares (Oswalt et al. 2014) with the southern region of the United States containing the most forest land (Figure 6-2). A substantial portion of this accrued forest land is from the conversion of abandoned croplands to forest (e.g., Woodall et al. 2015b). Current trends in the forest land area in the conterminous United States and coastal Alaska represented here show an average annual rate of increase of 0.1 percent. In addition to the increase in forest area, the major influences to the current net C flux from forest land are management activities and the ongoing impacts of previous land-use changes. These activities affect the net flux of C by altering the amount of C stored in forest ecosystems. For example, intensified management of forests that leads to an increased rate of growth may increase the eventual biomass density of the forest, thereby increasing the uptake and storage of C.[29] Though harvesting forests removes much of the aboveground C, on average the estimated volume of annual net growth in the conterminous U.S. states is about double the volume of annual removals on timberlands (Oswalt et al. 2014). The reversion of cropland or grassland to forest land increases C storage in all pools. In concert with this trend, conversion of croplands and grasslands to forest lands continues to drive net increases in forest C stocks over time especially in northern and southern regions. The net effects of forest management and the effects of land-use change involving forest land are captured in the

---

[29] The term "biomass density" refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. Dry biomass is 50 percent C by weight.

estimates of C stocks and fluxes presented in this section [outside of the “hold-out” period (i.e., the time period lands remain in a conversion category) of the estimates contained within the lands converted to forest section].

Figure 6-2: Changes in Forest Area by Region for *Forest Land Remaining Forest Land* in the conterminous United States and coastal Alaska (1990-2014)



Forest Carbon Stocks and Stock Change

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, and timber harvesting and use have resulted in net uptake (i.e., net sequestration) of C each year from 1990 through 2014. The rate of forest clearing in the 17th century following European settlement had slowed by the late 19th century. Through the later part of the 20th century many areas of previously forested land in the United States were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still influence C fluxes from these forest lands. More recently, the 1970s and 1980s saw a resurgence of federally-sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests have also affected net C fluxes. Because most of the timber harvested from U.S. forest land is used in wood products, and many discarded wood products are disposed in solid-waste disposal sites (SWDS) rather than by incineration, significant quantities of C in harvested wood are transferred to long-term storage pools rather than being released rapidly to the atmosphere (Skog 2008). The size of the stocks in these long-term C storage pools has increased during the last century with the question arising as to how long U.S. forest land can remain a net C sink (Woodall et al. 2013; Coulston et al. 2015; Wear and Coulston 2015). Changes in C stocks in U.S. forests and harvested wood associated with *Forest Land Remaining Forest Land* were estimated to account for net sequestration of 583.4 MMT CO_2 Eq. (159.1 MMT C) in 2014 (Table 6-8 and Table 6-9). In addition to the net accumulation of C in harvested wood pools, sequestration is a reflection of net forest growth. Overall, estimates of average C density in forest ecosystems (including all pools) remained stable at approximately 0.0003 T C/ha from 1990 to 2014 (Table 6-9 and Table 6-10). The stable forest ecosystem C density when combined with increasing forest area results in net C accumulation over time. Management practices that increase C stocks on forest land, as well as legacy effects of afforestation and reforestation efforts, influence the trends of increased C densities in forests and increased forest land in the United States (see Section 6.3 *Land Converted to Forest Land* for details) (Woodall et al. 2015b). By region, the southern and northern regions of the United States were the largest contributors to net forest ecosystem C flux (Figure 6-3). As per prior submissions, aboveground live biomass accounted for the majority of net sequestration among all forest ecosystem pools (Figure 6-4).

Estimated annual net additions to HWP C stock increased slightly between 2013 and 2014. Estimated net additions to solidwood products in use slightly increased due to a further recovery of the housing market. Estimated net additions to products in use for 2014 are about 20 percent of the level of net additions to products in use in 2007, i.e., prior to the recession. 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 due, in large part, to updated data on Products in Use from 2010 to the present.

Table 6-8: Net CO_2 Flux from Forest Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools. (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2010	2011	2012	2013	2014
Forest	**(444.3)**	**(430.0)**	**(492.8)**	**(483.4)**	**(478.0)**	**(476.9)**	**(475.7)**
Aboveground	(311.8)	(309.7)	(330.6)	(328.8)	(324.0)	(323.0)	(321.9)
Belowground	(66.5)	(65.5)	(69.5)	(69.1)	(68.1)	(67.8)	(67.5)
Dead Wood	(34.7)	(44.0)	(50.2)	(52.8)	(53.6)	(53.8)	(54.1)
Litter	(35.8)	(28.4)	(34.4)	(33.9)	(33.1)	(32.8)	(32.6)
Soil Organic C	4.5	17.7	(8.2)	1.2	0.7	0.6	0.4
Harvested Wood	**(131.7)**	**(102.4)**	**(92.2)**	**(94.7)**	**(98.7)**	**(103.2)**	**(107.7)**
Products in Use	(64.7)	(42.7)	(29.2)	(30.3)	(33.1)	(36.3)	(39.5)
SWDS	(67.0)	(59.7)	(63.0)	(64.3)	(65.6)	(66.9)	(68.2)
Total Net Flux	**(576.0)**	**(532.4)**	**(585.0)**	**(578.1)**	**(576.7)**	**(580.1)**	**(583.4)**

Note: Forest C stocks do not include forest stocks in U.S. Territories, Hawaii, a portion of managed forests in Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Table 6-9: Net C Flux from Forest Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

Carbon Pool	1990	2005	2010	2011	2012	2013	2014
Forest	**(121.2)**	**(117.3)**	**(134.4)**	**(131.8)**	**(130.4)**	**(130.1)**	**(129.7)**
Aboveground Biomass	(85.0)	(84.5)	(90.2)	(89.7)	(88.4)	(88.1)	(87.8)
Belowground Biomass	(18.1)	(17.9)	(19.0)	(18.9)	(18.6)	(18.5)	(18.4)
Dead Wood	(9.5)	(12.0)	(13.7)	(14.4)	(14.6)	(14.7)	(14.7)
Litter	(9.8)	(7.8)	(9.4)	(9.2)	(9.0)	(9.0)	(8.9)

Soil Organic C	1.2	4.8	(2.2)	0.3	0.2	0.2	0.1
Harvested Wood	**(35.9)**	**(27.9)**	**(25.1)**	**(25.8)**	**(26.9)**	**(28.2)**	**(29.4)**
Products in Use	(17.7)	(11.7)	(8.0)	(8.3)	(9.0)	(9.9)	(10.8)
SWDS	(18.3)	(16.3)	(17.2)	(17.5)	(17.9)	(18.3)	(18.6)
Total Net Flux	**(157.1)**	**(145.2)**	**(159.5)**	**(157.7)**	**(157.3)**	**(158.2)**	**(159.1)**

Note: Forest C stocks do not include forest stocks in U.S. Territories, Hawaii, a portion of managed lands in Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Stock estimates for forest and harvested wood C storage pools are presented in Table 6-10. Together, the estimated aboveground live and forest soil pools account for a large proportion of total forest C stocks. The estimated C stocks summed for non-soil pools increased over time. Therefore, the estimated C sequestration was greater than C emissions from forests, as discussed above. Note that the forest land area estimates in Table 6-10 do not precisely match those in the Representation of the U.S. Land Base section for *Forest Land Remaining Forest Land*. This is because the forest land area estimates in Table 6-10 only include managed forest land in the conterminous 48 states and southeast/southcentral coastal Alaska (which is the current area encompassed by FIA survey data, approximately 6.2 million ha) while the estimates in the Representation of the U.S. Land Base section include all managed forest land in Alaska (approximately 28.0 million ha).

Table 6-10: Forest area (1,000 ha) and C Stocks in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

	1990	2005	2010	2011	2012	2013	2014	2015
Forest Area (1000 ha)	***261,796***	***268,029***	***270,065***	***270,462***	***270,871***	***271,871***	***271,719***	***272,158***
Carbon Pools (MMT C)								
Forest	**84,891**	**87,271**	**88,444**	**88,270**	**88,444**	**88,618**	**88,790**	**88,962**
Aboveground Biomass	11,896	13,076	13,688	13,598	13,688	13,777	13,865	13,953
Belowground Biomass	2,442	2,691	2,820	2,801	2,820	2,839	2,857	2,876
Dead Wood	2,404	2,574	2,665	2,651	2,665	2,680	2,695	2,710
Litter	5,833	5,958	6,016	6,006	6,016	6,025	6,034	6,042
Soil Organic C	62,316	62,972	63,255	63,214	63,255	63,297	63,339	63,381
Harvested Wood	**1,897**	**2,356**	**2,527**	**2,500**	**2,527**	**2,555**	**2,584**	**2,615**
Products in Use	1,250	1,449	1,499	1,490	1,499	1,509	1,520	1,531
SWDS	647	906	1,028	1,010	1,028	1,046	1,065	1,084
Total C Stock	**86,788**	**89,627**	**90,971**	**90,770**	**90,971**	**91,173**	**91,374**	**91,577**

Note: Forest area and C stock estimates include all forest land in the conterminous 48 states plus managed forests in southeast/southcentral coastal Alaska, which is the current area encompassed by FIA survey data. Forest C stocks do not include forest stocks in U.S. Territories, Hawaii, a large portion of interior Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding. Inventories are assumed to represent stocks as of January 1 of the Inventory year. Flux is the net annual change in stock. Thus, an estimate of flux for 2014 requires estimates of C stocks for 2014 and 2015.

Figure 6-3: Forest Ecosystem C Stock Change by Region in *Forest Land Remaining Forest Land* in the conterminous U.S. and coastal Alaska (1990-2014)

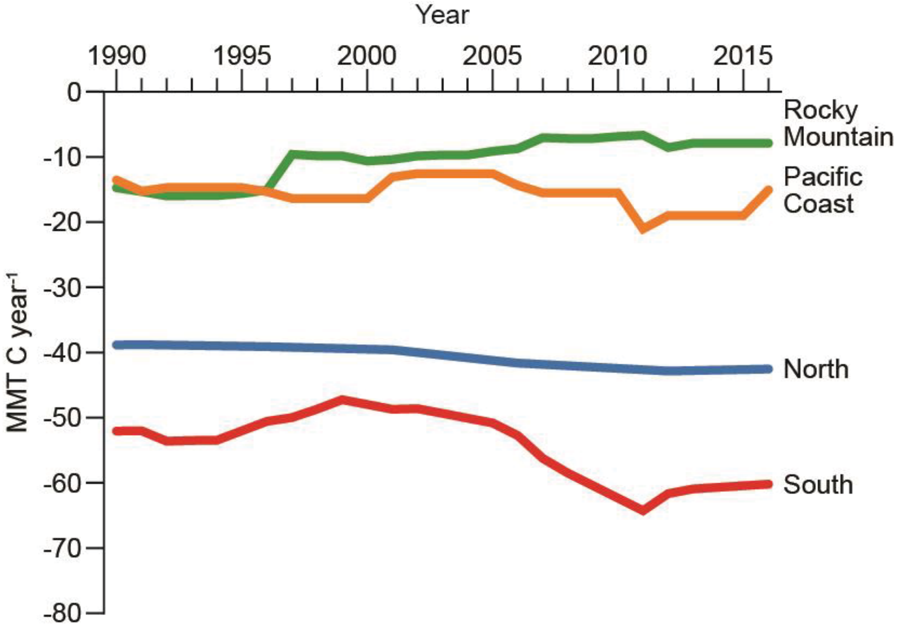
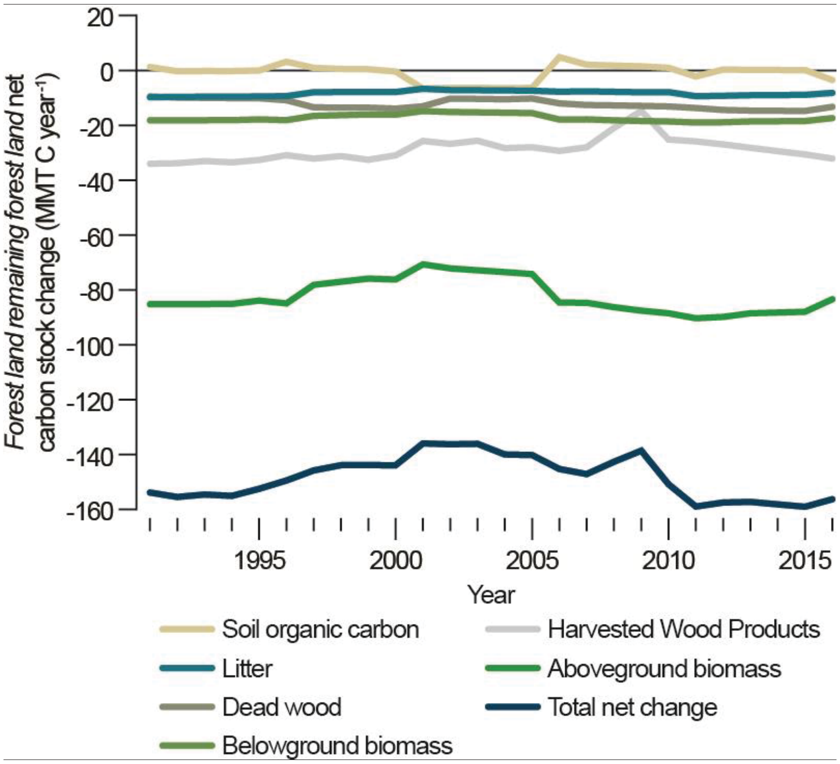


Figure 6-4: Estimated Net Annual Changes in C Stocks for Major C Pools in *Forest Land Remaining Forest Land* in the Conterminous U.S. and Coastal Alaska (MMT C/year)



Box 6-3: CO_2 Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly accounts for all C losses due to disturbances such as forest fires, because only C remaining in the forest is estimated. Net C stock change is estimated by subtracting consecutive C stock estimates. A forest fire disturbance removes C from the forest. The inventory data on which net C stock estimates are based already reflect this C loss. Therefore, estimates of net annual changes in C stocks for U.S. forest land already account for CO_2 emissions from forest fires occurring in the conterminous states as well as the portion of managed forest lands in Alaska that are captured in this Inventory. Because it is of interest to quantify the magnitude of CO_2 emissions from fire disturbance, these separate estimates are highlighted here. Non-CO_2 greenhouse gas emissions from forest fires are also quantified in a separate section below.

The IPCC (2006) methodology and a combination of U.S.-specific data on annual area burned and potential fuel availability together with default combustion factors were employed to estimate CO_2 emissions from forest fires. CO_2 emissions for wildfires in the conterminous 48 states and in Alaska as well as prescribed fires in 2014 were estimated to be 92.3 MMT CO_2/year (Table 6-11). Most of this quantity is an embedded component of the net annual forest C stock change estimates provided previously (e.g., Table 6-9), but this separate approach to estimate emissions is necessary in order to associate a portion of emissions, including estimates of CH_4 and N_2O with fire. See the discussion in Annex 3.13 for more details on this methodology. Note that the estimates for Alaska provided in Table 6-11 include all managed forest land in the state and are not limited to the subset with permanent inventory plots on managed lands as specified elsewhere in this chapter (e.g., Table 6-9).

Table 6-11: Estimates of CO_2 (MMT/yr) Emissions from Forest Fires in the Conterminous 48 States and Alaska[a]

Year	CO_2 emitted from Wildfires in the Conterminous 48 States (MMT/yr)	CO_2 emitted from Wildfires in Alaska (MMT/yr)	CO_2 emitted from Prescribed Fires (MMT/yr)	Total CO_2 emitted (MMT/yr)
1990	21.3	19.5	0.2	40.9
2005	42.9	80.7	1.3	124.9
2010	12.2	11.2	18.4	41.7
2011	73.9	3.5	5.9	83.3
2012	133.7	2.7	2.9	139.3
2013	64.7	22.3	5.3	92.3
2014[b]	64.7	22.3	5.3	92.3

[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 2014 were incomplete when these estimates were summarized; therefore 2013, the most recent available estimate, is applied to 2014.

Methodology and Data Sources

The methodology described herein is consistent with IPCC (2006). Forest ecosystem C stocks and net annual C stock change were determined according to stock-difference methods, which involved applying C estimation factors to annual forest inventories across time to derive stock change. Harvested wood C estimates were based on factors such as the allocation of wood to various primary and end-use products as well as half-life (the time at which half of the amount placed in use will have been discarded from use) and expected disposition (e.g., product pool, SWDS, combustion). An overview of the different methodologies and data sources used to estimate the C in forest ecosystems or harvested wood products is provided here. See Annex 3.13 for details and additional information related to the methods and data.

Forest Ecosystem Carbon from Forest Inventory

The United States adopted Forest Carbon Accounting Framework (FCAF) (Woodall et al. 2015a), a new approach that removes the older inventory information from the accounting procedures and enables the delineation of forest C accumulation by forest growth, land use change, and natural disturbances such as fire as suggested in the report provided by the UNFCCC's Expert Review Team (UNFCCC 2012). This framework adheres to accounting guidelines set forth by the Intergovernmental Panel on Climate Change (IPCC 2006) while charting a path forward for the incorporation of emerging research, data, and the needs of stakeholders (e.g., reporting at small scales and boreal forest C). Preliminary results from the new FCAF demonstrate the ability of the new framework to both backcast the annual inventory system while attributing changes in forest C to disturbances and delineating *Land Converted to Forest Land* from *Forest Land Remaining Forest Land*. Numerous improvements are planned, such as refining the estimation of individual C pools and land use change identification, which can be incorporated into the framework with future iterations (see the Planned Improvements section below).

The FCAF system is comprised of a forest dynamics module and a land use dynamics module (Coulston et al. 2015, Woodall et al. 2015a). The forest dynamics module assesses forest C sequestration, forest aging, and disturbance effects (e.g., 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. 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 non-forest observations in the FIA national database (U.S. Forest Service 2015a, b, c). Model predictions for before or after the annual inventory period are constructed from the FCAF system using 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. The accounting system is flexible and can incorporate emerging inventory data (e.g., remeasured western plots and Alaskan lichen biomass), future image-based change estimation information (see Planned Improvements sub-section), information from the Monitoring Trends in Burn Severity database (Eidenshink et al. 2007), and process model output (e.g., inform future forest C densities or land use dynamics). The future accounting system will be increasingly transparent and verifiable through open-source, publicly available R software that links with the FIA database and associated distillations. The accounting system is scalable to allow other users to parameterize models at scales relevant to them, but inherently the framework is built for application at the strategic scale, using FIA data to parameterize the matrices. This introduction to the FCAF is just the first step in a process to engage the public and policy makers in interpreting forest C status and trends.

The FCAF is fundamentally driven by the annual forest inventory system conducted by the FIA program of the USDA Forest Service (Frayer and Furnival 1999, Bechtold and Patterson 2005, USDA Forest Service 2015d, 2015a). The FIA program relies on a rotating panel statistical design with a sampling intensity of one 674.5 m^2 ground plot per 2,403 ha of land and water area. A five-panel design, with 20 percent of the field plots typically measured each year, is used in the eastern United States and a ten-panel design, with 10 percent of the field plots measured each year, is used in the western United States. The interpenetrating hexagonal design across the U.S. landscape enables the sampling of plots at various intensities in a spatially and temporally unbiased manner. Typically, tree and site attributes are measured with higher sample intensity while other ecosystem attributes such as downed dead wood are sampled during summer months at lower intensities. The first step in incorporating FIA data into FCAF was to identify annual inventory datasets by U.S. state. Inventories include data collected on permanent inventory plots on forest lands and were organized as separate datasets, each representing a complete inventory, or survey, of an individual state at a specified time. Many of the annual inventories reported for states are represented as "moving window" averages, which mean that a portion—but not all—of the previous year's inventory is updated each year (USDA Forest Service 2015d). Forest C calculations are organized according to these state surveys, and the frequency of surveys varies by state.

Separate estimates were prepared for the five IPCC C storage pools described above. All estimates 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 2015b, 2015c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. Tier 3 methods, as outlined by IPCC (2006), were used for the five IPCC (2006) reporting pools.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates were made for above- and below-ground biomass components. If inventory plots included data on individual trees, tree C was based on Woodall et al. (2011a), which is also known as the component ratio method (CRM), and is a function of volume, species, and diameter. An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each tree following the same CRM method.

Understory vegetation is a minor component of biomass, which is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground. Estimates of C density were based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory frequently represented over 1 percent of C in biomass, but its contribution rarely exceeded 2 percent of the total.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, downed dead wood, and litter—with C stocks estimated from sample data or from models. The standing dead tree C pools include aboveground and belowground (coarse root) mass and include trees of at least 12.7 cm dbh. Calculations followed the basic method applied to live trees (Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Domke et al. 2011, Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013, Woodall and Monleon 2008, Woodall et al. 2013). 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. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter C. A novel modeling approach, using litter C measurements from FIA plots (Domke et al. In Review), was used to estimate litter C for every FIA plot used in FCAF.

Carbon in Forest Soil

Soil organic carbon (SOC) is the largest terrestrial C sink, and management of this pool is a critical component of efforts to mitigate atmospheric C concentrations. SOC also affects essential biological, chemical, and physical soil functions such as nutrient cycling, water retention, and soil structure (Jandl et al. 2014). Much of the SOC on earth is found in forest ecosystems and is thought to be relatively stable. However, there is growing evidence that SOC is sensitive to global change effects, particularly land use histories, resource management, and climate. In the United States, SOC in forests is monitored by the national forest inventory conducted by the FIA program (O'Neill et al. 2005). In previous C inventory submissions, SOC predictions were based, in part, on a model using the State Soil Geographic (STATSGO) database compiled by the Natural Resources Conservation Service (NRCS) (Amichev and Glabraith 2004). Estimates of forest SOC found in the STATSGO database may be based on expert opinion rather than actual measurements, but these country-specific model predictions have been used in past submissions. The FIA program has been consistently measuring soil attributes as part of the inventory since 2001 and has amassed an extensive inventory of SOC in forest land in the conterminous United States and coastal Alaska (O'Neill et al. 2005). More than 5,000 profile observations of SOC on forest land from FIA and the International Soil Carbon Monitoring Network were used to develop and implement an approach that enabled the prediction of soil C to a depth of 100 cm from empirical measurements to a depth of 20 cm and included site-, stand-, and climate-specific variables that yield predictions of SOC stocks and stock changes specific to forest land in the United States (Domke et al. In Prep).

Harvested Wood Carbon

Estimates of the HWP contribution to forest C sinks and emissions (hereafter called "HWP Contribution") were 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. IPCC (2006) provides methods that allow for reporting of HWP contribution using one of several different accounting approaches: Production, stock change and atmospheric flow, as well as a default method that assumes there is no change in HWP C stocks (see Annex 3.13 for more details about each approach). The United States used the production accounting approach to report HWP Contribution. Under the production approach, C in exported wood was estimated as if it remains in the United States, and C in imported wood was not included in Inventory estimates. Though reported U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches, the stock change and atmospheric flow approaches, are also presented for comparison (see Annex 3.13). Annual estimates of change were 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). Emissions from HWP associated with wood biomass energy are not included in this accounting—a net of zero sequestration and emissions as they are a part of energy accounting (see Chapter 3).

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 were tracked beginning in 1900, with the exception that additions of softwood lumber to housing began in 1800. Solidwood and paper product production and trade data were taken 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, forthcoming). Estimates for disposal of products reflected the change over time in the fraction of products discarded to SWDS (as opposed to burning or recycling) and the fraction of SWDS that were in sanitary landfills versus dumps.

There are five annual HWP variables that were used in varying combinations to estimate HWP contribution using any one of the three main approaches listed above. These are:

(1A) annual change of C in wood and paper products in use in the United States,

(1B) annual change of C in wood and paper products in SWDS in the United States,

(2A) annual change of C in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,

(2B) annual change of C in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,

(3) C in imports of wood, pulp, and paper to the United States,

(4) C in exports of wood, pulp and paper from the United States, and

(5) C in annual harvest of wood from forests in the United States.

The sum of variables 2A and 2B yielded the estimate for HWP contribution under the production accounting approach. A key assumption for estimating these variables was that products exported from the United States and held in pools in other countries have the same half-lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS as they would in the United States.

Uncertainty and Time Series Consistency

A quantitative uncertainty analysis placed bounds on current flux for forest ecosystems through a combination of sample based and model based approaches to uncertainty for forest ecosystem CO_2 flux (Approach 1). A Monte Carlo Stochastic Simulation of the Methods described above and probabilistic sampling of C conversion factors was used to determine the harvested wood product uncertainty (Approach 2). See Annex 3.13 for additional information. The 2014 net annual change for forest C stocks was estimated to be between –823.0 and –351.4 MMT CO_2 Eq. around a central estimate of -583.4 MMT CO_2 Eq. at a 95 percent confidence level. This includes a range of –686.2 to –269.3 MMT CO_2 Eq. around a central estimate of -475.7 MMT CO_2 Eq. for forest ecosystems and -136.8 to -82.2 MMT CO_2 Eq. around a central estimate of -107.7 for HWP.

Table 6-12: Quantitative Uncertainty Estimates for Net CO_2 Flux from *Forest Land Remaining Forest Land*: Changes in Forest C Stocks (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest C Pools[a]	CO_2	(475.7)	(686.2)	(269.3)	−43.6%	+43.6%
Harvested Wood Products[b]	CO_2	(107.7)	(136.8)	(82.2)	−27.0%	+23.7%
Total Forest	**CO_2**	**(583.4)**	**(823.0)**	**(351.4)**	**−40.6%**	**+40.0%**

Note: Parentheses indicate negative values or net sequestration.

[a] Range of flux estimates predicted through a combination of sample based and model based uncertainty, Approach 1.

[b] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval, Approach 2.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

As discussed above, the FIA program has conducted consistent forest surveys based on extensive statistically-based sampling of most of the forest land in the conterminous United States, dating back to 1952. The FIA program includes numerous quality assurance and quality control (QA/QC) procedures, including calibration among field crews, duplicate surveys of some plots, and systematic checking of recorded data. Because of the statistically-based sampling, the large number of survey plots, and the quality of the data, the survey databases developed by the FIA program form a strong foundation for C stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available on the Internet (USDA Forest Service 2015d).

General quality control procedures were used in performing calculations to estimate C stocks based on survey data. For example, the derived C datasets, which include inventory variables such as areas and volumes, were compared to standard inventory summaries such as the forest resource statistics of Oswalt et al. (2014) or selected population estimates generated from FIADB 6.0, which are available at an FIA internet site (USDA Forest Service 2015b). Agreement between the C datasets and the original inventories is important to verify accuracy of the data used. Finally, C stock estimates were compared with previous Inventory report estimates to ensure that any differences could be explained by either new data or revised calculation methods (see the "Recalculations" discussion, below).

Estimates of the HWP variables and the HWP contribution under the production accounting approach use data from U.S. Census and USDA Forest Service surveys of production and trade. Factors to convert wood and paper to units of C are based on estimates by industry and Forest Service published sources. The WOODCARB II model uses estimation methods suggested by IPCC (2006). Estimates of annual C change in solidwood and paper products in use were calibrated to meet two independent criteria. The first criterion is that the WOODCARB II model estimate of C in houses standing in 2001 needs to match an independent estimate of C in housing based on U.S. Census and USDA Forest Service survey data. Meeting the first criterion resulted in an estimated half-life of about 80 years for single family housing built in the 1920s, which is confirmed by other U.S. Census data on housing. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needs to match EPA estimates of discards each year over the period 1990 to 2000 (EPA 2006). These criteria help reduce uncertainty in estimates of annual change in C in products in use in the U.S. and, to a lesser degree, reduce uncertainty in estimates of annual change in C in products made from wood harvested in the United States. In addition, WOODCARB II landfill decay rates have been validated by ensuring that estimates of CH_4 emissions from landfills based on EPA (2006) data are reasonable in comparison to CH_4 estimates based on WOODCARB II landfill decay rates.

Recalculations Discussion

Forest ecosystem stock and stock-change estimates differ from the previous Inventory report principally due to the adoption of a new accounting approach (FCAF; Woodall et al. 2015a). The major differences between FCAF and past accounting approaches is the sole use of annual forest inventory data and the back casting of forest C stocks across the 1990s based on forest C stock density and land use change information derived from the nationally consistent forest inventory (coupled with in situ observations of non-tree C pools such as soils, dead wood, and litter). The adoption of FCAF has enabled the creation of the two land use sections for forest C stocks: *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. In prior submissions (e.g., the 1990-2013 Inventory submission), these two land use sections were combined. A second major change was the adoption of a new approach to estimating forest soil C, the largest stock in the United States. For detailed discussion of these new approaches please refer to the Methodology section, Annex 3.13, Domke et al. (in prep), and Woodall et al. (2015a). In addition to these major changes, the model of Ogle et al. (in preparation) identifies some of the forest land in south central and southeastern coastal Alaska as unmanaged; this is in contrast to past assumptions of "managed" for these forest lands included in the FIADB. Therefore, the estimates for coastal Alaska as included here reflect that adjustment, which effectively reduces the forest area included here by about 5 percent.

In addition to the creation of explicit estimates of removals and emissions by *Forest Land Remaining Forest Land* versus *Land Converted to Forest Land*, the FCAF eliminated the use of inconsistent periodic data which contributed to a data artefact in prior estimates of emissions/removals from 1990 to the present. In the previous Inventory report, there was a reduction in net sequestration from 1995 to 2000 followed by an increase in net sequestration from 2000 to 2004. This artefact of comparing inconsistent inventories of the 1980s through 1990s to the nationally consistent inventories of the 2000s has been removed in this Inventory submission. This has resulted in a fairly consistent annual net sequestration estimate of approximately -160.0 MMT C. Overall, there were net C additions to HWP in use and in landfills combined due, in large part, to updated data on Products in Use from 2010 through present.

Planned Improvements

Reliable estimates of forest C across the diverse ecosystems/industries of the United States require a high level of investment in both annual monitoring and associated analytical techniques. Development of improved monitoring/reporting techniques is a continuous process that occurs simultaneously with annual Inventory submissions. Planned improvements can be broadly assigned to the following categories: continued development of the FCAF, individual C pool estimation, and annual inventory data incorporation.

As this is the first report to explicitly delineate C change by *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* via a new technical approach (FCAF), there are many improvements envisioned. First, the length of time that land remains in a conversion category after a change in land use is currently based on the remeasurement period from the FIA inventory, not the 20 year default (IPCC 2006). Research into the length of time that land remains in a conversion category will be undertaken and a mechanism to account for this in the FCAF will be developed. Second, as FCAF currently operates at the regional scale for the United States research will occur to enable FCAF to operate at finer scales. Third, as the FCAF system was not fully developed in time for this year's inventory report, only *Land Converted to Forest Land* (i.e., LCFL, reforestation or afforestation) was delineated from *Forest Land Remaining Forest Land* (i.e., FLRFL). The explicit accounting of C stock changes associated with land conversion and disturbance will be developed in the 1990-2015 Inventory submission. As in past submissions, deforestation is implicitly included in the report given the annual forest inventory system but not explicitly estimated. Fourth, the transparency and repeatability of FCAF will be increased through the dissemination of open source code (R programming language) which was used in development of this report in concert with the public availability of the annual forest inventory data (USDA 2015b). Fifth, several FIA database processes will be institutionalize to increase efficiency in reporting and further improve transparency, consistency, and availability of data used in reporting. Finally, a Tier 1 approach was used to estimate uncertainty associated with C stock changes in the FLRFL and LCFL categories in this report. There is research underway investigating more robust approaches to total uncertainty (Woodall et al. 2015a) which will be considered in future Inventory reports.

In an effort to reduce the uncertainty associated with the estimation of stocks and stock changes in individual forest C pools, the empirical data and associated models for each pool are annually evaluated for potential improvement (Woodall 2012). In the 1990 through 2010 Inventory report, the approach to tree volume/biomass estimation was evaluated and refined (Domke et al. 2012). In the 1990 through 2011 Inventory report, the standing dead tree C model was replaced with a nationwide inventory and associated empirical estimation techniques (Woodall et al. 2012, Domke et al. 2011, Harmon et al. 2011). In the 1990 through 2012 Inventory report, the downed dead tree C estimates were refined by incorporation of a national field inventory of downed dead wood (Woodall et al. 2013, Domke et al. 2013). In the 1990 through 2013 Inventory report, the litter C model was refined with a nearly nationwide field inventory (Domke et al. in review). In the current Inventory, the approach to estimating the soil C pool was greatly improved (Domke et al. in prep) by incorporating a national inventory of SOC (O'Neil et al. 2005, Woodall et al. 2011b) in combination with auxiliary soil, site, and climate information (Domke et al. in prep). The model used to estimate downed dead wood within the dead wood pool will be refined using nationwide inventory data and auxiliary information similar to the litter and soil C pools (Domke et al. in review, Domke et al. in prep). Finally, components of other pools, such as C in belowground biomass (Russell et al. 2015) and understory vegetation (Russell et al. 2014), are being explored but may require additional investment in field inventories before improvements can be realized with Inventory submissions.

The foundation of forest C accounting is the annual forest inventory system. The ongoing annual surveys by the FIA Program are expected to improve the accuracy and precision of forest C estimates as new state surveys become available (USDA Forest Service 2015b), particularly in western states. Hawaii and U.S. Territories will be included when appropriate forest C data are available (as of July 21, 2015, Hawaii is not yet reporting any data from the annualized sampling design). Forest lands in interior Alaska (AK) are not yet included in this report as an annual inventory has never been conducted in this remote region. A pilot study of an efficient method for inventorying forest C stocks in interior AK (Woodall et al. 2015) has been conducted with results still being evaluated. Although an annual forest inventory of interior AK may be implemented in the 2016 field season, alternative methods of estimating C stock change will need to be explored as it may take over a decade to remeasure newly established plots in the 2016 field season. Leveraging auxiliary information, particularly remotely sensed data (e.g., LiDar and Landsat) and climate information will aid not only the interior AK effort but the entire inventory system. In addition, to fully inventorying all managed forest land in the United States, the more intensive sampling of fine woody debris, litter, and SOC on a subset of FIA plots continues and will substantially improve resolution of C pools (i.e., greater sample intensity; Westfall et al. 2013) as this information becomes available (Woodall et al. 2011b). Increased sample intensity of some C pools and using annualized sampling data as it becomes available for those states currently not reporting are planned for future submissions. The USDA Forest Service FIA Program's forest and wooded land inventories extend beyond the forest land-use (e.g., woodlands and urban areas) with inventory-relevant information for these lands which will likely become increasingly available in coming years.

Non-CO_2 Emissions from Forest Fires

Emissions of non-CO_2 gases from forest fires were estimated using U.S.-specific data for annual area of forest burned and potential fuel availability as well as the default IPCC (2006) emissions and combustion factors applied to the IPCC methodology. Emissions from this source in 2014 were estimated to be 7.3 MMT CO_2 Eq. of CH_4 and 4.8 MMT CO_2 Eq. of N_2O (Table 6-13, kt units available in Table 6-14). The estimates of non-CO_2 emissions from forest fires account for wildfires in the conterminous 48 states and Alaska as well as prescribed fires.

Table 6-13: Estimated Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq.) for U.S. Forests

Gas	1990		2005		2010	2011	2012	2013	2014[a]
CH_4	3.3		9.9		3.3	6.6	11.1	7.3	7.3
N_2O	2.2		6.5		2.2	4.4	7.3	4.8	4.8
Total	**5.4**		**16.5**		**5.4**	**11.0**	**18.3**	**12.2**	**12.2**

[a] The data for 2014 were incomplete when these estimates were summarized; therefore 2013, the most recent available estimate, is applied to 2014.

Table 6-14: Estimated Non-CO_2 Emissions from Forest Fires (kt) for U.S. Forests

Gas	1990		2005		2010	2011	2012	2013	2014[a]
CH_4	131		397		131	265	443	294	294
N_2O	7		22		7	15	24	16	16

[a] The data for 2014 were incomplete when these estimates were summarized; therefore 2013, the most recent available estimate, is applied to 2014.

Methodology

Non-CO_2 emissions from forest fires – specifically for CH_4 and N_2O emissions – were calculated following IPCC (2006) methodology, which included a combination of U.S. specific data on area burned and potential fuel available for combustion along with IPCC default combustion and emission factors. The estimates were calculated according to equation 2.27 of IPCC (2006, Volume 4, Chapter 2), which in general terms is:

$$\text{Emissions} = \text{Area burned} \times \text{Fuel available} \times \text{Combustion factor} \times \text{Emission factor} \times 10^{-3}$$

where area burned is based on Monitoring Trends in Burn Severity (MTBS) data summaries (MTBS 2015), fuel estimates are based on current inventory to carbon estimates as applied in EPA (2015), and combustion and emission factors are from IPCC (2006, Volume 4, Chapter 2). See Annex 3.13 for further details.

Uncertainty and Time-Series Consistency

In order to quantify the uncertainties for emissions from forest fires calculated as described above, a Monte Carlo ("Approach 2") sampling approach was employed to propagate uncertainty in the equation as it was applied for U.S. forest land. See IPCC (2006) and Annex 3.13 for the quantities and assumptions employed to define and propagate uncertainty. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-15.

Table 6-15: Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires in *Forest Land Remaining Forest Land* (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Non-CO_2 Emissions from Forest Fires	CH_4	7.3	1.0	20.1	−86%	+174%
Non-CO_2 Emissions from Forest Fires	N_2O	4.8	1.2	12.4	−76%	+157%

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

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for forest fires included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process. In addition, alternate sources of data for annual areas burned and possible fuel availability were found to be similar to the data in use here. The QA/QC analysis did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The current non-CO_2 emissions estimates are based on the calculation described above and in IPCC (2006), which is a very similar form to the basic calculation of previous Inventory reports (i.e., this report, and the previous). However, some of the data summarized and applied to the calculation are for the current Inventory very different. The use of the MTBS data summaries is the most prominent example (see Planned Improvements discussion in previous Inventories). Annual burned areas on managed forest lands were identified according to Ruefenacht et al. (2008) and Ogle et al. (in preparation). The other change with the current Inventory estimates is in the use of the underlying plot level carbon densities based on forest inventory plots. Although the base data are similar to past years, the current uncertainty estimates are based on an assumption that plot-to-plot variability is a greater influence on uncertainty than the uncertainty in the forest-inventory to C conversion factors (as employed for uncertainty in the past). See Annex 3.13 for additional details.

Planned Improvements

Possible future improvements within the context of this same IPCC (2006) methodology are most likely to involve greater specificity by fire or groups of fires and less reliance on wide regional values or IPCC defaults. Spatially relating potential fuel to more localized forest structure is the best example of this. An additional improvement would be combustion factors more locally appropriate for the type, location, and intensity of fire. All planned improvements depend on future availability of appropriate U.S.-specific data.

N_2O Fluxes from Forest Soils (IPCC Source Category 4A1)

Of the synthetic nitrogen (N) fertilizers applied to soils in the United States, no more than one percent is applied to forest soils. Application rates are similar to those occurring on cropland soils, but in any given year, only a small proportion of total forested land receives N fertilizer. This is because forests are typically fertilized only twice during their approximately 40-year growth cycle (once at planting and once midway through their life cycle). While the rate of N fertilizer application for the area of forests that receives N fertilizer in any given year is relatively high, the annual application rate is quite low over the entire forestland area.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions. Indirect emissions result from fertilizer N that is transformed and transported to another location in a form other than N_2O (NH_3 and NO_x volatilization, NO_3 leaching and runoff), and later converted into N_2O at the off-site location. The indirect emissions are assigned to forest land because the management activity leading to the emissions occurred in forest land.

Direct N_2O emissions from forest soils in 2014 were 0.3 MMT CO_2 Eq. (1 kt), and the indirect emissions were 0.1 MMT CO_2 Eq. (0.4 kt). Total emissions for 2014 were 0.5 MMT CO_2 Eq. (2 kt) and have increased by 455 percent from 1990 to 2014. Increasing emissions over the time series is a result of greater area of N fertilized pine plantations in the southeastern United States and Douglas-fir timberland in western Washington and Oregon. Total forest soil N_2O emissions are summarized in Table 6-16.

Table 6-16: N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* (MMT CO_2 Eq. and kt N_2O)

	1990	2005	2010	2011	2012	2013	2014
Direct N_2O Fluxes from Soils							
MMT CO_2 Eq.	0.1	0.3	0.3	0.3	0.3	0.3	0.3
kt N_2O	+	1	1	1	1	1	1
Indirect N_2O Fluxes from Soils							
MMT CO_2 Eq.	0.0	0.1	0.1	0.1	0.1	0.1	0.1
kt N_2O	+	+	+	+	+	+	+
Total							
MMT CO_2 Eq.	**0.1**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
kt N_2O	**+**	**2**	**2**	**2**	**2**	**2**	**2**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.5 kt.

Methodology

The IPCC Tier 1 approach is used to estimate N_2O from soils within *Forest Land Remaining Forest Land*. According to U.S. Forest Service statistics for 1996 (USDA Forest Service 2001), approximately 75 percent of trees planted are for timber, and about 60 percent of national total harvested forest area is in the southeastern United States. Although southeastern pine plantations represent the majority of fertilized forests in the United States, this Inventory also accounted for N fertilizer application to commercial Douglas-fir stands in western Oregon and Washington. For the Southeast, estimates of direct N_2O emissions from fertilizer applications to forests are based on the area of pine plantations receiving fertilizer in the southeastern United States and estimated application rates (Albaugh et al. 2007; Fox et al. 2007). Not accounting for fertilizer applied to non-pine plantations is justified because fertilization is routine for pine forests but rare for hardwoods (Binkley et al. 1995). For each year, the area of pine receiving N fertilizer is multiplied by the weighted average of the reported range of N fertilization rates (121 lbs. N per acre). Area data for pine plantations receiving fertilizer in the Southeast are not available for 2005-2014, so data from 2004 are used for these years. For commercial forests in Oregon and Washington, only fertilizer applied to Douglas-fir is addressed in the inventory because the vast majority (approximately 95 percent) of the total fertilizer applied to forests in this region is applied to Douglas-fir (Briggs 2007). Estimates of total Douglas-fir area and the portion of fertilized area are multiplied to obtain annual area estimates of fertilized Douglas-fir stands. Similar to the Southeast, data are not available for 2005 through 2014, so data from 2004 are used for these years.

The annual area estimates are multiplied by the typical rate used in this region (200 lbs. N per acre) to estimate total N applied (Briggs 2007), and the total N applied to forests is multiplied by the IPCC (2006) default emission factor of 1 percent to estimate direct N_2O emissions.

For indirect emissions, the volatilization and leaching/runoff N fractions for forest land are calculated using the IPCC default factors of 10 percent and 30 percent, respectively. The amount of N volatilized is multiplied by the IPCC default factor of 1 percent for the portion of volatilized N that is converted to N_2O off-site. The amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site The resulting estimates are summed to obtain total indirect emissions.

Uncertainty and Time-Series Consistency

The amount of N_2O emitted from forests depends not only on N inputs and fertilized area, but also on a large number of variables, including organic C availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and tree planting/harvesting cycles. The effect of the combined interaction of these variables on N_2O flux is complex and highly uncertain. IPCC (2006) does not incorporate any of these variables into the default methodology, except variation in estimated fertilizer application rates and estimated areas of forested land receiving N fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only synthetic N fertilizers are captured, so applications of organic N fertilizers are not estimated. However, the total quantity of organic N inputs to soils is included in the *Agricultural Soil Management* and *Settlements Remaining Settlements* sections.

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates are assigned a default level[30] of uncertainty at ±50 percent, and area receiving fertilizer is assigned a ±20 percent according to expert knowledge (Binkley 2004). The uncertainty ranges around the 2005 activity data and emission factor input variables are directly applied to the 2014 emission estimates. IPCC (2006) provided estimates for the uncertainty associated with direct and indirect N_2O emission factor for synthetic N fertilizer application to soils.

Uncertainty is quantified using simple error propagation methods (IPCC 2006). The results of the quantitative uncertainty analysis are summarized in Table 6-17. Direct N_2O fluxes from soils in 2014 are estimated to be between 0.1 and 1.1 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the 2014 emission estimate of 0.3 MMT CO_2 Eq. Indirect N_2O emissions in 2014 are between 0.02 and 0.4 MMT CO_2 Eq., ranging from 86 percent below to 238 percent above the 2014 emission estimate of 0.1 MMT CO_2 Eq.

Table 6-17: Quantitative Uncertainty Estimates of N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
Forest Land Remaining Forest Land			**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct N_2O Fluxes from Soils	N_2O	0.3	0.1	1.1	-59%	+211%
Indirect N_2O Fluxes from Soils	N_2O	0.1	+	0.4	-86%	+238%

Note: These estimates include direct and indirect N_2O emissions from N fertilizer additions to both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.
+ Does not exceed 0.05 MMT CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

---

[30] Uncertainty is unknown for the fertilization rates so a conservative value of ±50 percent is used in the analysis.

QA/QC and Verification

The spreadsheet tab containing fertilizer applied to forests and calculations for N_2O and uncertainty ranges are checked and verified.

Planned Improvements

Additional data will be compiled to update estimates of forest areas receiving N fertilizer as new reports are made available. Another improvement is to further disaggregate emissions by state for southeastern pine plantations and northwestern Douglas-fir forests to estimate soil N_2O emission. This improvement is contingent on the availability of state-level N fertilization data for forest land.

6.3 Land Converted to Forest Land (IPCC Source Category 4A2) (TO BE UPDATED)

Estimates for the *Land Converted to Forest Land* source category are currently under development.

6.4 Cropland Remaining Cropland (IPCC Source Category 4B1)

Mineral and Organic Soil Carbon Stock Changes

Carbon (C) in cropland ecosystems occurs in biomass, dead biomass, and soils. However, C storage in biomass and dead organic matter is relatively ephemeral, with the exception of C stored in perennial woody crop biomass, such as citrus groves and apple orchards. Within soils, C is found in organic and inorganic forms of C, but soil organic C (SOC) is the main source and sink for atmospheric CO_2 in most soils. IPCC (2006) recommends reporting changes in SOC stocks due to agricultural land-use and management activities on both mineral and organic soils.[31]

Well-drained mineral soils typically contain from 1 to 6 percent organic C by weight, whereas mineral soils with high water tables for substantial periods during the year may contain significantly more C (NRCS 1999). Conversion of mineral soils from their native state to agricultural land uses can cause up to half of the SOC to be lost to the atmosphere due to enhanced microbial decomposition. The rate and ultimate magnitude of C loss depends on subsequent management practices, climate and soil type (Ogle et al. 2005). Agricultural practices, such as clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, and flooding, can modify both organic matter inputs and decomposition, and thereby result in a net C stock change (Parton et al. 1987, Paustian et al. 1997a, Conant et al. 2001, Ogle et al. 2005). Eventually, the soil can reach a new equilibrium that reflects a balance between C inputs (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and C loss through microbial decomposition of organic matter (Paustian et al. 1997b).

Organic soils, also referred to as histosols, include all soils with more than 12 to 20 percent organic C by weight, depending on clay content (NRCS 1999, Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. When organic soils are prepared for crop production, they are drained and tilled, leading to aeration of the soil that accelerates both the decomposition rate and CO_2 emissions. Due to the depth and richness of the organic layers, C loss from drained organic soils can continue over long periods of time, which varies depending on climate and

---

[31] CO_2 emissions associated with liming are also estimated but are included in a separate section of the report.

composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986). Due to deeper drainage and more intensive management practices, the use of organic soils for annual crop production leads to higher C loss rates than drainage of organic soils in grassland or forests (IPCC 2006).

Cropland Remaining Cropland includes all cropland in an Inventory year that has been used as cropland for the previous 20 years according to the 2010 USDA National Resources Inventory (NRI) land-use survey (USDA-NRCS 2013).[32] The inventory includes croplands on privately-owned lands, as well as a small amount of cropland on public federal lands in the conterminous United States and Hawaii. Cropland in Alaska is not included in the inventory, but is a relatively small amount of United States cropland area (Approximately 28,700 hectares). Some miscellaneous croplands are also not included in the Inventory due to limited understanding of greenhouse gas emissions from these management systems (e.g., aquaculture). This leads to a small discrepancy between the total amount of managed area in *Cropland Remaining Cropland* (see Section 6.1 – *Representation of the U.S. Land Base*) and the cropland area included in the Inventory analysis (0.5 to 0.7 million hectares between 1990 and 2014). Improvements are underway to include croplands in Alaska and other miscellaneous cropland areas as part of future C inventories.

Carbon dioxide emissions and removals[33] due to changes in mineral soil C stocks are estimated using a Tier 3 approach for the majority of annual crops (Ogle et al. 2010). A Tier 2 IPCC method is used for the remaining crops not included in the Tier 3 method (see methodology section for a list of crops in the Tier 2 and 3 methods) (Ogle et al. 2003, 2006). In addition, a Tier 2 method is used for very gravelly, cobbly, or shaley soils (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale) regardless of crop, and for additional changes in mineral soil C stocks that are not addressed with the Tier 3 approach (i.e., change in C stocks after 2010 due to Conservation Reserve Program enrollment). Emissions from organic soils are estimated using a Tier 2 IPCC method.

Land-use and land management of mineral soils are the largest contributor to total net C stock change, especially in the early part of the time series (see Table 6-18 and Table 6-19). (Note: Estimates after 2010 are based on NRI data from 2010 and therefore do not fully reflect changes occurring in the latter part of the time series). In 2014, mineral soils are estimated to remove 43.8 MMT CO_2 Eq. (11.9 MMT C). This rate of C storage in mineral soils represents about a 39 percent decrease in the rate since the initial reporting year of 1990. Emissions from organic soils are 27.8 MMT CO_2 Eq. (7.6 MMT C) in 2014, which is a 0.8 percent decrease compared to 1990. In total, United States agricultural soils in *Cropland Remaining Cropland* sequestered approximately 16.0 MMT CO_2 Eq. (4.4 MMT C) in 2014.

Table 6-18: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT CO_2 Eq.)

Soil Type	**1990**		**2005**		**2010**	**2011**	**2012**	**2013**	**2014**
Mineral Soils	(71.2)		(45.2)		(32.5)	(47.9)	(46.5)	(44.6)	(43.8)
Organic Soils	28.0		28.7		27.8	27.8	27.8	27.8	27.8
Total Net Flux	**(43.2)**		**(16.5)**		**(4.7)**	**(20.0)**	**(18.7)**	**(16.8)**	**(16.0)**

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

Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series.

---

[32] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an overestimation of *Cropland Remaining Cropland* in the early part of the time series to the extent that some areas are converted to cropland prior to 1979.

[33] Note that removals occur through uptake of CO_2 into crop and forage biomass that is later incorporated into soil C pools.

Table 6-19: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT C)

Soil Type	1990	2005	2010	2011	2012	2013	2014
Mineral Soils	(19.4)	(12.3)	(8.9)	(13.1)	(12.7)	(12.2)	(11.9)
Organic Soils	7.6	7.8	7.6	7.6	7.6	7.6	7.6
Total Net Flux	**(11.8)**	**(4.5)**	**(1.3)**	**(5.5)**	**(5.1)**	**(4.6)**	**(4.4)**

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

Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series.

The major cause of the reduction in soil C accumulation over the time series (i.e., 2014 is 63 percent less than 1990) is the decline in annual cropland enrolled in the Conservation Reserve Program (CRP)[34] which was initiated in 1985 (Jones et al., in prep). For example, over 2 million hectares of land in the CRP were returned to agricultural production during the last 5 years resulting in a loss of soil C. However, positive increases in C stocks continue on the nearly 10 million hectares of land currently enrolled in the CRP, as well as from intensification of crop production by limiting the use of bare-summer fallow in semi-arid regions, increased hay production, and adoption of conservation tillage (i.e., reduced- and no-till practices).

The spatial variability in the 2014 annual CO_2 stock changes are displayed in Figure 6-5 and Figure 6-6 for C stock changes in mineral and organic soils, respectively. The highest rates of net C accumulation in mineral soils occurred in the Midwest, which is the region with the largest amounts of conservation tillage, with the next highest rates of accumulation in the South-central and Northwest regions of the United States. The regions with the highest rates of emissions from organic soils occur in the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and the Pacific Coast (particularly California), which coincides with largest concentrations of organic soils in the United States that are used for agricultural production.

Figure 6-5: Total Net Annual CO_2 Flux for Mineral Soils under Agricultural Management within States, 2014, *Cropland Remaining Cropland* (TO BE UPDATED)

Figure 6-6: Total Net Annual CO_2 Flux for Organic Soils under Agricultural Management within States, 2014, *Cropland Remaining Cropland* (TO BE UPDATED)

Methodology

The following section includes a description of the methodology used to estimate changes in soil C stocks for *Cropland Remaining Cropland*, including (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils.

Soil C stock changes are estimated for *Cropland Remaining Cropland* (as well as agricultural land falling into the IPCC categories *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*) according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2013). The NRI is a statistically-based sample of all non-federal land, and includes approximately 596,787 survey locations in agricultural land for the conterminous United States and Hawaii.[35] Each survey location is associated with an "expansion factor" that allows scaling of C stock changes from NRI survey locations to the entire country (i.e., each expansion factor represents the amount of area with the same land-use/management history as the sample point). Land-use and some

---

[34] The Conservation Reserve Program (CRP) is a land conservation program administered by the Farm Service Agency (FSA). In exchange for a yearly rental payment, farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality. Contracts for land enrolled in CRP are 10-15 years in length. The long-term goal of the program is to re-establish valuable land cover to help improve water quality, prevent soil erosion, and reduce loss of wildlife habitat.

[35] NRI survey locations are classified as agricultural if under grassland or cropland management between 1990 and 2010.

management information (e.g., crop type, soil attributes, and irrigation) were collected for each NRI point on a 5-year cycle beginning from 1982 through 1997. For cropland, data had been collected for 4 out of 5 years during each survey cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through1997). In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2012 (USDA-NRCS 2015). However, this Inventory only uses NRI data through 2010 because newer data were not available in time to incorporate the additional years. NRI survey locations are classified as *Cropland Remaining Cropland* in a given year between 1990 and 2010 if the land use had been cropland for a continuous time period of at least 20 years.[36] Cropland includes all land used to produce food and fiber, in addition to forage that is harvested and used as feed (e.g., hay and silage), and cropland that has been enrolled in the Conservation Reserve Program (i.e., considered reserve cropland).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes for mineral soils on the majority of land that is used to produce annual crops in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat. The model-based approach uses the DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011) to estimate soil C stock changes and soil nitrous oxide emissions from agricultural soil management. Carbon and N dynamics are linked in plant-soil systems through the biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil C and 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.

The remaining crops on mineral soils are estimated using an IPCC Tier 2 method (Ogle et al. 2003), including some vegetables, tobacco, perennial/horticultural crops, and crops that are rotated with these crops. The Tier 2 method is also used for very gravelly, cobbly, or shaley soils (greater than 35 percent by volume), and stock changes on federal croplands are estimated with the Tier 2 method. Mineral SOC stocks are estimated using a Tier 2 method for these areas because the DAYCENT model, which is used for the Tier 3 method, has not been fully tested for estimating C stock changes associated with these crops and rotations, as well as cobbly, gravelly, or shaley soils. In addition, there is insufficient information to simulate croplands on federal lands. The Tier 2 methods is also used to estimate additional stock changes on lands enrolled in CRP after 2010, which is the last year of data in the NRI time series, using aggregated data on CRP enrollment compiled by the USDA Farm Services Agency.

Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described below and in Annex 3.12.

Tier 3 Approach

Mineral SOC stocks and stock changes are estimated using the DAYCENT biogeochemical[37] model (Parton et al. 1998; Del Grosso et al. 2001, 2011), which simulates cycling of C, N and other nutrients in cropland, grassland, forest, and savanna ecosystems. 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. The modeling approach uses daily weather data as an input, along with information about soil physical properties. Input data on land use and management are specified at a daily resolution and include land-use type, crop/forage type, and management activities (e.g., planting, harvesting, fertilization, manure amendments, tillage, irrigation, residue removal, grazing, and fire). The model simulates net primary productivity using the NASA-CASA production algorithm for most croplands[38] (Potter et al. 1993, Potter et al. 2007) and subsequent C

---

[36] NRI survey locations are classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification prior to 2002 was based on less than 20 years of recorded land-use history for the time series.

[37] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment

[38] NPP is estimated with the NASA-CASA algorithm for most of the cropland that is used to produce major commodity crops in the central United States from 2000-2010. Other regions and years prior to 2000 are simulated with a method that incorporates water, temperature and moisture stress on crop production (see Metherell et al. 1993), but does not incorporate the additional information about crop condition provided with remote sensing data.

additions to soil. The model also simulates soil temperature, and water dynamics, in addition to turnover, stabilization, and mineralization of soil organic matter C and nutrients (N, P, K, S). This method is more accurate than the Tier 1 and 2 approaches provided by the IPCC (2006) because the simulation model treats changes as continuous over time as opposed to the simplified discrete changes represented in the default method (see Box 6-4 for additional information).

Box 6-4: Tier 3 Approach for Soil C Stocks Compared to Tier 1 or 2 Approaches

A Tier 3 model-based approach is used to estimate soil C stock changes on the majority of agricultural land on mineral soils. This approach results in a more complete accounting of soil C stock changes and entails several fundamental differences from the IPCC Tier 1 or 2 methods, as described below.

(1) The IPCC Tier 1 and 2 methods are simplified and classify land areas into discrete categories based on highly aggregated information about climate (six regions), soil (seven types), and management (eleven management systems) in the United States. In contrast, the Tier 3 model incorporates the same variables (i.e., climate, soils, and management systems) with considerably more detail both temporally and spatially, and captures multi-dimensional interactions through the more complex model structure.
(2) The IPCC Tier 1 and 2 methods have a simplified spatial resolution in which data are aggregated to soil types in climate regions, and there about 30 of combinations in the United States. In contrast, the Tier 3 model simulates soil C dynamics at more than 300,000 individual NRI survey locations in individual fields.
(3) The IPCC Tier 1 and 2 methods use simplified equilibrium step changes for changes in carbon emissions. In contrast, the Tier 3 approach simulates a continuous time period. More specifically, the DAYCENT model (i.e., daily time-step version of the Century model) simulates soil C dynamics (and CO_2 emissions and uptake) on a daily time step based on C emissions and removals from plant production and decomposition processes. These changes in soil C stocks are influenced by multiple sources that affect primary production and decomposition, including changes in land use and management, weather variability and secondary feedbacks between management activities, climate, and soils.

Historical land-use patterns and irrigation histories are simulated with DAYCENT based on the 2010 USDA NRI survey (USDA-NRCS 2013). Additional sources of activity data are used to supplement the land-use information from NRI. The Conservation Technology Information Center (CTIC 2004) provided annual data on tillage activity at the county level for the conterminous United States between 1989 and 2004, and these data are adjusted for long-term adoption of no-till agriculture (Towery 2001). Information on fertilizer use and rates by crop type for different regions of the United States are obtained primarily from the USDA Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of manure application to cropland during 1997 are estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. Specifically, county-scale ratios of manure available for application to soils in other years relative to 1997 are used to adjust the area amended with manure (see Annex 3.12 for further details). Greater availability of managed manure N relative to 1997 is assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 is assumed to reduce the amended area. Data on the county-level N available for application are estimated for managed systems based on the total amount of N excreted in manure minus N losses during storage and transport, and including the addition of N from bedding materials. Nitrogen losses include direct N_2O emissions, volatilization of ammonia and NO_x, runoff and leaching, and poultry manure used as a feed supplement. More information on livestock manure production is available in Section 5.2 - Manure Management and Annex 3.11.

Daily weather data are another input to the model simulations, and these data are based on a 4 km gridded product from the PRISM Climate Group (2015). Soil attributes are obtained from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2015). The C dynamics at each NRI point are simulated 100 times as part of the uncertainty analysis, yielding a total of over 18 million simulation runs for the analysis. Uncertainty in the C stock estimates from DAYCENT associated with parameterization and model algorithms are adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Ogle et al. 2007, 2010). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2010. C stock changes from 2011 to 2014 are assumed to be similar to 2010 for this Inventory. Future Inventories will be updated with new activity data and the time series will be recalculated (see Planned Improvements section).

Tier 2 Approach

In the IPCC Tier 2 method, data on climate, soil types, land-use, and land management activity are used to classify land area and apply appropriate stock change factors (Ogle et al. 2003, 2006). Reference C stocks are estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provided a more robust sample for estimating the reference condition. U.S.-specific stock change factors are derived from published literature to determine the impact of management practices on SOC storage (Ogle et al. 2003, Ogle et al. 2006). The factors include changes in tillage, cropping rotations, intensification, and land-use change between cultivated and uncultivated conditions. U.S. factors associated with organic matter amendments are not estimated due to an insufficient number of studies in the United States to analyze the impacts. Instead, factors from IPCC (2006) are used to estimate the effect of those activities.

Climate zones in the United States are classified using mean precipitation and temperature (1950-2000) variables from the WorldClim data set (Hijmans et al. 2005) and potential evapotranspiration data from the Consortium for Spatial Information (CGIAR-CSI) (Zomer et al. 2008, Zomer et al. 2007) (Figure A-14). IPCC climate zones are then assigned to NRI point locations.

Activity data are primarily based on the historical land-use/management patterns recorded in the 2010 NRI (USDA-NRCS 2013). Each NRI point is classified by land use, soil type, climate region, and management condition. Survey locations on federal lands are included in the NRI, but land use and cropping history are not compiled at these locations in the survey program (i.e., NRI is restricted to data collection on non-federal lands). Land use patterns at the NRI survey locations on federal lands are based on the National Land Cover Database (NLCD) (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). Classification of cropland area by tillage practice is based on data from the Conservation Technology Information Center (CTIC 2004, Towery 2001) as described above. Activity data on wetland restoration of Conservation Reserve Program land are obtained from Euliss and Gleason (2002). Manure N amendments over the inventory time period are based on application rates and areas amended with manure N from Edmonds et al. (2003), in addition to the managed manure production data discussed in the methodology subsection for the Tier 3 analysis.

Combining information from these data sources, SOC stocks for mineral soils are estimated 50,000 times for 1985, 1990, 1995, 2000, 2005, and 2010, using a Monte Carlo stochastic simulation approach and probability distribution functions for U.S.-specific stock change factors, reference C stocks, and land-use activity data (Ogle et al. 2002, Ogle et al. 2003, Ogle et al. 2006). The annual C stock changes for 1990 through 2014 for the Tier 2 method are determined by calculating the average annual change in stocks between each of the five-year blocks, and assuming that C stock changes from 2011-2014 are similar to 2006-2010.

Additional Mineral C Stock Change

Annual C stock change estimates for mineral soils between 2011 and 2014 are adjusted to account for additional C stock changes associated with gains or losses in soil C after 2010 due to changes in CRP enrollment (USDA-FSA 2014). The change in enrollment relative to 2010 is based on data from USDA-FSA (2014) for 2011 through 2014. The differences in mineral soil areas are multiplied by 0.5 metric tons C per hectare per year to estimate the net effect on soil C stocks. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.12 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Cropland Remaining Cropland* are estimated using the Tier 2 method provided in IPCC (2006), with U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. The final estimates included a measure of uncertainty as determined from the Monte Carlo Stochastic Simulation with 50,000 iterations. Emissions are based on the annual data for drained organic soils from 1990 to 2010 for

Cropland Remaining Cropland areas in the 2010 NRI (USDA-NRCS 2013). The annual emissions estimated for 2010 are applied to 2011 through 2014.[39]

Uncertainty and Time-Series Consistency

Uncertainty associated with the *Cropland Remaining Cropland* land-use category is addressed for changes in agricultural soil C stocks (including both mineral and organic soils). Uncertainty estimates are presented in Table 6-20 for each subsource (mineral soil C stocks and organic soil C stocks) and the method that is used in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty for the Tier 2 and 3 approaches is derived using a Monte Carlo approach (see Annex 3.12 for further discussion), but the C stock changes from the individual Tier 2 and 3 approaches are combined using the simple error propagation method provided by the IPCC (2006). The combined uncertainty is calculated by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The combined uncertainty for soil C stocks in *Cropland Remaining Cropland* ranged from 211 percent below to 217 percent above the 2014 stock change estimate of -16.0 MMT CO_2 Eq.

Table 6-20: Approach 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Cropland Remaining Cropland* (MMT CO_2 Eq. and Percent)

Source	2014 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology	(44.3)	(76.4)	(12.2)	-72%	+72%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(3.2)	(5.2)	(1.5)	-64%	+54%
Mineral Soil C Stocks: Cropland Remaining Cropland (Change in CRP enrollment relative to 2003)	3.7	1.9	5.6	-50%	+50%
Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	27.8	17.8	41.0	-36%	+48%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	**(16.0)**	**(49.7)**	**18.8**	**-211%**	**+217%**

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
Notes: Parentheses indicate net sequestration.

Uncertainty is also associated with lack of reporting of agricultural biomass and litter C stock changes. Biomass C stock changes are likely minor in perennial crops, such as orchards and nut plantations, given the small amount of change in land that is used to produce these commodities in the United States. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may be significantly changing biomass C stocks over the Inventory times series, at least in some regions of the United States, but there are currently no datasets to evaluate the trends. Changes in litter C stocks are also assumed to be negligible in croplands over annual time frames, although there are certainly significant changes at sub-annual time scales across seasons. However, this trend may change in the future, particularly if crop residue becomes a viable feedstock for bioenergy production.

Methodological recalculations are applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

---

[39] Future inventories will be updated with new activity data and the time series will be recalculated; see Planned Improvements section.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. Results from the DAYCENT model are compared to field measurements, and a statistical relationship has been developed to assess uncertainties in the predictive capability of the model. The comparisons included over 45 long-term experiments, representing about 800 combinations of management treatments across all of the sites (Ogle et al. 2007) (See Annex 3.12 for more information). Quality control identified problems with simulation of hydric soils in the equilibrium and base histories, which proceed the simulation of the NRI histories from 1979 to 2010. Hydric soils were draining more quickly than expected in the simulations, and so parameters were adjusted to reduce the drainage rate on these soils.

Recalculations Discussion

Methodological recalculations in the current Inventory are associated with the following improvements: 1) incorporation of updated NRI data for 1990 through 2010; and 2) inclusion of federal croplands; and 3) improving the simulation of hydric soil. As a result of these changes, the change in SOC stocks declined by an average of 8.4 MMT CO_2 Eq. over the time series.

Planned Improvements

Two major planned improvements are underway. The first is to update the time series of land use and management data from the USDA NRI so that it is extended from 2010 through 2012 for both the Tier 2 and 3 methods (USDA-NRCS 2015). Fertilization and tillage activity data will also be updated as part of this improvement. The remote-sensing based data on the Enhanced Vegetation Index will be extended through 2012 in order to use the EVI data to drive crop production in DAYCENT. Overall, this improvement will extend the time series of activity data for the Tier 2 and 3 analyses through 2012.

The second major planned improvement is to analyze C stock changes in Alaska for cropland and managed grassland, using the Tier 2 method for mineral and organic soils that is described earlier in this section. This analysis will initially focus on land use change, which typically has a larger impact on soil C stock changes, but will be further refined over time to incorporate more of the management data.

An improvement is also underway to simulate crop residue burning in the DAYCENT based on the amount of crop residues burned according to the data that is used in the Field Burning of Agricultural Residues source category (Section 5.5). This improvement will more accurately represent the C inputs to the soil that are associated with residue burning. Other improvements are underway to refine the production part of the DAYCENT biogeochemical model. For example, senescence events following grain filling in crops, such as wheat, have been refined based on recent model algorithm development, and will be incorporated into next year’s Inventory.

All of these improvements are expected to be completed for the 1990 through 2015 Inventory. However, the time line may be extended if there are insufficient resources to fund all or part of these planned improvements.

CO_2 Emissions from Liming

IPCC (2006) recommends reporting CO_2 emissions from lime additions (in the form of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) to soils. Limestone and dolomite are added by land managers to increase soil pH (i.e., to reduce acidification). Carbon dioxide emissions occur as these compounds react with hydrogen ions in soils. The rate and ultimate magnitude of degradation of applied limestone and dolomite depends on the soil conditions, soil type, climate regime, and whether limestone or dolomite is applied. Emissions from liming of soils have fluctuated over the past 24 years, ranging from 3.7 MMT CO_2 Eq. to 6.0 MMT CO_2 Eq. In 2014, liming of soils in the United States resulted in emissions of 4.1 MMT CO_2 Eq. (1.1 MMT C), representing an 11 percent decrease in emissions since 1990 (see Table 6-21 and Table 6-22). The trend is driven by the amount of limestone and dolomite applied to soils over the time period.

Table 6-21: Emissions from Liming (MMT CO_2 Eq.)

Source	1990	2005	2010	2011	2012	2013	2014
Limestone	4.1	3.9	4.3	3.4	4.5	3.6	3.8
Dolomite	0.6	0.4	0.5	0.4	1.5	0.3	0.3
Total[a]	**4.7**	**4.3**	**4.8**	**3.9**	**6.0**	**3.9**	**4.1**

[a] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements, Forest Land Remaining Forest Land* and *Land Converted to Forest Land* as it is not currently possible to apportion the data by land-use category.

Note: Totals may not sum due to independent rounding.

Table 6-22: Emissions from Liming (MMT C)

Source	1990	2005	2010	2011	2012	2013	2014
Limestone	1.1	1.1	1.2	0.9	1.2	1.0	1.0
Dolomite	0.2	0.1	0.1	0.1	0.4	0.1	0.1
Total[a]	**1.3**	**1.2**	**1.3**	**1.1**	**1.6**	**1.1**	**1.1**

[a] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland*, and *Settlements Remaining Settlements, Forest Land Remaining Forest Land* and *Land Converted to Forest Land* as it is not currently possible to apportion the data by land-use category.

Note: Totals may not sum due to independent rounding.

Methodology

Carbon dioxide emissions from application of limestone and dolomite to soils were estimated using a Tier 2 methodology consistent with IPCC (2006). The annual amounts of limestone and dolomite applied (see Table 6-23) were multiplied by CO_2 emission factors from West and McBride (2005). These emission factors (0.059 metric ton C/metric ton limestone, 0.064 metric ton C/metric ton dolomite) are lower than the IPCC default emission factors because they account for the portion of carbonates that are transported from soils through hydrological processes and eventually deposited in ocean basins (West and McBride 2005). This analysis of lime dissolution is based on studies in the Mississippi River basin, where the vast majority of lime application occurs in the United States (West 2008). Moreover, much of the remaining lime application is occurring under similar precipitation regimes, and so the emission factors are considered a reasonable approximation for all lime application in the United States (West 2008).

The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Industry Surveys* (Tepordei 1993 through 2006; Willett 2007a, 2007b, 2009, 2010, 2011a, 2011b, 2013a, 2014 and 2015; USGS 2008 through 2015). The U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) compiled production and use information through surveys of crushed stone manufacturers. However, manufacturers provided different levels of detail in survey responses so the estimates of total crushed limestone and dolomite production and use were divided into three components: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "estimated" production).

Box 6-5: Comparison of the Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from liming of soils were estimated using a Tier 2 methodology based on emission factors specific to the United States that are lower than the IPCC (2006) emission default factors. Most lime application in the United States occurs in the Mississippi River basin, or in areas that have similar soil and rainfall regimes as the Mississippi River basin. Under these conditions, a significant portion of dissolved agricultural lime leaches through the soil into groundwater. Groundwater moves into channels and is transported to larger rives and eventually the ocean where

$CaCO_3$ precipitates to the ocean floor (West and McBride 2005). The U.S. specific emission factors (0.059 metric ton C/metric ton limestone and 0.064 metric ton C/metric ton dolomite) are about half of the IPCC (2006) emission factors (0.12 metric ton C/metric ton limestone and 0.13 metric ton C/metric ton dolomite). For comparison, the 2014 U.S. emissions estimate from liming of soils is 4.1 MMT CO_2 Eq. using the U.S.-specific factors. In contrast, emissions would be estimated at 8.4 MMT CO_2 Eq. using the IPCC (2006) default emission factors.

Data on "specified" limestone and dolomite amounts were used directly in the emission calculation because the end use is provided by the manufactures and can be used to directly determine the amount applied to soils. However, it is not possible to determine directly how much of the limestone and dolomite is applied to soils for manufacturer surveys in the "unspecified" and "estimated" categories. For these categories, the amounts of crushed limestone and dolomite applied to soils were determined by multiplying the percentage of total "specified" limestone and dolomite production applied to soils by the total amounts of "unspecified" and "estimated" limestone and dolomite production. In other words, the proportion of total "unspecified" and "estimated" crushed limestone and dolomite that was applied to soils is proportional to the amount of total "specified" crushed limestone and dolomite that was applied to soils.

In addition, data were not available for 1990, 1992, and 2013 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate the 1990 and 1992 data, a set of average fractions were calculated using the 1991 and 1993 data. These average fractions were applied to the quantity of "total crushed stone produced or used" reported for 1990 and 1992 in the 1994 *Minerals Yearbook* (Tepordei 1996). To estimate 2014 data, 2013 fractions were applied to a 2014 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2015* (USGS 2015).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1994 and by the USGS from 1995 to the present. In 1994, the "Crushed Stone" chapter in the *Minerals Yearbook* began rounding (to the nearest thousand metric tons) quantities for total crushed stone produced or used. It then reported revised (rounded) quantities for each of the years from 1990 to 1993. In order to minimize the inconsistencies in the activity data, these revised production numbers have been used in all of the subsequent calculations.

Emissions from limestone and dolomite are estimated at the state level and summed to obtain the national estimate. The state-level estimates are not reported here, but are available upon request. Also, it is important to note that all emissions from liming are reported in *Cropland Remaining Cropland* because it is not possible to subdivide the data to each land-use category (i.e., *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements, Forest Land Remaining Forest Land* and *Land Converted to Forest Land*).

Table 6-23: Applied Minerals (MMT)

Mineral	1990		2005		2010	2011	2012	2013	2014
Limestone[a]	19.0		18.1		20.0	15.9	20.8	16.6	17.5
Dolomite[a]	2.4		1.9		1.9	1.9	6.3	1.4	1.5

[a] Data represent amounts applied to *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements, Forest Land Remaining Forest Land* and *Land Converted to Forest Land* as it is not currently possible to apportion the data by land-use category.

Uncertainty and Time-Series Consistency

Uncertainty regarding the amount of limestone and dolomite applied to soils was estimated at ±15 percent with normal densities (Tepordei 2003, Willett 2013b). Analysis of the uncertainty associated with the emission factors included the fraction of lime dissolved by nitric acid versus the fraction that reacts with carbonic acid, and the portion of bicarbonate that leaches through the soil and is transported to the ocean. Uncertainty regarding the time associated with leaching and transport was not addressed in this analysis, but is assumed to be a relatively small contributor to the overall uncertainty (West 2005). The probability distribution functions for the fraction of lime dissolved by nitric acid and the portion of bicarbonate that leaches through the soil were represented as smoothed triangular distributions between ranges of zero and 100 percent of the estimates. The uncertainty surrounding these two components largely drives the overall uncertainty. More information on the uncertainty estimates for CO_2 Emissions from Liming is contained within the Uncertainty Annex 7.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty in CO_2 emissions from liming. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-24. CO_2 emissions from *Liming* in 2014 were estimated to be between -0.5 and 7.8 MMT CO_2 Eq. at the 95 percent confidence level. This confidence interval represents a range of -111 percent below to 88 percent above the 2014 emission estimate of 4.1 MMT CO_2 Eq.

Table 6-24: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Liming (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Liming[b]	CO_2	4.1	(0.5)	7.8	-111%	+88%

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

[b] Includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements, Forest Land Remaining Forest Land* and *Land Converted to Forest Land* as it is not possible to subdivide the data by land-use category.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for liming has been developed and implemented, and the quality control effort focused on the Tier 1 procedures for this Inventory. Quality control procedures did uncover a transcription error in the spreadsheets that was corrected.

Recalculations Discussion

Adjustments were made in the current Inventory to improve the results. First, limestone and dolomite application data for 2013 were approximated in the previous Inventory using a ratio of total crushed stone for 2013 relative to 2012 (similar to 2014 in the current Inventory). The estimates for 2013 were updated with the recently published data from USGS (2015). Second, quality control measures uncovered a transcription error in the 2012 activity data that increased the emission estimate by 0.2 MMT CO_2 Eq. related to the previous Inventory. With these revisions in the activity data, the emissions increased by 3.5 percent in 2012 and decreased by 34 percent in 2013 relative to the previous Inventory.

CO_2 Emissions from Urea Fertilization

The use of urea ($CO(NH_2)_2$) as a fertilizer leads to CO_2 emissions through the release of CO_2 that was fixed during the industrial production process. In the presence of water and urease enzymes, urea is converted into ammonium (NH_4^+), hydroxyl ion (OH), and bicarbonate (HCO_3^-). The bicarbonate then evolves into CO_2 and water. Emissions from urea fertilization in the United States totaled 4.5 MMT CO_2 Eq. (1.2 MMT C) in 2014 (Table 6-25 and Table 6-26). Due to an increase in application of urea fertilizers between 1990 and 2014, CO_2 emissions have increased by 87 percent from this management activity.

Table 6-25: CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq.)

Source	1990		2005		2010	2011	2012	2013	2014
Urea Fertilization[a]	2.4		3.5		3.8	4.1	4.2	4.3	4.5

[a] Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements*, *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* because it is not currently possible to apportion the data by land-use category.

Table 6-26: CO_2 Emissions from Urea Fertilization (MMT C)

Source	1990		2005		2010	2011	2012	2013	2014
Urea Fertilization[a]	0.7		1.0		1.0	1.1	1.2	1.2	1.2

[a] Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements*, *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* because it is not currently possible to apportion the data by land-use category.

Methodology

Carbon dioxide emissions from the application of urea to agricultural soils were estimated using the IPCC (2006) Tier 1 methodology. The method assumes that all CO_2 fixed during the industrial production process of urea are released after application. The annual amounts of urea applied to croplands (see Table 6-27) were derived from the state-level fertilizer sales data provided in *Commercial Fertilizers* (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2014). These amounts were multiplied by the default IPCC (2006) emission factor (0.20 metric tons of C per metric ton of urea), which is equal to the C content of urea on an atomic weight basis. Because fertilizer sales data are reported in fertilizer years (July previous year through June current year), a calculation was performed to convert the data to calendar years (January through December). According to monthly fertilizer use data (TVA 1992b), 35 percent of total fertilizer used in any fertilizer year is applied between July and December of the previous calendar year, and 65 percent is applied between January and June of the current calendar year. For example, for the 2000 fertilizer year, 35 percent of the fertilizer was applied in July through December 1999, and 65 percent was applied in January through June 2000.

Fertilizer sales data for the 2013 and 2014 fertilizer years (i.e., July 2012 through June 2013 and July 2013 through June 2014) were not available for this Inventory. Therefore, urea application in the 2013 and 2014 fertilizer years were estimated using a linear, least squares trend of consumption over the data from the previous five years (2008 through 2012) at the state level. A trend of five years was chosen as opposed to a longer trend as it best captures the current inter-state and inter-annual variability in consumption. State-level estimates of CO_2 emissions from the application of urea to agricultural soils were summed to estimate total emissions for the entire United States. The fertilizer year data is then converted into calendar year data using the method described above.

Emissions are estimated at the state level and summed to obtain the national estimate. The state-level estimates are not reported here, but are available upon request. Also, it is important to note that all emissions from urea fertilization are reported in *Cropland Remaining Cropland* because it is not currently possible to apportion the emissions to each land-use category (i.e., *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland*, *Settlements Remaining Settlements, Forest Land Remaining Forest Land* and *Land Converted to Forest Land*), however, the majority of urea fertilization is likely to have occurred on *Cropland Remaining Cropland*.

Table 6-27: Applied Urea (MMT)

	1990		2005		2010	2011	2012	2013	2014
Urea Fertilizer[a]	3.3		4.8		5.2	5.6	5.8	5.9	6.2

[a] These numbers represent amounts applied to all agricultural land, including *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, *Settlements Remaining Settlements*, *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* because it is not currently possible to apportion the data by land-use category.

Uncertainty and Time-Series Consistency

Uncertainty estimates are presented in Table 6-28 for *Urea Fertilization*. An Approach 2 Monte Carlo analysis was completed. The largest source of uncertainty was the default emission factor, which assumes that 100 percent of the C in $CO(NH_2)_2$ applied to soils is ultimately emitted into the environment as CO_2. This factor does not incorporate the possibility that some of the C may be retained in the soil, and therefore the uncertainty range was set from 0 percent emissions to the maximum emission value of 100 percent using a triangular distribution. In addition, each urea consumption data point has an associated uncertainty. CO_2 emissions from urea fertilization of agricultural soils in 2014 were estimated to be between 2.6 and 4.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 42 percent below to 0 percent above the 2014 emission estimate of 4.5 MMT CO_2 Eq.

Table 6-28: Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Fertilization	CO_2	4.5	2.6	4.5	-42%	0%

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

There are additional uncertainties that are not quantified in this analysis. Urea for non-fertilizer use, such as aircraft deicing, may be included in consumption totals, but the amount is likely very small. For example, research on aircraft deicing practices is consistent with this assumption based on a 1992 survey that found a known annual usage of approximately 2,000 tons of urea for deicing; this would constitute 0.06 percent of the 1992 consumption of urea (EPA 2000). Similarly, surveys conducted from 2002 to 2005 indicate that total urea use for deicing at U.S. airports is estimated to be 3,740 metric tons per year, or less than 0.07 percent of the fertilizer total for 2007 (Itle 2009). In addition, there is uncertainty surrounding the underlying assumptions behind the calculation that converts fertilizer years to calendar years. These uncertainties are negligible over multiple years, however, because an over- or under-estimated value in one calendar year is addressed with corresponding increase or decrease in the value for the subsequent year.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for Urea has been developed and implemented. For this year, the Tier 1 analysis was performed and an error was found in a formula reference to an incorrect cell in the spreadsheets.

Recalculations Discussion

In the current Inventory, the 2013 emission estimate was updated to reflect a correction to the calculations made in the previous Inventory report. Quality control checks uncovered an incorrect spreadsheet cell reference influencing the state-level emission calculations. The 2013 emission estimate increased by 8.3 percent, relative to the previous report, due to this correction.

Planned Improvements

No improvements are planned for this source.

6.5 Land Converted to Cropland (IPCC Source Category 4B2)

Land Converted to Cropland includes all cropland in an Inventory year that had been in another land use(s) during the previous 20 years[40] (USDA-NRCS 2013). For example, grassland or forestland converted to cropland during the past 20 years would be reported in this category. Recently-converted lands are retained in this category for 20 years as recommended in the IPCC guidelines (IPCC 2006). This Inventory includes all croplands in the conterminous United States and Hawaii, but does not include a minor amount of *Land Converted to Cropland* in Alaska. Some miscellaneous croplands are also not included in the inventory due to limited understanding of greenhouse gas dynamics in management systems (e.g., aquaculture) or climate zones (e.g., boreal climates). Consequently there is a discrepancy between the total amount of managed area in *Land Converted to Cropland* (see Section 6.1 – *Representation of the U.S. Land Base*) and the cropland area included in the Inventory. Improvements are underway to include croplands in Alaska and miscellaneous crops in future C inventories.

Background on agricultural carbon (C) stock changes is provided in Section 0 *Cropland Remaining Cropland* and therefore will only be briefly summarized here. Soils are the largest pool of C in agricultural land, and also have the greatest potential for long-term storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared with soils, with the exception of C stored in perennial woody crop biomass. The *2006 IPCC Guidelines* recommend reporting changes in soil organic carbon (SOC) stocks due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[41]

Land use and management of mineral soils in *Land Converted to Cropland* is the largest contributor to C loss throughout the time series, accounting for approximately 71 percent of the emissions in the category (Table 6-29 and Table 6-30). The conversion of grassland to cropland is the largest source of soil C loss (accounting for approximately 84 percent of the average emissions in the category), though losses declined over the time series. The net change in soil C stocks for 2014 is 14.7 MMT CO_2 Eq. (4.0 MMT C), including 10.4 MMT CO_2 Eq. (2.8 MMT C) from mineral soils and 4.3 MMT CO_2 Eq. (1.2 MMT C) from drainage and cultivation of organic soils.

Table 6-29: Net CO_2 Flux from Soil C Stock Changes in *Land Converted to Cropland* by Land Use Change Category (MMT CO_2 Eq.)

Soil Type	1990	2005	2010	2011	2012	2013	2014
Grassland Converted to Cropland							
Mineral	17.3	7.6	8.8	7.3	7.6	7.8	7.8
Organic	3.2	4.2	3.8	3.8	3.8	3.8	3.8
Forest Converted to Cropland							
Mineral	(+)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic	(+)	+	+	+	+	+	+
Other Lands Converted Cropland							
Mineral	1.3	1.2	1.3	1.3	1.3	1.3	1.3

---

[40] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001, which may have led to an underestimation of *Land Converted to Cropland* in the early part of the time series to the extent that some areas are converted to cropland prior to 1979.

[41] CO_2 emissions associated with liming urea fertilization are also estimated but included in 6.4 *Cropland Remaining Cropland*.

Organic	(+)	0.0	0.0	0.0	0.0	0.0	0.0
Settlements Converted Cropland							
Mineral	1.3	1.1	1.2	1.2	1.3	1.3	1.3
Organic	(+)	0.1	0.1	0.1	0.1	0.1	0.1
Wetlands Converted Cropland							
Mineral	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Organic	(0.2)	0.5	0.4	0.4	0.4	0.4	0.4
Total Mineral Soil Flux	**19.8**	**9.9**	**11.3**	**9.8**	**10.2**	**10.4**	**10.4**
Total Organic Soil Flux	**3.0**	**4.8**	**4.3**	**4.3**	**4.3**	**4.3**	**4.3**
Total Net Flux	**22.8**	**14.6**	**15.6**	**14.2**	**14.5**	**14.8**	**14.7**

Notes: Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series.
Parentheses indicate net sequestration.
+ Does not exceed 0.05 MMT CO_2 Eq.

Table 6-30: Net CO_2 Flux from Soil C Stock Changes in *Land Converted to Cropland* (MMT C)

Soil Type	1990	2005	2010	2011	2012	2013	2014
Grassland Converted to Cropland							
Mineral	4.7	2.1	2.4	2.0	2.1	2.1	2.1
Organic	0.9	1.1	1.0	1.0	1.0	1.0	1.0
Forest Converted to Cropland							
Mineral	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Organic	(+)	+	+	+	+	+	+
Other Lands Converted Cropland							
Mineral	0.4	0.3	0.4	0.4	0.4	0.4	0.4
Organic	(+)	0.0	0.0	0.0	0.0	0.0	0.0
Settlements Converted Cropland							
Mineral	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Organic	(+)	+	+	+	+	+	+
Wetlands Converted Cropland							
Mineral	0.0	+	+	+	+	+	+
Organic	(+)	0.1	0.1	0.1	0.1	0.1	0.1
Total Mineral Soil Flux	**5.4**	**2.7**	**3.1**	**2.7**	**2.8**	**2.8**	**2.8**
Total Organic Soil Flux	**0.8**	**1.3**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
Total Net Flux	**6.2**	**4.0**	**4.3**	**3.9**	**4.0**	**4.0**	**4.0**

Notes: Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series.
Parentheses indicate net sequestration.
+ Does not exceed 0.05 MMT C

The spatial variability in the 2014 annual C stock changes for mineral soils is displayed in Figure 6-7 and from organic soils in Figure 6-8. Losses occurred in most regions of the United States. In particular, conversion of grassland and forestland to cropland led to enhanced decomposition of soil organic matter and a net loss of C from the soil pool. The regions with the highest rates of emissions from organic soils coincide with the largest concentrations of organic soils used for agricultural production, including Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and the Pacific Coast (particularly California).

Figure 6-7: Total Net Annual CO_2 Flux for Mineral Soils under Agricultural Management within States, 2014, *Land Converted to Cropland* (TO BE UPDATED)

Figure 6-8: Total Net Annual CO_2 Flux for Organic Soils under Agricultural Management within States, 2014, *Land Converted to Cropland* (TO BE UPDATED)

Methodology

The following section includes a description of the methodology used to estimate changes in soil C stocks for *Land Converted to Cropland*, including (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils Biomass and litter C stock changes associated with conversion of forest to cropland are not explicitly included in this category, but are included in the *Forest Land Remaining Forest Land* section. Further elaboration on the methodologies and data used to estimate stock changes for mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.12.

Soil C stock changes are estimated for *Land Converted to Cropland* according to land-use histories recorded in the 2010 USDA NRI survey (USDA-NRCS 2013). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) had been collected for each NRI point on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and data are currently available through 2012 (USDA-NRCS 2015). However, this Inventory only uses NRI data through 2010 because newer data were not available in time to incorporate the additional years. NRI survey locations are classified as *Land Converted to Cropland* in a given year between 1990 and 2010 if the land use is cropland but had been another use during the previous 20 years. Cropland includes all land used to produce food or fiber, or forage that is harvested and used as feed (e.g., hay and silage).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes for mineral soils on the majority of land that is used to produce annual crops in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat. Soil C stock changes on the remaining soils are estimated with the IPCC Tier 2 method (Ogle et al. 2003), including land used to produce some vegetables, tobacco, perennial/horticultural crops and crops rotated with these crops; land on very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from another land use or federal ownership.[42]

Tier 3 Approach

For the Tier 3 method, mineral SOC stocks and stock changes are estimated using the DAYCENT biogeochemical[43] model (Parton et al. 1998; Del Grosso et al. 2001, 2011). 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. National estimates are obtained by using the model to simulate historical land-use change patterns as recorded in the USDA NRI (USDA-NRCS 2013). C stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2010, but C stock changes from 2010 to 2014 are assumed to be similar to 2010. (Future inventories will be updated with new activity data and the time series will be recalculated; See Planned Improvements section in *Cropland Remaining Cropland*). The methods used for *Land Converted to Cropland* are the same as those described in the Tier 3 portion of *Cropland Remaining Cropland* section for mineral soils.

Tier 2 Approach

For the mineral soils not included in the Tier 3 analysis, SOC stock changes are estimated using a Tier 2 Approach for *Land Converted to Cropland* as described in the Tier 2 Approach for mineral soils in the *Grassland Remaining Grassland* section.

---

[42] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2013).

[43] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Cropland* are estimated using the Tier 2 method provided in IPCC (2006), with U.S.-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section for organic soils.

Uncertainty and Time-Series Consistency

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described for *Cropland Remaining Cropland*. The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Cropland* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 6-31 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The combined uncertainty for soil C stocks in *Land Converted to Cropland* ranged from 94 percent below to 95 percent above the 2014 stock change estimate of 14.7 MMT CO_2 Eq. The uncertainties are large for some of the estimates due to small change in soil C stocks, even though the absolute amount of uncertainty is relatively small.

Table 6-31: Approach 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Cropland* (MMT CO_2 Eq. and Percent)

Source	2014 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a]			
		(MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Converted to Cropland	**11.6**	**(2.1)**	**25.0**	**-118%**	**+115%**
Mineral Soil C Stocks: Tier 3	10.9	(0.8)	22.6	-107%	+107%
Mineral Soil C Stocks: Tier 2	(3.1)	(0.1)	2.2	-97%	+172%
Organic Soil C Stocks: Tier 2	3.8	10.2	+	-168%	+99%
Forests Converted to Cropland	**(+)**	**(0.1)**	**0.1**	**-172%**	**+372%**
Mineral Soil C Stocks: Tier 2	(0.1)	(+)	0.1	-92%	+232%
Organic Soil C Stocks: Tier 2	+	0.1	0.0	-154%	+100%
Other Lands Converted to Cropland	**1.3**	**(+)**	**2.3**	**-102%**	**+76%**
Mineral Soil C Stocks: Tier 2	1.3	(+)	0.3	-102%	+76%
Organic Soil C Stocks: Tier 2	0.0	0.0	0.1	0%	0%
Settlements Converted to Cropland	**1.3**	**0.1**	**2.6**	**-95%**	**+90%**
Mineral Soil C Stocks: Tier 2	1.3	(+)	0.1	-101%	+92%
Organic Soil C Stocks: Tier 2	0.1	0.1	0.4	-91%	+454%
Wetlands Converted to Croplands	**0.5**	**0.2**	**4.4**	**-58%**	**+801%**
Mineral Soil C Stocks: Tier 2	0.1	+	0.2	-43%	+246%
Organic Soil C Stocks: Tier 2	0.4	0.7	4.3	-65%	+908%
Total: Land Converted to Cropland	**14.7**	**0.9**	**28.8**	**-94%**	**+95%**
Mineral Soil C Stocks: Tier 3	**10.9**	**(0.8)**	**22.6**	**-107%**	**+107%**
Mineral Soil C Stocks: Tier 2	**(0.5)**	**(4.1)**	**5.0**	**-677%**	**+1,065%**
Organic Soil C Stocks: Tier 2	**4.3**	**(2.1)**	**9.8**	**-148%**	**+126%**

Note: Parentheses indicate negative values or net sequestration.

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

+ Does not exceed 0.05 MMT CO_2 Eq.

Uncertainty is also associated with lack of reporting of agricultural biomass and litter C stock changes other than the loss of forest biomass and litter, which is reported in the *Forest Land Remaining Forest Land* section of this report. Biomass C stock changes are likely minor in perennial crops, such as orchards and nut plantations, given the small amount of change in land used to produce these commodities in the United States. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have led to significant changes in biomass C stocks, at least in some regions of the United States, but there are currently no datasets to evaluate the trends. Changes in litter C stocks are also assumed to be negligible in croplands over annual time frames, although there are certainly significant changes at sub-annual time scales across seasons. However, this trend may change in the future, particularly if crop residue becomes a viable feedstock for bioenergy production.

Methodological recalculations are applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland*.

Recalculations Discussion

Methodological recalculations in the current Inventory are associated with the following improvements: 1) incorporation of updated NRI data for 1990 through 2010; 2) inclusion of federal croplands; and 3) improving the simulation of hydric soils in DAYCENT. As a result of these improvements to the Inventory, SOC stock changes declined on average, leading to less carbon loss from *Land Converted to Cropland* by an average of 4.4 MMT CO_2 Eq. over the time series.

Planned Improvements

Soil C stock changes with land use conversion from forest land to cropland are undergoing further evaluation to ensure consistency in the time series. Different methods are used to estimate soil C stock changes in forest land and croplands, and while the areas have been reconciled between these land uses, there has been limited evaluation of the consistency in C stock changes with conversion from forest land to cropland. This planned improvement may not be fully implemented for another year, depending on resource availability. Additional planned improvements are discussed in the *Cropland Remaining Cropland* section.

6.6 Grassland Remaining Grassland (IPCC Source Category 4C1)

Grassland Remaining Grassland includes all grassland in an Inventory year that had been classified as grassland for the previous 20 years[44] (USDA-NRCS 2013). Grassland includes pasture and rangeland that are primarily but not exclusively used for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding of legumes. This Inventory includes all privately-owned and federal grasslands in the conterminous United States and Hawaii, but does not include approximately 50 million hectares of *Grassland Remaining Grassland* in Alaska. This leads to a discrepancy with the total amount of managed area in *Grassland Remaining Grassland* (see Section 6.1 – *Representation of the U.S. Land Base*) and the grassland area included in the Inventory analysis (IPCC Source Category 4C1—Section 6.6).

Background on agricultural carbon (C) stock changes is provided in Section 0, *Cropland Remaining Cropland*, and will only be summarized here. Soils are the largest pool of C in agricultural land, and also have the greatest potential for longer-term storage or release of C. Biomass and dead organic matter C pools are relatively small and ephemeral compared to the soil C pool, with the exception of C stored in tree and shrub biomass that occurs in

---

[44] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an overestimation of *Grassland Remaining Grassland* in the early part of the time series to the extent that some areas are converted to grassland prior to 1979.

grasslands. The *2006 IPCC Guidelines* (IPCC 2006) recommend reporting changes in soil organic C (SOC) stocks due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[45]

In *Grassland Remaining Grassland*, there has been considerable variation in soil C stocks between 1990 and 2014. These changes are driven by variability in weather patterns and associated interaction with land management activity. Moreover, changes remain small on a per hectare rate across the time series even in the years with a larger total change in stocks. Land use and management generally increased soil C in mineral soils for *Grassland Remaining Grassland* between 1990 and 2010, after which the trend is reversed to a small decline in soil C. In contrast, organic soils lost relatively small amounts of C annually from 1990 through 2014. Overall, the average change in soil C stocks is an increase by 24.8 MMT CO_2 Eq., from 1990 to 2014 (6.8 MMT C) (Table 6-32 and Table 6-33). Soil C stocks decreased in 2014 by 11.9 MMT CO_2 Eq. (3.3 MMT C), with 7.6 MMT CO_2 Eq. (2.1 MMT C) from mineral soils and 4.3 MMT CO_2 Eq. (1.2 MMT C) from organic soils.

Table 6-32: Net CO_2 Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (MMT CO_2 Eq.)

Soil Type	1990	2005	2010	2011	2012	2013	2014
Mineral Soils	(19.0)	(1.6)	(1.8)	6.9	7.4	7.6	7.6
Organic Soils	6.1	4.5	4.4	4.4	4.3	4.3	4.3
Total Net Flux	**(12.9)**	**2.9**	**2.6**	**11.3**	**11.7**	**11.9**	**11.9**

Note: Totals may not sum due to independent rounding. Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series. Parentheses indicate net sequestration.

Table 6-33: Net CO_2 Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (MMT C)

Soil Type	1990	2005	2010	2011	2012	2013	2014
Mineral Soils	(5.2)	(0.4)	(0.5)	1.9	2.0	2.1	2.1
Organic Soils	1.7	1.2	1.2	1.2	1.2	1.2	1.2
Total Net Flux	**(3.5)**	**0.8**	**0.7**	**3.1**	**3.2**	**3.3**	**3.3**

Notes: Totals may not sum due to independent rounding. Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series. Parentheses indicate net sequestration.

The spatial variability in the 2014 annual flux in CO_2 from mineral soils is displayed in Figure 6-9 and organic soils in Figure 6-10. Although relatively small on a per-hectare basis, grassland soils gained C in several regions during 2014, including the Northeast, Southeast, portions of the Midwest, and Pacific Coastal Region. The regions with the highest rates of emissions from organic soils coincide with the largest concentrations of organic soils used for managed grassland, including the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and the Pacific Coast (particularly California).

Figure 6-9: Total Net Annual CO_2 Flux for Mineral Soils under Agricultural Management within States, 2014, *Grassland Remaining Grassland* (TO BE UPDATED)

Figure 6-10: Total Net Annual CO_2 Flux for Organic Soils under Agricultural Management within States, 2014, *Grassland Remaining Grassland* (TO BE UPDATED)

---

[45] CO_2 emissions associated with liming and urea fertilization are also estimated but included in 6.4 *Cropland Remaining Cropland*.

Methodology

The following section includes a brief description of the methodology used to estimate changes in soil C stocks for *Grassland Remaining Grassland*, including (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils. Further elaboration on the methodologies and data used to estimate stock changes from mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.12.

Soil C stock changes are estimated for *Grassland Remaining Grassland* according to land use histories recorded in the 2010 USDA NRI survey (USDA-NRCS 2013). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI survey location on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2012 (USDA-NRCS 2015). However, this Inventory only uses NRI data through 2010 because newer data were not available in time to incorporate the additional years. NRI survey locations are classified as *Grassland Remaining Grassland* in a given year between 1990 and 2010 if the land use had been grassland for 20 years.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes for most mineral soils in *Grassland Remaining Grassland*. The C stock changes for the remaining soils are estimated with an IPCC Tier 2 method (Ogle et al. 2003), including gravelly, cobbly, or shaley soils (greater than 35 percent by volume) and additional stock changes associated with sewage sludge amendments.

Tier 3 Approach

Mineral SOC stocks and stock changes for *Grassland Remaining Grassland* are estimated using the DAYCENT biogeochemical[46] model (Parton et al. 1998; Del Grosso et al. 2001, 2011), as described in *Cropland Remaining Cropland*. 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. Historical land-use patterns and irrigation histories are simulated with DAYCENT based on the 2010 USDA NRI survey (USDA-NRCS 2013), with supplemental information on fertilizer use and rates from the USDA Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011) and National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of manure application to grassland during 1997 are estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds, et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. Specifically, county-scale ratios of manure available for application to soils in other years relative to 1997 are used to adjust the area amended with manure (see *Cropland Remaining Cropland* for further details). Greater availability of managed manure nitrogen (N) relative to 1997 is, thus, assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 is assumed to reduce the amended area.

The amount of manure produced by each livestock type is calculated for managed and unmanaged waste management systems based on methods described in Section 5.2 - Manure Management and Annex 3.11. Manure N deposition from grazing animals (i.e., PRP manure) is an input to the DAYCENT model (see Annex 3.11), and included approximately percent of total PRP manure (the remainder is deposited on federal lands, which are not included in this Inventory). C stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2010, but C stock changes from 2011 to 2014 are assumed to be similar to 2010 (Future inventories will be updated with new activity data and the time series will be recalculated; See Planned Improvements section in *Cropland Remaining Cropland*). The methods used for *Grassland Remaining Grassland* are the same as those described in the Tier 3 portion of *Cropland Remaining Cropland* section for mineral soils.

---

[46] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

Tier 2 Approach

The Tier 2 approach is based on the same methods described in the Tier 2 portion of *Cropland Remaining Cropland* section for mineral soils, with the exception of the land use and management data that are used in the Inventory for federal grasslands. The NRI (USDA-NRCS 2013) provides land use and management histories for all non-federal lands, and is the basis for the Tier 2 analysis for these areas. However, NRI does not provide land use information on federal lands. These data are based on the National Land Cover Database (NLCD) (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). In addition, the Bureau of Land Management (BLM) manages some of the federal grassland, and has compiled information on grassland condition through the BLM Rangeland Inventory (BLM 2014). Rangeland conditions in the BLM data are aligned with IPCC grassland categories of nominal, moderately degraded, and severely degraded. Further elaboration on the Tier 2 methodology and data used to estimate stock changes from mineral soils are described in Annex 3.12.

Additional Mineral C Stock Change Calculations

A Tier 2 method is used to adjust annual C stock change estimates for mineral soils between 1990 and 2014 to account for additional C stock changes associated with sewage sludge amendments. Estimates of the amounts of sewage sludge N applied to agricultural land are derived from national data on sewage sludge generation, disposition, and N content. Total sewage sludge generation data for 1988, 1996, and 1998, in dry mass units, are obtained from EPA (1999) and estimates for 2004 are obtained from an independent national biosolids survey (NEBRA 2007). These values are linearly interpolated to estimate values for the intervening years, and linearly extrapolated to estimate values for years since 2004. N application rates from Kellogg et al. (2000) are used to determine the amount of area receiving sludge amendments. Although sewage sludge can be added to land managed for other land uses, it is assumed that agricultural amendments occur in grassland. Cropland is not likely to be amended with sewage sludge due to the high metal content and other pollutants in human waste. The soil C storage rate is estimated at 0.38 metric tons C per hectare per year for sewage sludge amendments to grassland. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.12 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Grassland Remaining Grassland* are estimated using the Tier 2 method provided in IPCC (2006), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. For more information, see the *Cropland Remaining Cropland* section for organic soils.

Uncertainty and Time-Series Consistency

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described in the *Cropland Remaining Cropland* section. The uncertainty for annual C emission estimates from drained organic soils in *Grassland Remaining Grassland* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 6-34 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The combined uncertainty for soil C stocks in *Grassland Remaining Grassland* ranges from 344 percent below to 346 percent above the 2014 stock change estimate of 11.9 MMT CO_2 Eq. The large relative uncertainty is due to the small net C stock change estimate in 2014, particularly on federal grasslands, even though the absolute amount of uncertainty is relatively small.

Table 6-34: Approach 2 Quantitative Uncertainty Estimates for C Stock Changes Occurring Within *Grassland Remaining Grassland* (MMT CO_2 Eq. and Percent)

Source	2014 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks Grassland Remaining Grassland, Tier 3 Methodology	9.2	(30.8)	49.2	-433%	+433%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	(0.3)	(8.8)	9.3	-3,308%	+3,680%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Sewage Sludge Amendments)	(1.4)	(2.1)	(0.7)	-50%	+50%
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	4.3	2.2	7.2	-49%	+66%
Combined Uncertainty for Flux Associated with Agricultural Soil Carbon Stock Change in Grassland Remaining Grassland	**11.9**	**(29.0)**	**53.2**	**-344%**	**+346%**

Note: Parentheses indicate negative values.

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

Uncertainty is also associated with a lack of reporting on agricultural biomass and litter C stock changes and non-CO_2 greenhouse gas emissions from burning. Biomass C stock changes may be significant for managed grasslands with woody encroachment that has not attained enough tree cover to be considered forest lands. This Inventory does not currently include the non-CO_2 greenhouse gas emissions that occur with biomass burning. Grassland burning is not as common in the United States as in other regions of the world, but fires do occur through both natural ignition sources and prescribed burning. Changes in litter C stocks are assumed to be negligible in grasslands over annual time frames, although there are certainly significant changes at sub-annual time scales across seasons.

Methodological recalculations are applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland*.

Recalculations Discussion

Methodological recalculations in the current Inventory are associated with the following improvements, including 1) incorporation of updated NRI data for 1990 through 2010; 2) inclusion of federal grasslands in the Tier 2 analysis; and 3) improving the simulation of hydric soils in DAYCENT. As a result of these improvements to the Inventory, changes in SOC stocks increased by an average of 4.3 MMT CO_2 eq. annually over the time series.

Planned Improvements

Grasslands in Alaska are not currently included in the Inventory. This is a significant planned improvement and estimates are expected to be available for the 1990 through 2015 Inventory. Another key planned improvement is to estimate non-CO_2 greenhouse gas emissions from burning of grasslands. For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland*.

6.7 Land Converted to Grassland (IPCC Source Category 4C2)

Land Converted to Grassland includes all grassland in an Inventory year that had been in another land use(s) during the previous 20 years[47] (USDA-NRCS 2013). For example, cropland or forestland converted to grassland during the past 20 years would be reported in this category. Recently-converted lands are retained in this category for 20 years as recommended by IPCC (2006). Grassland includes pasture and rangeland that are used primarily but not exclusively for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding of legumes. This Inventory includes all grasslands in the conterminous United States and Hawaii, but does not include *Land Converted to Grassland* in Alaska. Consequently there is a discrepancy between the total amount of managed area for *Land Converted to Grassland* (see Section 6.1—*Representation of the U.S. Land Base*) and the grassland area included in in the inventory analysis (IPCC Source Category 4C2—Section 6.7).

Background on agricultural carbon (C) stock changes is provided in *Cropland Remaining Cropland* and therefore will only be briefly summarized here. Soils are the largest pool of C in agricultural land, and also have the greatest potential for long-term storage or release of C. Biomass and dead organic matter C pools are relatively small and ephemeral compared with soils, with the exception of C stored in tree and shrub biomass that occurs in grasslands. IPCC (2006) recommend reporting changes in soil organic C (SOC) stocks due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[48]

Land use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil C stocks between 1990 and 2014 (see Table 6-35 and Table 6-36). The average soil C stock change for mineral soils between 1990 and 2014 is 12.4 MMT CO_2 Eq. (3.4 MMT C). In contrast, over the same period, drainage of organic soils for grassland management led to an increase in C emissions to the atmosphere of 1.5 MMT CO_2 Eq. (0.4 MMT C). The total soil C stock change in 2014 for *Land Converted to Grassland* is estimated at 10.9 MMT CO_2 Eq. (3.0 MMT C).

Table 6-35: Net CO_2 Flux from Soil C Stock Changes for *Land Converted to Grassland* (MMT CO_2 Eq.)

Soil Type	1990	2005	2010	2011	2012	2013	2014
Cropland Converted to Grassland							
Mineral	(7.5)	(11.3)	(11.8)	(10.4)	(10.4)	(10.4)	(10.4)
Organic	0.5	1.0	1.1	1.2	1.2	1.2	1.2
Forest Converted to Grassland							
Mineral	(0.5)	(1.0)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Organic	+	+	+	+	+	+	+
Other Lands Converted Grassland							
Mineral	(0.6)	(1.1)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Organic	+	0.0	+	+	+	+	+
Settlements Converted Grassland							
Mineral	(0.1)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic	+	0.0	+	+	+	+	+
Wetlands Converted Grassland							
Mineral	(0.5)	(0.6)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic	0.1	0.2	0.3	0.3	0.3	0.3	0.3
Total Mineral Soil Flux	**(9.2)**	**(14.1)**	**(13.8)**	**(12.5)**	**(12.4)**	**(12.4)**	**(12.4)**

---

[47] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of *Land Converted to Grassland* in the early part of the time series to the extent that some areas are converted to grassland prior to 1979.

[48] CO_2 emissions associated with liming are also estimated but included in 6.4 Cropland Remaining Cropland.

Total Organic Soil Flux	**0.7**	**1.2**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Total Net Flux	**(8.5)**	**(12.8)**	**(12.3)**	**(11.0)**	**(10.9)**	**(10.9)**	**(10.9)**

Notes: Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series. Parentheses indicate net sequestration.

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 6-36: Net CO_2 Flux from Soil C Stock Changes for *Land Converted to Grassland* (MMT C)

Soil Type	**1990**	**2005**	**2010**	**2011**	**2012**	**2013**	**2014**
Cropland Converted to Grassland							
Mineral	(2.0)	(3.1)	(3.2)	(2.8)	(2.8)	(2.8)	(2.8)
Organic	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Forest Converted to Grassland							
Mineral	(0.1)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic	+	+	+	+	+	+	+
Other Lands Converted Grassland							
Mineral	(0.2)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic	+	0.0	+	+	+	+	+
Settlements Converted Grassland							
Mineral	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Organic	+	+	+	+	+	+	+
Wetlands Converted Grassland							
Mineral	(0.1)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic	+	0.1	0.1	0.1	0.1	0.1	0.1
Total Mineral Soil Flux	**(2.5)**	**(3.8)**	**(3.8)**	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4)**
Total Organic Soil Flux	**0.2**	**0.3**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total Net Flux	**(2.3)**	**(3.5)**	**(3.4)**	**(3.0)**	**(3.0)**	**(3.0)**	**(3.0)**

Notes: Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series. Parentheses indicate net sequestration.

+ Does not exceed 0.05 MMT CO_2 Eq.

The spatial variability in the 2014 annual flux in CO_2 from mineral soils is displayed in Figure 6-11 and from organic soils in Figure 6-12. Soil C stocks increased in most states for *Land Converted to Grassland*, which is driven by conversion of annual cropland into continuous pasture. The largest gains are in the Southeastern region, Northeast, South-Central, Midwest, and northern Great Plains. The regions with the highest rates of emissions from organic soils coincide with the largest concentrations of organic soils used for managed grasslands, including Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and the Pacific Coast (particularly California).

Figure 6-11: Total Net Annual CO_2 Flux for Mineral Soils under Agricultural Management within States, 2014, *Land Converted to Grassland* (TO BE UPDATED)

Figure 6-12: Total Net Annual CO_2 Flux for Organic Soils under Agricultural Management within States, 2014, *Land Converted to Grassland* (TO BE UPDATED)

Methodology

The following section includes a description of the methodology used to estimate changes in soil C stocks for *Land Converted to Grassland*, including (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils. Biomass and litter C stock changes associated with conversion of forest to grassland are not explicitly included in this category, but are included in the *Forest Land Remaining Forest Land* section. Further elaboration on the methodologies and data used to estimate stock changes for mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.12.

Soil C stock changes are estimated for *Land Converted to Grassland* according to land-use histories recorded in the 2010 USDA NRI survey (USDA-NRCS 2013). Land use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI survey locations on a 5-year cycle beginning in 1982 In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2012 (USDA-NRCS 2015). However, this Inventory only uses NRI data through 2010 because newer data were not available in time to incorporate the additional years. NRI survey locations are classified as *Land Converted to Grassland* in a given year between 1990 and 2010 if the land use is grassland but had been classified as another use during the previous 20 years.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes for *Land Converted to Grassland* on most mineral soils. C stock changes on the remaining soils are estimated with an IPCC Tier 2 approach (Ogle et al. 2003), including prior cropland used to produce vegetables, tobacco, and perennial/horticultural crops; land areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted to grassland from another land use other than cropland.

Tier 3 Approach

Mineral SOC stocks and stock changes are estimated using the DAYCENT biogeochemical[49] model (Parton et al. 1998; Del Grosso et al. 2001, 2011). 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. Historical land-use patterns and irrigation histories are simulated with DAYCENT based on the 2010 USDA NRI survey (USDA-NRCS 2013), with supplemental information on fertilizer use and rates from the USDA Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011) and the National Agricultural Statistics Service (NASS 1992, 1999, 2004). See the *Cropland Remaining Cropland* section for additional discussion of the Tier 3 methodology for mineral soils.

Tier 2 Approach

For the mineral soils not included in the Tier 3 analysis, SOC stock changes are estimated using a Tier 2 Approach for *Land Converted to Grassland* as described in the Tier 2 Approach for mineral soils in the *Grassland Remaining Grassland* section.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Grassland* are estimated using the Tier 2 method provided in IPCC (2006), with U.S.-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section for organic soils.

Uncertainty and Time-Series Consistency

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described in the *Cropland Remaining Cropland* section. The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Grassland* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 6-37 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The

---

[49] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

combined uncertainty for soil C stocks in *Land Converted to Grassland* ranges from 82 percent below to 82 percent above the 2014 stock change estimate of -10.9 MMT CO_2 Eq.

Table 6-37: Approach 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Grassland* (MMT CO_2 Eq. and Percent)

Source	2014 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a]			
		(MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Grassland	**(9.2)**	**(18.1)**	**(0.3)**	**-96%**	**+96%**
Mineral Soil C Stocks: Tier 3	(9.0)	(17.8)	(0.2)	-98%	+98%
Mineral Soil C Stocks: Tier 2	(1.4)	(2.2)	(0.8)	-55%	+47%
Organic Soil C Stocks: Tier 2	1.2	0.4	2.3	-63%	+96%
Forests Converted to Grassland	**(0.8)**	**(4.3)**	**0.1**	**-433%**	**+112%**
Mineral Soil C Stocks: Tier 2	(0.8)	(1.8)	0.1	-120%	+112%
Organic Soil C Stocks: Tier 2	+	0.0	+	-100%	+300%
Other Lands Converted to Grassland	**(0.8)**	**(1.3)**	**(0.4)**	**-55%**	**+47%**
Mineral Soil C Stocks: Tier 2	(0.8)	(1.3)	(0.4)	-54%	+46%
Organic Soil C Stocks: Tier 2	+	0.0	+	-100%	+179%
Settlements Converted to Grassland	**(0.1)**	**(0.2)**	**(0.0)**	**-63%**	**+56%**
Mineral Soil C Stocks: Tier 2	(0.1)	(0.2)	(0.1)	-55%	+47%
Organic Soil C Stocks: Tier 2	+	+	+	-79%	+125%
Wetlands Converted to Grasslands	**0.1**	**(0.1)**	**0.3**	**-314%**	**+382%**
Mineral Soil C Stocks: Tier 2	(0.2)	(0.4)	(0.1)	-52%	+44%
Organic Soil C Stocks: Tier 2	0.3	0.1	0.5	-51%	+71%
Total: Land Converted to Grassland	**(10.9)**	**(19.8)**	**(2.0)**	**-82%**	**+82%**
Mineral Soil C Stocks: Tier 3	**(9.0)**	**(17.8)**	**(0.2)**	**-98%**	**+98%**
Mineral Soil C Stocks: Tier 2	**(3.4)**	**(4.7)**	**(2.2)**	**-39%**	**+35%**
Organic Soil C Stocks: Tier 2	**1.5**	**0.7**	**2.6**	**-50%**	**+77%**

Note: Parentheses indicate negative values.

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

Uncertainty is also associated with lack of reporting of agricultural biomass and litter C stock changes, other than the loss of forest biomass and litter, which is reported in the *Forest Land Remaining Forest Land* section of the report. Biomass C stock changes may be significant for managed grasslands with woody encroachment that has not attained enough tree cover to be considered forest lands. This Inventory does not currently include the non-CO_2 greenhouse gas emissions that occur with biomass burning. Grassland burning is not as common in the United States as in other regions of the world, but fires do occur through both natural ignition sources and prescribed burning. Changes in litter C stocks are assumed to be negligible in grasslands over annual time frames, although there are likely significant changes at sub-annual time scales across seasons.

Methodological recalculations are applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the above Methodology section.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland*.

Recalculations Discussion

Methodological recalculations in the current Inventory are associated with the following improvements, including 1) incorporation of updated NRI data for 1990 through 2010; 2) inclusion of federal grasslands in the Tier 2 analysis; and 3) improving the simulation of hydric soils in DAYCENT. As a result of these improvements to the Inventory, changes in SOC stocks increased by an average of 0.2 MMT CO_2 eq. annually over the time series.

Planned Improvements

Soil C stock changes with land use conversion from forest land to grassland are undergoing further evaluation to ensure consistency in the time series. Different methods are used to estimate soil C stock changes in forest land and grasslands, and while the areas have been reconciled between these land uses, there has been limited evaluation of the consistency in C stock changes with conversion from forest land to grassland. This planned improvement may not be fully implemented for another year, depending on resource availability. Another planned improvement for the *Land Converted to Grassland* category is to develop an inventory of carbon stock changes for grasslands in Alaska. For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland* and *Grassland Remaining Grassland*.

6.8 Wetlands Remaining Wetlands (IPCC Source Category 4D1)

Peatlands Remaining Peatlands

Emissions from Managed Peatlands

Managed peatlands are peatlands which have been cleared and drained for the production of peat. The production cycle of a managed peatland has three phases: land conversion in preparation for peat extraction (e.g., clearing surface biomass, draining), extraction, and abandonment, restoration, or conversion of the land to another use.

Carbon dioxide emissions from the removal of biomass and the decay of harvested peat constitute the major greenhouse gas flux from managed peatlands. Managed peatlands may also emit CH_4 and N_2O, however, this is a very small component of total emissions from this source category in the United States. The natural production of CH_4 is largely reduced but not entirely shut down when peatlands are drained in preparation for peat extraction (Strack et al. 2004 as cited in the *2006 IPCC Guidelines*). Drained land surface and ditch networks contribute to the CH_4 flux in peatlands managed for peat extraction. Methane emissions were considered insignificant under IPCC Tier 1 methodology (IPCC 2006), but are included in the emissions estimates for *Peatlands Remaining Peatlands* consistent with the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013). Nitrous Oxide emissions from managed peatlands depend on site fertility. In addition, abandoned and restored peatlands continue to release greenhouse gas emissions. This Inventory estimates CO_2, N_2O, and CH_4 emissions from peatlands managed for peat extraction in accordance with IPCC (2006 and 2013) guidelines.

CO_2, N_2O, and CH_4 Emissions from Peatlands Remaining Peatlands

IPCC (2013) recommends reporting CO_2, N_2O, and CH_4 emissions from lands undergoing active peat extraction (i.e., *Peatlands Remaining Peatlands*) as part of the estimate for emissions from managed wetlands. Peatlands occur where plant biomass has sunk to the bottom of water bodies and water-logged areas and exhausted the oxygen supply below the water surface during the course of decay. Due to these anaerobic conditions, much of the plant matter does not decompose but instead forms layers of peat over decades and centuries. In the United States, peat is extracted for horticulture and landscaping growing media, and for a wide variety of industrial, personal care, and other products. It has not been used for fuel in the United States for many decades. Peat is harvested from two types of peat deposits in the United States: sphagnum bogs in northern states (e.g., Minnesota) and wetlands in states further south (e.g., Florida). The peat from sphagnum bogs in northern states, which is nutrient poor, is generally corrected for acidity and mixed with fertilizer. Production from more southerly states is relatively coarse (i.e., fibrous) but nutrient rich.

IPCC (2006 and 2013) recommend considering both on-site and off-site emissions when estimating CO_2 emissions from *Peatlands Remaining Peatlands* using the Tier 1 approach. Current methodologies estimate only on-site N_2O

and CH_4 emissions, since off-site N_2O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat, and off-site CH_4 emissions are not relevant given the non-energy uses of peat, so methodologies are not provided in IPCC (2013) guidelines. On-site emissions from managed peatlands occur as the land is cleared of vegetation and the underlying peat is exposed to sun and weather. As this occurs, some peat deposit is lost and CO_2 is emitted from the oxidation of the peat. Since N_2O emissions from saturated ecosystems tend to be low unless there is an exogenous source of nitrogen, N_2O emissions from drained peatlands are dependent on nitrogen mineralization and therefore on soil fertility. Peatlands located on highly fertile soils contain significant amounts of organic nitrogen in inactive form. Draining land in preparation for peat extraction allows bacteria to convert the nitrogen into nitrates which leach to the surface where they are reduced to N_2O, and contributes to the activity of methanogens, which produce CH_4, and methanotrophs which oxidize CH_4 into CO_2 (Blodau 2002; Treat et al. 2007 as cited in IPCC 2013). Ditch networks, which are constructed in order to drain the water off in preparation for peat extraction, also contribute to the flux of CH_4 through *in situ* production and lateral transfer of CH_4 from the organic soil matrix (IPCC 2013).

The two sources of off-site CO_2 emissions from managed peatlands are waterborne carbon losses and the horticultural and landscaping use of peat. Drainage waters in peatlands accumulate dissolved organic carbon which then reacts within aquatic ecosystems and is converted to CO_2 where it is then emitted to the atmosphere (Billet et al. 2004 as cited in IPCC 2013). Most (nearly 98 percent) of the CO_2 emissions from peat occur off-site, as the peat is processed and sold to firms which, in the United States, use it predominantly forhorticultural and landscaping purposes. Nutrient-poor (but fertilizer-enriched) peat tends to be used in bedding plants and in greenhouse and plant nursery production, whereas nutrient-rich (but relatively coarse) peat is used directly in landscaping, athletic fields, golf courses, and plant nurseries.

Total emissions from *Peatlands Remaining Peatlands* were estimated to be 0.8 MMT CO_2 Eq. in 2014 (see Table 6-38) comprising 0.8 MMT CO_2 Eq. (842 kt) of CO_2, 0.001 MMT CO_2 Eq. (0.002 kt) of N_2O, and 0.004 MMT CO_2 Eq. (0.17 kt) of CH_4. Total emissions in 2014 were about 9 percent larger than total emissions in 2013. Peat production in Alaska in 2014 was not reported in *Alaska's Mineral Industry 2013* report. However, peat production reported in the lower 48 states in 2014 was 10 percent more than in 2013, and as a result, the emissions from *Peatlands Remaining Peatlands* in the lower 48 states and Alaska were greater in 2014 compared to 2013.

Total emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.8 and 1.3 MMT CO_2 Eq. across the time series with a decreasing trend from 1990 until 1993 followed by an increasing trend through 2000. After 2000, emissions generally decreased until 2006 and then increased until 2009, when the trend reversed until a slight increase from 2013 to 2014. Carbon dioxide emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.8 and 1.3 MMT CO_2 across the time series, and these emissions drive the trends in total emissions. CH_4 and N_2O emissions remained close to zero across the time series.

Table 6-38: Emissions from *Peatlands Remaining Peatlands* (MMT CO_2 Eq.)

Gas	1990	2005	2010	2011	2012	2013	2014
CO_2	1.1	1.1	1.0	0.9	0.8	0.8	0.8
Off-site	1.0	1.0	1.0	0.9	0.8	0.7	0.8
On-site	0.1	0.1	0.1	0.1	0.1	+	0.1
N_2O (On-site)	+	+	+	+	+	+	+
CH_4 (On-site)	+	+	+	+	+	+	+
Total	**1.1**	**1.1**	**1.0**	**0.9**	**0.8**	**0.8**	**0.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports, and stockpiles (i.e., apparent consumption). Off-site N_2O emissions are not estimated to avoid double-counting N_2O emitted from the fertilizer that the peat is mixed with prior to horticultural use (see IPCC 2006). Totals may not sum due to independent rounding.

Table 6-39: Emissions from *Peatlands Remaining Peatlands* (kt)

Gas	1990	2005	2010	2011	2012	2013	2014
CO_2	1,055	1,101	1,022	926	812	770	842
Off-site	985	1,030	956	866	760	720	787

On-site	70	71	66	60	53	50	55
N_2O (On-site)	+	+	+	+	+	+	+
CH_4 (On-site)	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports, and stockpiles (i.e., apparent consumption). Off-site N_2O emissions are not estimated to avoid double-counting N_2O emitted from the fertilizer that the peat is mixed with prior to horticultural use (see IPCC 2006). Totals may not sum due to independent rounding.

Methodology

Off-site CO_2 Emissions

Off-site CO_2 emissions from domestic peat production were estimated using a Tier 1 methodology consistent with IPCC (2006). The emissions were calculated by apportioning the annual weight of peat produced in the United States (Table 6-40) into peat extracted from nutrient-rich deposits and peat extracted from nutrient-poor deposits using annual percentage-by-weight figures. These nutrient-rich and nutrient-poor production values were then multiplied by the appropriate default C fraction conversion factor taken from IPCC (2006) in order to obtain off-site CO_2 emission estimates. For the lower 48 states, both annual percentages of peat type by weight and domestic peat production data were sourced from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Commodity Summaries* from the U.S. Geological Survey (USGS 1995–2015a; USGS 2015b). To develop these data, the U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) obtained production and use information by surveying domestic peat producers. On average, about 75 percent of the peat operations respond to the survey; and USGS estimates data for non-respondents on the basis of prior-year production levels (Apodaca 2011).

The Alaska estimates rely on reported peat production from the annual *Alaska's Mineral Industry* reports (DGGS 1997–2014). Similar to the U.S. Geological Survey, the Alaska Department of Natural Resources, Division of Geological & Geophysical Surveys (DGGS) solicits voluntary reporting of peat production from producers for the *Alaska's Mineral Industry* report. However, the report does not estimate production for the non-reporting producers, resulting in larger inter-annual variation in reported peat production from Alaska depending on the number of producers who report in a given year (Szumigala 2011). In addition, in both the lower 48 states and Alaska, large variations in peat production can also result from variations in precipitation and the subsequent changes in moisture conditions, since unusually wet years can hamper peat production. The methodology estimates Alaska emissions separately from lower 48 emissions because the state conducts its own mineral survey and reports peat production by volume, rather than by weight (Table 6-41). However, volume production data were used to calculate off-site CO_2 emissions from Alaska applying the same methodology but with volume-specific C fraction conversion factors from IPCC (2006).[50] Peat production was not reported for 2014 in *Alaska's Mineral Industry 2013* report (DGGS 2014); therefore Alaska's peat production in 2014 (reported in cubic yards) was assumed to be equal to its peat production in 2013.

Consistent with IPCC (2013) guidelines, off-site CO_2 emissions from dissolved organic carbon transported off-site were estimated based on the total area of peatlands managed for peat extraction, which is calculated from production data using the methodology described in the *On-Site CO_2 Emissions* section below. Carbon dioxide emissions from dissolved organic C were estimated by multiplying the area of peatlands by the default emission factor for dissolved organic C provided in IPCC (2013).

The *apparent consumption* of peat, which includes production plus imports minus exports plus the decrease in stockpiles, in the United States is over two-and-a-half times the amount of domestic peat production. However, consistent with the Tier 1 method whereby only domestic peat production is accounted for when estimating off-site emissions, off-site CO_2 emissions from the use of peat not produced within the United States are not included in the Inventory. The United States has largely imported peat from Canada for horticultural purposes; from 2010 to 2013,

---

[50] Peat produced from Alaska was assumed to be nutrient poor; as is the case in Canada, "where deposits of high-quality [but nutrient poor] sphagnum moss are extensive" (USGS 2008).

imports of sphagnum moss (nutrient-poor) peat from Canada represented 63 percent of total U.S. peat imports (USGS 2015c). Most peat produced in the United States is reed-sedge peat, generally from southern states, which is classified as nutrient rich by IPCC (2006). Higher-tier calculations of CO_2 emissions from apparent consumption would involve consideration of the percentages of peat types stockpiled (nutrient rich versus nutrient poor) as well as the percentages of peat types imported and exported.

Table 6-40: Peat Production of Lower 48 States (kt)

Type of Deposit	1990		2005		2010	2011	2012	2013	2014
Nutrient-Rich	595		658		559	511	410	419	459
Nutrient-Poor	55		27		69	57	78	47	51
Total Production	**692**		**685**		**628**	**568**	**488**	**465**	**510**

Sources: United States Geological Survey (USGS) (1991–2015a) *Minerals Yearbook: Peat* (1994–2014); United States Geological Survey (USGS) (2015b) *Mineral Commodity Summaries: Peat* (2014).

Table 6-41: Peat Production of Alaska (Thousand Cubic Meters)

	1990		2005		2010	2011	2012	2013	2014
Total Production	49.7		47.8		59.8	61.5	93.1	93.1	93.1

Sources: Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2014) *Alaska's Mineral Industry Report (1997–2013).*

On-site CO_2 Emissions

IPCC (2006) suggests basing the calculation of on-site emission estimates on the area of peatlands managed for peat extraction differentiated by the nutrient type of the deposit (rich versus poor). Information on the area of land managed for peat extraction is currently not available for the United States, but in accordance with IPCC (2006), an average production rate per area for the industry was applied to derive an area estimate. In a mature industrialized peat industry, such as exists in the United States and Canada, the vacuum method can extract up to 100 metric tons per hectare per year (Cleary et al. 2005 as cited in IPCC 2006).[51] In the lower 48 states, the area of land managed for peat extraction was estimated using nutrient-rich and nutrient-poor production data and the assumption that 100 metric tons of peat are extracted from a single hectare in a single year. The nutrient-rich and nutrient-poor annual land area estimates were then multiplied by the IPCC (2013) default emission factor in order to calculate on-site CO_2 emission estimates. Production data are not available by weight for Alaska. In order to calculate on-site emissions resulting from *Peatlands Remaining Peatlands* in Alaska, the production data by volume were converted to weight using annual average bulk peat density values, and then converted to land area estimates using the same assumption that a single hectare yields 100 metric tons. The IPCC (2006) on-site emissions equation also includes a term which accounts for emissions resulting from the change in C stocks that occurs during the clearing of vegetation prior to peat extraction. Area data on land undergoing conversion to peatlands for peat extraction is also unavailable for the United States. However, USGS records show that the number of active operations in the United States has been declining since 1990; therefore, it seems reasonable to assume that no new areas are being cleared of vegetation for managed peat extraction. Other changes in C stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodologies (IPCC 2006 and 2013).

On-site N_2O Emissions

IPCC (2006) suggests basing the calculation of on-site N_2O emission estimates on the area of nutrient-rich peatlands managed for peat extraction. These area data are not available directly for the United States, but the on-site CO_2 emissions methodology above details the calculation of area data from production data. In order to estimate N_2O

---

[51] The vacuum method is one type of extraction that annually "mills" or breaks up the surface of the peat into particles, which then dry during the summer months. The air-dried peat particles are then collected by vacuum harvesters and transported from the area to stockpiles (IPCC 2006).

emissions, the area of nutrient rich *Peatlands Remaining Peatlands* was multiplied by the appropriate default emission factor taken from IPCC (2013).

On-site CH_4 Emissions

IPCC (2013) also suggests basing the calculation of on-site CH_4 emission estimates on the total area of peatlands managed for peat extraction. Area data is derived using the calculation from production data described in the *On-site CO_2* Emissions section above. In order to estimate CH_4 emissions from drained land surface, the area of *Peatlands Remaining Peatlands* was multiplied by the emission factor for direct CH_4 emissions taken from IPCC (2013). In order to estimate CH_4 emissions from drainage ditches, the total area of peatland was multiplied by the default fraction of peatland area that contains drainage ditches, and the appropriate emission factor taken from IPCC (2013).

Uncertainty and Time-Series Consistency

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty of CO_2, CH_4, and N_2O emissions from *Peatlands Remaining Peatlands*, using the following assumptions:

- The uncertainty associated with peat production data was estimated to be ± 25 percent (Apodaca 2008) and assumed to be normally distributed.
- The uncertainty associated with peat production data stems from the fact that the USGS receives data from the smaller peat producers but estimates production from some larger peat distributors. The peat type production percentages were assumed to have the same uncertainty values and distribution as the peat production data (i.e., ± 25 percent with a normal distribution).
- The uncertainty associated with the reported production data for Alaska was assumed to be the same as for the lower 48 states, or ± 25 percent with a normal distribution. It should be noted that the DGGS estimates that around half of producers do not respond to their survey with peat production data; therefore, the production numbers reported are likely to underestimate Alaska peat production (Szumigala 2008).
- The uncertainty associated with the average bulk density values was estimated to be ± 25 percent with a normal distribution (Apodaca 2008).
- IPCC (2006 and 2013) gives uncertainty values for the emissions factors for the area of peat deposits managed for peat extraction based on the range of underlying data used to determine the emission factors. The uncertainty associated with the emission factors was assumed to be triangularly distributed.
- The uncertainty values surrounding the C fractions were based on IPCC (2006) and the uncertainty was assumed to be uniformly distributed.
- The uncertainty values associated with the fraction of peatland covered by ditches was assumed to be ± 100 percent with a normal distribution based on the assumption that greater than 10 percent coverage, the upper uncertainty bound, is not typical of drained organic soils outside of The Netherlands (IPCC 2013).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-42. Carbon dioxide emissions from *Peatlands Remaining Peatlands* in 2014 were estimated to be between 0.7 and 1.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 14 percent below to 19 percent above the 2014 emission estimate of 0.8 MMT CO_2 Eq. Methane emissions from *Peatlands Remaining Peatlands* in 2014 were estimated to be between 0.002 and 0.008 MMT CO_2 Eq. This indicates a range of 62 percent below to 61 percent above the 2014 emission estimate of 0.005 MMT CO_2 Eq. Nitrous Oxide emissions from *Peatlands Remaining Peatlands* in 2014 were estimated to be between 0.0003 and 0.0010 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 51 percent below to 61 percent above the 2014 emission estimate of 0.0006 MMT CO_2 Eq.

Table 6-42: Approach 2 Quantitative Uncertainty Estimates for CO_2, CH_4, and N_2O Emissions from *Peatlands Remaining Peatlands* (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Peatlands Remaining Peatlands	CO_2	0.8	0.7	1.0	−14%	+19%
Peatlands Remaining Peatlands	CH_4	+	+	+	−62%	+61%

Peatlands Remaining Peatlands	N_2O	+	+	+	−51%	+61%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
+ Does not exceed 0.05 MMT CO_2 Eq.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation and no issues were identified.

Recalculations Discussion

The emission estimates for *Peatlands Remaining Peatlands* were updated for 2014 using the Peat section of the *Mineral Commodity Summaries 2015*. The new edition provided 2014 data for the lower 48 states, but data for Alaska were still unavailable. Because no peat production has been reported since *Alaska's Mineral Industry 2012* report, the 2013 and 2014 values were assumed to be equal to the 2012 value. If updated data are available for the next inventory cycle, this will result in a recalculation in the next Inventory report.

Planned Improvements

In order to further improve estimates of CO_2, N_2O, and CH_4 emissions from *Peatlands Remaining Peatlands*, future efforts will investigate if data sources exist for determining the quantity of peat harvested per hectare and the total area undergoing peat extraction.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* describes inventory methodologies for various wetland source categories. In the 1990 through 2013 Inventory, updated methods for Peatlands Remaining Peatlands to align them with the IPCC Supplement were begun to be incorporated. For future inventories, the need for additional updates will be evaluated, in order to further address the IPCC Supplement for Peatlands Remaining Peatlands.

The *2006 IPCC Guidelines* do not cover all wetland types; they are restricted to peatlands drained and managed for peat extraction, conversion to flooded lands, and some guidance for drained organic soils. They also do not cover all of the significant activities occurring on wetlands (e.g., rewetting of peatlands). Since this Inventory only includes *Peatlands Remaining Peatlands*, additional wetland types and activities found in the *2013 IPCC Supplement* (IPCC 2013) will be reviewed to determine if they apply to the United States. For those that do, available data will be investigated to allow for the estimation of greenhouse gas fluxes in future Inventory reports.

Box 6-6: Progress on Inclusion of Managed Coastal Wetlands in the U.S. Greenhouse Gas Inventory

In 2014, the IPCC released the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (*Wetlands Supplement*). The *Wetlands Supplement* provides methods for estimating anthropogenic emissions and removals of greenhouse gases from wetlands and drained soils. Specific consideration is given here to the inclusion of coastal wetlands as part of LULUCF reporting for anthropogenic emissions and removals of CO_2 and CH_4 and N_2O emissions.

In preparation for the next submission of the U.S. Inventory, the United States is exploring methodological approaches based on guidance in the *Wetlands Supplement*. The goal is to assemble all necessary activity data and emission factors, implement the methods described in the *Wetlands Supplement* and generate estimates at the Tier 1 or 2 level for managed coastal wetlands in the conterminous United States.

Fundamental considerations for inclusion of coastal wetlands as part of LULUCF reporting are: (1) how to apply the guidance in the *Wetlands Supplement* to specify what coastal wetlands are managed, (2) understanding what land use categories coastal wetlands are in (i.e., Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land) and ensuring there is no overlap or missing lands within the U.S. land use matrix, and (3) understanding how the guidance can be applied when significant greenhouse gas emissions and removals occur in managed coastal wetlands outside of the U.S. land use matrix (i.e., seagrass meadows). These issues are under consideration and review by an interagency (U.S. Government) and academic team in anticipation of the next submission of the U.S. Inventory.

The availability of data and resources will be primary drivers in determining how the approaches in the *Wetlands Supplement* are applied. Specifically, the United States will work toward developing its inventory reporting of greenhouse gas emissions and removals from coastal wetlands by: (1) obtaining, collating and refining land use and land-use change data including (a) creating the coastal wetland boundary, (b) recognizing management activities and coastal wetland change resulting in land-use conversion (c) creating seamless integration where coastal wetlands may overlap with other land-use categories, (d) distinguishing salinity levels and soil types to apply appropriate C stocks and emission factors; and (2) developing the sector-specific inventory report for each new category and sub-category by: (a) increasing efforts toward reconciling land cover and land cover change spatial databases (i.e., Coastal Change Analysis Program) with vegetation, soil C stock and stock change data, and other levels of disaggregation that improve estimation accuracy, (b) developing Tier 1 (or Tier 2, if activity data and emission factors are available) emissions estimates for new source/sink categories under Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land, and (c) developing Tier 1 (or Tier 2, if activity data and emission factors are available) estimates of new source/sink categories that fall under new subcategories under Wetlands (Other Wetlands Remaining Other Wetlands and Land Converted to Other Wetlands) from the following activities: i) forest management in mangroves, ii) extraction in mangroves, tidal marshes and seagrass meadows (including excavation, aquaculture and salt production), iii) rewetting, revegetation and creation in mangroves, tidal marshes and seagrass meadows, iv) soil drainage in mangroves and tidal marshes (CO_2) and v) new categories of CH_4 emissions from rewetting of mangroves and tidal marshes and N_2O emissions from aquaculture, and (d) developing QA/QC procedures and protocols to be used in generating the estimates, and (e) refining uncertainty estimates.

6.9 Land Converted to Wetlands (IPCC Source Category 4D1) (TO BE UPDATED)

Estimates for the *Land Converted to Wetlands* source category are currently under development.

6.10 Settlements Remaining Settlements

Changes in Carbon Stocks in Urban Trees (IPCC Source Category 4E1)

Urban forests constitute a significant portion of the total U.S. tree canopy cover (Dwyer et al. 2000). Urban areas (cities, towns, and villages) are estimated to cover over 3 percent of the United States (U.S. Census Bureau 2012). With an average tree canopy cover of 35 percent, urban areas account for approximately 5 percent of total tree cover in the continental United States (Nowak and Greenfield 2012). Trees in urban areas of the United States were estimated to account for an average annual net sequestration of 76.4 MMT CO_2 Eq. (20.8 MMT C) over the period from 1990 through 2014. Net C flux from urban trees in 2014 was estimated to be −90.6 MMT CO_2 Eq. (−24.7 MMT C). Annual estimates of CO_2 flux (Table 6-43) were developed based on periodic (1990, 2000, and 2010) U.S. Census data on urbanized area. The estimate of urbanized area is smaller than the area categorized as *Settlements* in the *Representation of the U.S. Land Base* developed for this report: over the 1990 through 2014 time series the Census urban area totaled, on average, about 63 percent of the *Settlements* area.

In 2014, Census urban area totaled about 68 percent of the total area defined as *Settlements*. Census area data are preferentially used to develop C flux estimates for this source category since these data are more applicable for use with the available peer-reviewed data on urban tree canopy cover and urban tree C sequestration. Annual sequestration increased by 50 percent between 1990 and 2014 due to increases in urban land area. Data on C storage and urban tree coverage were collected since the early 1990s and have been applied to the entire time series in this report. As a result, the estimates presented in this chapter are not truly representative of changes in C stocks in urban trees for *Settlements* areas, but are representative of changes in C stocks in urban trees for Census urban area. The method used in this report does not attempt to scale these estimates to the *Settlements* area. Therefore, the estimates presented in this chapter are likely an underestimate of the true changes in C stocks in urban trees in all *Settlements* areas—i.e., the changes in C stocks in urban trees presented in this chapter are a subset of the changes in C stocks in urban trees in all *Settlements* areas.

Urban trees often grow faster than forest trees because of the relatively open structure of the urban forest (Nowak and Crane 2002). Because tree density in urban areas is typically much lower than in forested areas, the C storage per hectare of land is in fact smaller for urban areas than for forest areas. To quantify the C stored in urban trees, the methodology used here requires analysis per unit area of tree cover, rather than per unit of total land area (as is done for forests). Expressed in this way per unit of tree cover, areas covered by urban trees actually have a greater C density than do forested areas (Nowak and Crane 2002). Expressed per unit of land area, however, the situation is the opposite: because tree density is so much lower in urban areas, these areas have a smaller C density per unit land area than forest areas.

Table 6-43: Net C Flux from Urban Trees (MMT CO_2 Eq. and MMT C)

Year	MMT CO_2 Eq.	MMT C
1990	(60.4)	(16.5)
2005	(80.5)	(22.0)
2010	(86.1)	(23.5)
2011	(87.3)	(23.8)
2012	(88.4)	(24.1)
2013	(89.5)	(24.4)
2014	(90.6)	(24.7)

Note: Parentheses indicate net sequestration.

Methodology

Methods for quantifying urban tree biomass, C sequestration, and C emissions from tree mortality and decomposition were taken directly from Nowak et al. (2013), Nowak and Crane (2002), and Nowak (1994). In general, the methodology used by Nowak et al. (2013) to estimate net C sequestration in urban trees followed three steps, each of which is explained further in the paragraphs below. First, field data from cities and states were used to develop allometric equations that are then used to estimate C in urban tree biomass from data on measured tree dimensions. Second, estimates of annual tree growth and biomass increment were generated from published literature and adjusted for tree condition, land-use class, and growing season to generate estimates of gross C sequestration in urban trees for all 50 states and the District of Columbia. Third, estimates of C emissions due to mortality and decomposition were subtracted from gross C sequestration values to derive estimates of net C sequestration.

For this Inventory report, net C sequestration estimates for all 50 states and the District of Columbia, that were generated using the Nowak et al. (2013) methodology and expressed in units of C sequestered per unit area of tree cover, were then used to estimate urban tree C sequestration in the United States. To accomplish this, we used urban area estimates from U.S. Census data together with urban tree cover percentage estimates for each state and the District of Columbia from remote sensing data, an approach consistent with Nowak et al. (2013).

This approach is also consistent with the default IPCC Gain-Loss methodology in IPCC (2006), although sufficient field data are not yet available to separately determine interannual gains and losses in C stocks in the living biomass of urban trees. Instead, the methodology applied here uses estimates of net C sequestration based on modeled estimates of decomposition, as given by Nowak et al. (2013).

The first step in the methodology is to develop allometric equations that can be used to estimate C in urban tree biomass. In order to generate these allometric relationships between tree dimensions and tree biomass for cities and states, Nowak et al. (2013) and previously published research (Nowak and Crane 2002; Nowak 1994, 2007b, 2009) collected field measurements in a number of U.S. cities between 1989 and 2012. For a sample of trees in representative cities, data including tree measurements of stem diameter, tree height, crown height and crown width, and information on location, species, and canopy condition were collected. The data for each tree were converted into C storage by applying allometric equations to estimate aboveground biomass, a root-to-shoot ratio to convert aboveground biomass estimates to whole tree biomass, moisture content, a C content of 50 percent (dry weight basis), and an adjustment factor of 0.8 to account for urban trees having less aboveground biomass for a given stem diameter than predicted by allometric equations based on forest trees (Nowak 1994). Carbon storage estimates for deciduous trees include only C stored in wood. These calculations were then used to develop an allometric equation relating tree dimensions to C storage for each species of tree, encompassing a range of diameters.

The second step in the methodology is to estimate rates of tree growth for urban trees in the United States. Tree growth was estimated using annual height growth and diameter growth rates for specific land uses and diameter classes. In the Nowak et al. (2013) methodology that is applied here, growth calculations were adjusted by a factor to account for tree condition (fair to excellent, poor, critical, dying, or dead). For each tree, the difference in C storage estimates between year 1 and year (x + 1) represents the gross amount of C sequestered. These annual gross C sequestration rates for each species (or genus), diameter class, and land-use condition (e.g., parks, transportation, vacant, golf courses) were then scaled up to city estimates using tree population information. The area of assessment for each city or state was defined by its political boundaries; parks and other forested urban areas were thus included in sequestration estimates (Nowak 2011).

Most of the field data used to develop the methodology of Nowak et al. (2013) were analyzed using the U.S. Forest Service’s Urban Forest Effects (UFORE) model. UFORE is a computer model that uses standardized field data from random plots in each city and local air pollution and meteorological data to quantify urban forest structure, values of the urban forest, and environmental effects, including total C stored and annual C sequestration. UFORE was used with field data from a stratified random sample of plots in each city to quantify the characteristics of the urban forest (Nowak et al. 2007).

Where gross C sequestration accounts for all carbon sequestered, net C sequestration for urban trees takes into account C emissions associated with tree death and removals. In the third step in the methodology developed by Nowak et al. (2013), estimates of net C emissions from urban trees were derived by applying estimates of annual mortality and condition, and assumptions about whether dead trees were removed from the site to the total C stock estimate for each city. Estimates of annual mortality rates by diameter class and condition class were derived from a study of street-tree mortality (Nowak 1986). Different decomposition rates were applied to dead trees left standing compared with those removed from the site. For removed trees, different rates were applied to the removed/aboveground biomass in contrast to the belowground biomass. The estimated annual gross C emission rates for each species (or genus), diameter class, and condition class were then scaled up to city estimates using tree population information.

The data for all 50 states and the District of Columbia are described in Nowak et al. (2013) and reproduced in Table 6-44, which builds upon previous research, including: Nowak and Crane (2002), Nowak et al. (2007), Nowak and Greenfield (2012), and references cited therein. The full methodology development is described in the underlying literature, and key details and assumptions were made as follows. The allometric equations applied to the field data for the Nowak methodology for each tree were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), but if no allometric equation could be found for the particular species, the average result for the genus was used. The adjustment (0.8) to account for less live tree biomass in urban trees was based on information in Nowak (1994). Measured tree growth rates for street (Frelich 1992; Fleming 1988; Nowak 1994), park (deVries 1987), and forest (Smith and Shifley 1984) trees were standardized to an average length of growing season (153 frost free days) and adjusted for site competition and tree condition. Standardized growth rates of trees of the same species or genus were then compared to determine the average difference between standardized street tree growth and standardized park and forest growth rates. Crown light exposure (CLE) measurements (number of sides and/or top of tree exposed to sunlight) were used to represent forest, park, and open (street) tree growth conditions. Local tree base growth rates (BG) were then calculated as the average standardized growth rate for open-grown trees multiplied by the number of frost free days divided by 153. Growth rates were then adjusted for CLE. The CLE adjusted growth rate was then adjusted based on tree health and tree condition to determine the final growth rate. Assumptions for which dead trees would be removed versus left standing were developed specific to each land use and were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak et al. 2013).

Estimates of gross and net sequestration rates for each of the 50 states and the District of Columbia (Table 6-44) were compiled in units of C sequestration per unit area of tree canopy cover. These rates were used in conjunction with estimates of state urban area and urban tree cover data to calculate each state's annual net C sequestration by urban trees. This method was described in Nowak et al. (2013) and has been modified here to incorporate U.S. Census data.

Specifically, urban area estimates were based on 1990, 2000, and 2010 U.S. Census data. The 1990 U.S. Census defined urban land as "urbanized areas," which included land with a population density greater than 1,000 people per square mile, and adjacent "urban places," which had predefined political boundaries and a population total greater than 2,500. In 2000, the U.S. Census replaced the "urban places" category with a new category of urban land called an "urban cluster," which included areas with more than 500 people per square mile. In 2010, the Census updated its definitions to have "urban areas" encompassing Census tract delineated cities with 50,000 or more people, and "urban clusters" containing Census tract delineated locations with between 2,500 and 50,000 people. Urban land area increased by approximately 23 percent from 1990 to 2000 and 14 percent from 2000 to 2010; Nowak et al. (2005) estimate that the changes in the definition of urban land are responsible for approximately 20 percent of the total reported increase in urban land area from 1990 to 2000. Under all Census (i.e., 1990, 2000, and 2010) definitions, the urban category encompasses most cities, towns, and villages (i.e., it includes both urban and suburban areas). *Settlements* area, as assessed in the *Representation of the U.S. Land Base* developed for this report, encompassed all developed parcels greater than 0.1 hectares in size, including rural transportation corridors, and as previously mentioned represents a larger area than the Census-derived urban area estimates. However, the smaller, Census-derived urban area estimates were deemed to be more suitable for estimating national urban tree cover given the data available in the peer-reviewed literature (i.e., the data set available is consistent with Census urban rather than *Settlements* areas), and the recognized overlap in the changes in C stocks between urban forest and non-urban forest (see Planned Improvements below). U.S. Census urban area data is reported as a series of continuous blocks of urban area in each state. The blocks or urban area were summed to create each state's urban area estimate.

Net annual C sequestration estimates were derived for all 50 states and the District of Columbia by multiplying the gross annual emission estimates by 0.74, the standard ratio for net/gross sequestration set out in Table 3 of Nowak et al. (2013) (unless data existed for both gross and net sequestration for the state in Table 2 of Nowak et. al. (2013), in which case they were divided to get a state-specific ratio). The gross and net annual C sequestration values for each state were multiplied by each state's area of tree cover, which was the product of the state's urban/community area as defined in the U.S. Census (2012) and the state's urban/community tree cover percentage. The urban/community tree cover percentage estimates for all 50 states were obtained from Nowak and Greenfield (2012), which compiled ten years of research including Dwyer et al. (2000), Nowak et al. (2002), Nowak (2007a), and Nowak (2009). The urban/community tree cover percentage estimate for the District of Columbia was obtained from Nowak et al. (2013). The urban area estimates were taken from the 2010 U.S. Census (2012). The equation, used to calculate the summed carbon sequestration amounts, can be written as follows:

$$\text{Net annual C sequestration} = \text{Gross sequestration rate} \times \text{Net to Gross sequestration ratio} \times \text{Urban Area} \times \text{\% Tree Cover}$$

Table 6-44: Annual C Sequestration (Metric Tons C/yr), Tree Cover (Percent), and Annual C Sequestration per Area of Tree Cover (kg C/m²-yr) for 50 states plus the District of Columbia (2014)

State	Gross Annual Sequestration	Net Annual Sequestration	Tree Cover	Gross Annual Sequestration per Area of Tree Cover	Net Annual Sequestration per Area of Tree Cover	Net: Gross Annual Sequestration Ratio
Alabama	1,165,574	862,524	55.2	0.343	0.254	0.74
Alaska	44,744	33,111	39.8	0.168	0.124	0.74
Arizona	385,644	285,376	17.6	0.354	0.262	0.74
Arkansas	424,922	314,443	42.3	0.331	0.245	0.74

California	2,106,024	1,558,458	25.1	0.389	0.288	0.74
Colorado	153,806	113,817	18.5	0.197	0.146	0.74
Connecticut	771,006	570,544	67.4	0.239	0.177	0.74
Delaware	136,070	100,692	35.0	0.335	0.248	0.74
DC	14,559	11,569	35.0	0.263	0.209	0.79
Florida	3,429,742	2,538,009	35.5	0.475	0.352	0.74
Georgia	2,580,659	1,909,688	54.1	0.353	0.261	0.74
Hawaii	246,168	182,164	39.9	0.581	0.430	0.74
Idaho	25,533	18,894	10.0	0.184	0.136	0.74
Illinois	760,263	562,594	25.4	0.283	0.209	0.74
Indiana	406,015	375,425	23.7	0.250	0.231	0.92
Iowa	119,006	88,064	19.0	0.240	0.178	0.74
Kansas	186,077	144,799	25.0	0.283	0.220	0.78
Kentucky	243,641	180,295	22.1	0.286	0.212	0.74
Louisiana	749,632	554,727	34.9	0.397	0.294	0.74
Maine	108,092	79,988	52.3	0.221	0.164	0.74
Maryland	597,897	442,444	34.3	0.323	0.239	0.74
Massachusetts	1,309,649	969,140	65.1	0.254	0.188	0.74
Michigan	740,048	547,635	35.0	0.220	0.163	0.74
Minnesota	354,139	262,063	34.0	0.229	0.169	0.74
Mississippi	494,558	365,973	47.3	0.344	0.255	0.74
Missouri	498,925	369,205	31.5	0.285	0.211	0.74
Montana	53,940	39,916	36.3	0.184	0.136	0.74
Nebraska	50,920	42,970	15.0	0.238	0.201	0.84
Nevada	44,096	32,631	9.6	0.207	0.153	0.74
New Hampshire	250,531	185,393	66.0	0.217	0.161	0.74
New Jersey	1,201,070	888,792	53.3	0.294	0.218	0.74
New Mexico	70,002	51,801	12.0	0.263	0.195	0.74
New York	1,096,654	811,524	42.6	0.240	0.178	0.74
North Carolina	2,076,636	1,536,711	51.1	0.312	0.231	0.74
North Dakota	14,946	7,102	13.0	0.223	0.106	0.48
Ohio	927,316	686,214	31.5	0.248	0.184	0.74
Oklahoma	366,160	270,959	31.2	0.332	0.246	0.74
Oregon	261,067	193,190	36.6	0.242	0.179	0.74
Pennsylvania	1,264,702	935,879	41.0	0.244	0.181	0.74
Rhode Island	137,147	101,489	51.0	0.258	0.191	0.74
South Carolina	1,107,882	819,832	48.9	0.338	0.250	0.74
South Dakota	21,348	18,513	14.0	0.236	0.205	0.87
Tennessee	1,063,362	950,771	43.8	0.303	0.271	0.89
Texas	2,808,539	2,078,319	31.4	0.368	0.272	0.74
Utah	91,713	67,868	16.4	0.215	0.159	0.74
Vermont	46,571	34,462	53.0	0.213	0.158	0.74
Virginia	839,610	621,311	39.8	0.293	0.217	0.74
Washington	571,062	422,586	34.6	0.258	0.191	0.74
West Virginia	255,369	188,973	61.0	0.241	0.178	0.74
Wisconsin	364,611	269,812	31.8	0.225	0.167	0.74
Wyoming	19,203	14,210	19.9	0.182	0.135	0.74
Total	**33,056,852**	**24,712,872**				

Uncertainty and Time-Series Consistency

Uncertainty associated with changes in C stocks in urban trees includes the uncertainty associated with urban area, percent urban tree coverage, and estimates of gross and net C sequestration for each of the 50 states and the District of Columbia. A 10 percent uncertainty was associated with urban area estimates based on expert judgment. Uncertainty associated with estimates of percent urban tree coverage for each of the 50 states was based on standard error estimates reported by Nowak and Greenfield (2012). Uncertainty associated with estimate of percent urban tree coverage for the District of Columbia was based on the standard error estimate reported by Nowak et al. (2013). Uncertainty associated with estimates of gross and net C sequestration for each of the 50 states and the District of Columbia was based on standard error estimates for each of the state-level sequestration estimates reported by Nowak et al. (2013). These estimates are based on field data collected in each of the 50 states and the District of Columbia, and uncertainty in these estimates increases as they are scaled up to the national level.

Additional uncertainty is associated with the biomass equations, conversion factors, and decomposition assumptions used to calculate C sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil C stocks, and there may be some overlap between the urban tree C estimates and the forest tree C estimates. Due to data limitations, urban soil flux is not quantified as part of this analysis, while reconciliation of urban tree and forest tree estimates will be addressed through the land-representation effort described in the Planned Improvements section of this chapter.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-45. The net C flux from changes in C stocks in urban trees in 2014 was estimated to be between −134.0 and −47.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 51 percent more sequestration to 46 percent less sequestration than the 2014 flux estimate of −90.6 MMT CO_2 Eq.

Table 6-45: Approach 2 Quantitative Uncertainty Estimates for Net C Flux from Changes in C Stocks in Urban Trees (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Changes in C Stocks in Urban Trees	CO_2	(90.6)	(134.0)	(47.4)	-51%	+46%

Note: Parentheses indicate negative values or net sequestration.

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

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for urban trees included checking input data, documentation, and calculations to ensure data were properly handled through the Inventory process. Errors that were found during this process were corrected as necessary. One key edit in the current Inventory report is that Table 6-44 has been updated. For this Table, the values in the 2014 (1990-2012) and 2015 (1990-2013) Inventory reports were the same. The updated values for the 2016 (1990-2014) Inventory were inserted here, noting that they represent a two-year increment in urban tree C sequestration from what was presented in the previous Inventory.

Planned Improvements

A consistent representation of the managed land base in the United States is discussed in the *Representation of the U.S. Land Base* chapter, and discusses a planned improvement by the USDA Forest Service to reconcile the overlap between urban forest and non-urban forest greenhouse gas inventories. Because some plots defined as "forest" in the Forest Inventory and Analysis (FIA) program of the USDA Forest Service actually fall within the boundaries of the areas also defined as Census urban, there may be "double-counting" of these land areas in estimates of C stocks and fluxes for this report. Specifically, Nowak et al. (2013) estimates that 1.5 percent of forest plots measured by the FIA program fall within land designated as Census urban, suggesting that approximately 1.5 percent of the C reported in the Forest source category might also be counted in the Urban Trees source category.

Future research may also enable more complete coverage of changes in the C stock in urban trees for all *Settlements* land. To provide estimates for all *Settlements*, research would need to establish the extent of overlap between the areas of land included in the *Settlements* land use category and Census-defined urban areas, and would have to separately characterize sequestration on non-urban *Settlements* land.

N_2O Fluxes from Settlement Soils (IPCC Source Category 4E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 3.1 percent are currently applied to lawns, golf courses, and other landscaping occurring within settlement areas. Application rates are lower than those occurring on cropped soils, and, therefore, account for a smaller proportion of total U.S. soil N_2O emissions per unit area. In addition to synthetic N fertilizers, a portion of surface applied sewage sludge is applied to settlement areas.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions. Indirect emissions result from fertilizer and sludge N that is transformed and transported to another location in a form other than N_2O (NH_3 and NO_x volatilization, NO_3 leaching and runoff), and later converted into N_2O at the off-site location. The indirect emissions are assigned to settlements because the management activity leading to the emissions occurred in settlements.

Total N_2O emissions from settlement soils were 2.4 MMT CO_2 Eq. (8 kt of N_2O) in 2014. There was an overall increase of 78 percent from 1990 to 2014 due to an expanding settlement area requiring more synthetic N fertilizer. Interannual variability in these emissions is directly attributable to interannual variability in total synthetic fertilizer consumption and sewage sludge applications in the United States. Emissions from this source are summarized in Table 6-46.

Table 6-46: N_2O Fluxes from Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and kt N_2O)

	1990		2005		2010	2011	2012	2013	2014
Direct N_2O Fluxes from Soils									
MMT CO_2 Eq.	1.0		1.8		1.8	1.9	1.9	1.8	1.8
kt N_2O	3		6		6	6	6	6	6
Indirect N_2O Fluxes from Soils									
MMT CO_2 Eq.	0.4		0.6		0.6	0.6	0.6	0.6	0.6
kt N_2O	1		2		2	2	2	2	2
Total									
MMT CO_2 Eq.	**1.4**		**2.3**		**2.4**	**2.5**	**2.5**	**2.4**	**2.4**
kt N_2O	**5**		**8**		**8**	**8**	**9**	**8**	**8**

Methodology

For soils within *Settlements Remaining Settlements*, the IPCC Tier 1 approach is used to estimate soil N_2O emissions from synthetic N fertilizer and sewage sludge additions. Estimates of direct N_2O emissions from soils in settlements are based on the amount of N in synthetic commercial fertilizers applied to settlement soils, and the amount of N in sewage sludge applied to non-agricultural land and surface disposal (see Annex 3.12 for a detailed discussion of the methodology for estimating sewage sludge application).

Nitrogen applications to settlement soils are estimated using data compiled by the USGS (Ruddy et al. 2006). The USGS estimated on-farm and non-farm fertilizer use is based on sales records at the county level from 1982 through 2001 (Ruddy et al. 2006). Non-farm N fertilizer is assumed to be applied to settlements and forest lands; values for 2002 through 2014 are based on 2001 values adjusted for annual total N fertilizer sales in the United States because there is no new activity data on application after 2001. Settlement application is calculated by subtracting forest application from total non-farm fertilizer use. Sewage sludge applications are derived from national data on sewage sludge generation, disposition, and N content (see Annex 3.12 for further detail). The total amount of N resulting from these sources is multiplied by the IPCC default emission factor for applied N (1 percent) to estimate direct N_2O emissions (IPCC 2006).

For indirect emissions, the total N applied from fertilizer and sludge is multiplied by the IPCC default factors of 10 percent for volatilization and 30 percent for leaching/runoff to calculate the amount of N volatilized and the amount of N leached/runoff. The amount of N volatilized is multiplied by the IPCC default factor of 1 percent for the portion of volatilized N that is converted to N_2O off-site and the amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site. The resulting estimates are summed to obtain total indirect emissions.

Uncertainty and Time-Series Consistency

The amount of N_2O emitted from settlements depends not only on N inputs and fertilized area, but also on a large number of variables, including organic C availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and irrigation/watering practices. The effect of the combined interaction of these variables on N_2O flux is complex and highly uncertain. The IPCC default methodology does not explicitly incorporate any of these variables, except variations in fertilizer N and sewage sludge application rates. All settlement soils are treated equivalently under this methodology.

Uncertainties exist in both the fertilizer N and sewage sludge application rates in addition to the emission factors. Uncertainty in fertilizer N application is assigned a default level of ±50 percent.[52] Uncertainty in the amounts of sewage sludge applied to non-agricultural lands and used in surface disposal is derived from variability in several factors, including: (1) N content of sewage sludge; (2) total sludge applied in 2000; (3) wastewater existing flow in 1996 and 2000; and (4) the sewage sludge disposal practice distributions to non-agricultural land application and surface disposal. In addition, the uncertainty ranges around 2005 activity data and emission factor input variables are directly applied to the 2014 emission estimates. Uncertainty in the direct and indirect emission factors is provided by IPCC (2006).

Uncertainty is quantified using simple error propagation methods (IPCC 2006), and the results are summarized in Table 6-47. Direct N_2O emissions from soils in *Settlements Remaining Settlements* in 2014 are estimated to be between 0.9 and 4.8 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 49 percent below to 163 percent above the 2014 emission estimate of 1.8 MMT CO_2 Eq. Indirect N_2O emissions in 2014 are between 0.1 and 1.9 MMT CO_2 Eq., ranging from a -85 percent to 212 percent around the estimate of 0.6 MMT CO_2 Eq.

Table 6-47: Quantitative Uncertainty Estimates of N_2O Emissions from Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emissions (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
Settlements Remaining Settlements:			**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct N_2O Fluxes from Soils	N_2O	1.8	0.9	4.8	-49%	+163%
Indirect N_2O Fluxes from Soils	N_2O	0.6	0.1	1.9	-85%	+212%

Note: These estimates include direct and indirect N_2O emissions from N fertilizer additions to both *Settlements Remaining Settlements* and from *Land Converted to Settlements*.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

The spreadsheet containing fertilizer and sewage sludge applied to settlements and calculations for N_2O and uncertainty ranges have been checked and verified.

Planned Improvements

A minor improvement is planned to update the uncertainty analysis for direct emissions from settlements to be consistent with the most recent activity data for this source.

---

[52] No uncertainty is provided with the USGS fertilizer consumption data (Ruddy et al. 2006) so a conservative ±50 percent is used in the analysis.

6.11 Land Converted to Settlements (IPCC Source Category 4E2)

Land-use change is constantly occurring, and land under a number of uses undergoes urbanization in the United States each year. However, data on the amount of land converted to settlements is currently lacking. Given the lack of available information relevant to this particular IPCC source category, it is not possible to separate CO_2 or N_2O fluxes on *Land Converted to Settlements* from fluxes on *Settlements Remaining Settlements* at this time.

6.12 Other (IPCC Source Category 4H)

Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills

In the United States, yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps account for a significant portion of the municipal waste stream, and a large fraction of the collected yard trimmings and food scraps are put in landfills. Carbon (C) contained in landfilled yard trimmings and food scraps can be stored for very long periods.

Carbon-storage estimates are associated with particular land uses. For example, harvested wood products are accounted for under *Forest Land Remaining Forest Land* because these wood products are considered a component of the forest ecosystem. The wood products serve as reservoirs to which C resulting from photosynthesis in trees is transferred, but the removals in this case occur in the forest. Carbon stock changes in yard trimmings and food scraps are associated with settlements, but removals in this case do not occur within settlements. To address this complexity, yard trimming and food scrap C storage is reported under the “Other” source category.

Both the amount of yard trimmings collected annually and the fraction that is landfilled have declined over the last decade. In 1990, over 53 million metric tons (wet weight) of yard trimmings and food scraps were generated (i.e., put at the curb for collection to be taken to disposal sites or to composting facilities) (EPA 2015a). Since then, programs banning or discouraging yard trimmings disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent 2.3 percent decrease in the tonnage of yard trimmings generated (i.e., collected for composting or disposal). At the same time, an increase in the number of municipal composting facilities has reduced the proportion of collected yard trimmings that are discarded in landfills—from 72 percent in 1990 to 32 percent in 2014. The net effect of the reduction in generation and the increase in composting is a 57 percent decrease in the quantity of yard trimmings disposed of in landfills since 1990.

Food scrap generation has grown by 55 percent since 1990, and though the proportion of food scraps discarded in landfills has decreased slightly from 82 percent in 1990 to 76 percent in 2014, the tonnage disposed of in landfills has increased considerably (by 45 percent). Although the total tonnage of food scraps disposed in landfills has increased from 1990 to 2014, the annual carbon stock net changes from food scraps have decreased (as shown in Table 6-48 and Table 6-49), due to smaller annual differences in the amount of food waste disposed in landfills. Overall, the decrease in the landfill disposal rate of yard trimmings has more than compensated for the increase in food scrap disposal in landfills, and the net result is a decrease in annual landfill C storage from 26.0 MMT CO_2 Eq. (7.1 MMT C) in 1990 to 11.6 MMT CO_2 Eq. (3.2 MMT C) in 2014 (Table 6-48 and Table 6-49).

Table 6-48: Net Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills (MMT CO_2 Eq.)

Carbon Pool	1990		2005		2010	2011	2012	2013	2014
Yard Trimmings	**(21.0)**		**(7.4)**		**(9.3)**	**(9.2)**	**(9.1)**	**(8.5)**	**(8.5)**
Grass	(1.8)		(0.6)		(0.9)	(0.9)	(0.9)	(0.8)	(0.8)
Leaves	(9.0)		(3.4)		(4.2)	(4.2)	(4.2)	(3.9)	(3.9)
Branches	(10.2)		(3.4)		(4.1)	(4.1)	(4.1)	(3.8)	(3.8)
Food Scraps	**(5.0)**		**(4.0)**		**(3.9)**	**(3.5)**	**(3.1)**	**(3.2)**	**(3.1)**
Total Net Flux	**(26.0)**		**(11.4)**		**(13.2)**	**(12.7)**	**(12.2)**	**(11.7)**	**(11.6)**

Note: Parentheses indicate net sequestration.

Table 6-49: Net Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills (MMT C)

Carbon Pool	1990		2005		2010	2011	2012	2013	2014
Yard Trimmings	**(5.7)**		**(2.0)**		**(2.5)**	**(2.5)**	**(2.5)**	**(2.3)**	**(2.3)**
Grass	(0.5)		(0.2)		(0.3)	(0.2)	(0.2)	(0.2)	(0.2)
Leaves	(2.5)		(0.9)		(1.2)	(1.1)	(1.1)	(1.1)	(1.1)
Branches	(2.8)		(0.9)		(1.1)	(1.1)	(1.1)	(1.0)	(1.0)
Food Scraps	**(1.4)**		**(1.1)**		**(1.1)**	**(1.0)**	**(0.9)**	**(0.9)**	**(0.8)**
Total Net Flux	**(7.1)**		**(3.1)**		**(3.6)**	**(3.5)**	**(3.3)**	**(3.2)**	**(3.2)**

Note: Parentheses indicate net sequestration.

Methodology

When wastes of biogenic origin (such as yard trimmings and food scraps) are landfilled and do not completely decompose, the C that remains is effectively removed from the terrestrial C cycle. Empirical evidence indicates that yard trimmings and food scraps do not completely decompose in landfills (Barlaz 1998, 2005, 2008; De la Cruz and Barlaz 2010), and thus the stock of C in landfills can increase, with the net effect being a net atmospheric removal of C. Estimates of net C flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled C stocks between inventory years, based on methodologies presented for the Land Use, Land-Use Change, and Forestry sector in IPCC (2003). Carbon stock estimates were calculated by determining the mass of landfilled C resulting from yard trimmings or food scraps discarded in a given year; adding the accumulated landfilled C from previous years; and subtracting the mass of C that was landfilled in previous years that decomposed.

To determine the total landfilled C stocks for a given year, the following were estimated: (1) The composition of the yard trimmings; (2) the mass of yard trimmings and food scraps discarded in landfills; (3) the C storage factor of the landfilled yard trimmings and food scraps; and (4) the rate of decomposition of the degradable C. The composition of yard trimmings was assumed to be 30 percent grass clippings, 40 percent leaves, and 30 percent branches on a wet weight basis (Oshins and Block 2000). The yard trimmings were subdivided, because each component has its own unique adjusted C storage factor (i.e., moisture content and C content) and rate of decomposition. The mass of yard trimmings and food scraps disposed of in landfills was estimated by multiplying the quantity of yard trimmings and food scraps discarded by the proportion of discards managed in landfills. Data on discards (i.e., the amount generated minus the amount diverted to centralized composting facilities) for both yard trimmings and food scraps were taken primarily from *Advancing Sustainable Materials Management: Facts and Figures 2013* (EPA 2015a), which provides data for 1960, 1970, 1980, 1990, 2000, 2005, 2009 and 2011 through 2013. To provide data for some of the missing years, detailed backup data were obtained from historical data tables that EPA developed for 1960 through 2013 (EPA 2015b). Remaining years in the time series for which data were not provided were estimated using linear interpolation. Data for 2014 are not yet available, so they were set equal to 2013 values. The EPA (2015a) report and historical data tables (EPA 2015b) do not subdivide the discards (i.e., total generated minus composted) of individual materials into masses landfilled and combusted, although it provides a mass of overall waste stream discards managed in landfills[53] and combustors with energy recovery (i.e., ranging from 67 percent and 33 percent, respectively, in 1960 to 92 percent and 8 percent, respectively, in 1985); it is assumed that the proportion of each individual material (food scraps, grass, leaves, branches) that is landfilled is the same as the proportion across the overall waste stream.

The amount of C disposed of in landfills each year, starting in 1960, was estimated by converting the discarded landfilled yard trimmings and food scraps from a wet weight to a dry weight basis, and then multiplying by the initial (i.e., pre-decomposition) C content (as a fraction of dry weight). The dry weight of landfilled material was calculated using dry weight to wet weight ratios (Tchobanoglous et al. 1993, cited by Barlaz 1998) and the initial C contents and the C storage factors were determined by Barlaz (1998, 2005, 2008) (Table 6-50).

The amount of C remaining in the landfill for each subsequent year was tracked based on a simple model of C fate. As demonstrated by Barlaz (1998, 2005, 2008), a portion of the initial C resists decomposition and is essentially persistent in the landfill environment. Barlaz (1998, 2005, 2008) conducted a series of experiments designed to measure biodegradation of yard trimmings, food scraps, and other materials, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). After measuring the initial C content, the materials were placed in sealed containers along with methanogenic microbes from a landfill. Once decomposition was complete, the yard trimmings and food scraps were re-analyzed for C content; the C remaining in the solid sample can be expressed as a proportion of the initial C (shown in the row labeled “C Storage Factor, Proportion of Initial C Stored (Percent)” in Table 6-50).

The modeling approach applied to simulate U.S. landfill C flows builds on the findings of Barlaz (1998, 2005, 2008). The proportion of C stored is assumed to persist in landfills. The remaining portion is assumed to degrade over time, resulting in emissions of CH_4 and CO_2. (The CH_4 emissions resulting from decomposition of yard trimmings and food scraps are accounted for in the *Waste* chapter.) The degradable portion of the C is assumed to decay according to first-order kinetics. The decay rates for each of the materials are shown in Table 6-50.

The first-order decay rates, k, for each refuse type were derived from De la Cruz and Barlaz (2010). De la Cruz and Barlaz (2010) calculate first-order decay rates using laboratory data published in Eleazer et al. (1997), and a correction factor, f, is found so that the weighted average decay rate for all components is equal to the EPA AP-42 default decay rate (0.04) for mixed MSW for regions that receive more than 25 inches of rain annually (EPA 1995). Because AP-42 values were developed using landfill data from approximately 1990, 1990 waste composition for the United States from EPA’s *Characterization of Municipal Solid Waste in the United States: 1990 Update* was used to calculate f. This correction factor is then multiplied by the Eleazer et al. (1997) decay rates of each waste component to develop field-scale first-order decay rates.

De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are found, including dry conditions (less than 25 inches of rain annually, k=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, k=0.12). As in the *Landfills* section of the Inventory (which estimates CH_4 emissions), the overall MSW decay rate is estimated by partitioning the U.S. landfill population into three categories, based on annual precipitation ranges of: (1) Less than 20 inches of rain per year, (2) 20 to 40 inches of rain per year, and (3) greater than 40 inches of rain per year. These correspond to overall MSW decay rates of 0.020, 0.038, and 0.057 $year^{-1}$, respectively.

De la Cruz and Barlaz (2010) calculate component-specific decay rates corresponding to the first value (0.020 $year^{-1}$), but not for the other two overall MSW decay rates. To maintain consistency between landfill methodologies across the Inventory, the correction factors (f) were developed for decay rates of 0.038 and 0.057 $year^{-1}$ through linear interpolation. A weighted national average component-specific decay rate was calculated by assuming that waste generation is proportional to population (the same assumption used in the landfill methane emission estimate), based on population data from the 2000 U.S. Census. The component-specific decay rates are shown in Table 6-50.

---

[53] EPA (2015a and 2015b) reports discards in two categories: “combustion with energy recovery” and “landfill, other disposal,” which includes combustion without energy recovery. For years in which there is data from previous EPA reports on combustion without energy recovery, EPA assumes these estimates are still applicable. For 2000 to present, EPA assumes that any combustion of MSW that occurs includes energy recovery, so all discards to “landfill, other disposal” are assumed to go to landfills.

For each of the four materials (grass, leaves, branches, food scraps), the stock of C in landfills for any given year is calculated according to Equation 1:

$$LFC_{i,t} = \sum_{n}^{t} W_{i,n} \times (1 - MC_i) \times ICC_i \times \{[CS_i \times ICC_i] + [(1 - (CS_i \times ICC_i)) \times e^{-k(t-n)}]\}$$

where,

t = Year for which C stocks are being estimated (year),
i = Waste type for which C stocks are being estimated (grass, leaves, branches, food scraps),
$LFC_{i,t}$ = Stock of C in landfills in year t, for waste i (metric tons),
$W_{i,n}$ = Mass of waste i disposed of in landfills in year n (metric tons, wet weight),
n = Year in which the waste was disposed of (year, where $1960 < n < t$),
MC_i = Moisture content of waste i (percent of water),
CS_i = Proportion of initial C that is stored for waste i (percent),
ICC_i = Initial C content of waste i (percent),
e = Natural logarithm, and
k = First-order decay rate for waste i, (year^{-1}).

For a given year t, the total stock of C in landfills ($TLFC_t$) is the sum of stocks across all four materials (grass, leaves, branches, food scraps). The annual flux of C in landfills (F_t) for year t is calculated in Equation 2 as the change in stock compared to the preceding year:

$$F_t = TLFC_t - TLFC_{(t-1)}$$

Thus, as seen in Equation 1, the C placed in a landfill in year n is tracked for each year t through the end of the Inventory period (2014). For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of C. Of this amount, 16 percent (179,000 metric tons) is persistent; the remaining 84 percent (956,000 metric tons) is degradable. By 1965, more than half of the degradable portion (518,000 metric tons) decomposes, leaving a total of 617,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2014, the total food scraps C originally disposed of in 1960 had declined to 179,000 metric tons (i.e., virtually all degradable C had decomposed). By summing the C remaining from 1960 with the C remaining from food scraps disposed of in subsequent years (1961 through 2014), the total landfill C from food scraps in 2014 was 41.5 million metric tons. This value is then added to the C stock from grass, leaves, and branches to calculate the total landfill C stock in 2014, yielding a value of 264.7 million metric tons (as shown in Table 6-51). In exactly the same way total net flux is calculated for forest C and harvested wood products, the total net flux of landfill C for yard trimmings and food scraps for a given year (Table 6-49) is the difference in the landfill C stock for that year and the stock in the preceding year. For example, the net change in 2014 shown in Table 6-49 (3.2 MMT C) is equal to the stock in 2014 (264.7 MMT C) minus the stock in 2013 (261.5 MMT C).

The C stocks calculated through this procedure are shown in Table 6-51.

Table 6-50: Moisture Contents, C Storage Factors (Proportions of Initial C Sequestered), Initial C Contents, and Decay Rates for Yard Trimmings and Food Scraps in Landfills

Variable	Yard Trimmings			Food Scraps
	Grass	Leaves	Branches	
Moisture Content (% H_2O)	70	30	10	70
C Storage Factor, Proportion of Initial C Stored (%)	53	85	77	16
Initial C Content (%)	45	46	49	51
Decay Rate (year^{-1})	0.323	0.185	0.016	0.156

Table 6-51: C Stocks in Yard Trimmings and Food Scraps in Landfills (MMT C)

Carbon Pool	1990	2005	2010	2011	2012	2013	2014
Yard Trimmings	**155.8**	**202.9**	**213.6**	**216.1**	**218.6**	**220.9**	**223.2**
Branches	14.5	18.1	19.0	19.3	19.5	19.7	20.0
Leaves	66.7	87.3	92.2	93.4	94.5	95.6	96.6
Grass	74.6	97.5	102.3	103.4	104.5	105.6	106.6
Food Scraps	**17.6**	**32.8**	**38.0**	**38.9**	**39.8**	**40.7**	**41.5**
Total Carbon Stocks	**173.5**	**235.6**	**251.6**	**255.0**	**258.4**	**261.5**	**264.7**

Uncertainty and Time-Series Consistency

The uncertainty analysis for landfilled yard trimmings and food scraps includes an evaluation of the effects of uncertainty for the following data and factors: disposal in landfills per year (tons of C), initial C content, moisture content, decay rate, and proportion of C stored. The C storage landfill estimates are also a function of the composition of the yard trimmings (i.e., the proportions of grass, leaves and branches in the yard trimmings mixture). There are respective uncertainties associated with each of these factors.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-52. Total yard trimmings and food scraps CO_2 flux in 2014 was estimated to be between -18.0 and -4.5 MMT CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo stochastic simulations). This indicates a range of 44 percent below to 64 percent above the 2014 flux estimate of -11.6 MMT CO_2 Eq. More information on the uncertainty estimates for Yard Trimmings and Food Scraps in Landfills is contained within the Uncertainty Annex.

Table 6-52: Approach 2 Quantitative Uncertainty Estimates for CO_2 Flux from Yard Trimmings and Food Scraps in Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Yard Trimmings and Food Scraps	CO_2	(11.6)	(18.0)	(4.5)	-44%	+64%

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

Note: Parentheses indicate negative values or net C sequestration.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. The QA/QC analysis did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The current Inventory has been revised relative to the previous report. Generation and recovery data for yard trimmings and food scraps was not previously provided for every year from 1960 in the *Advancing Sustainable Materials Management: Facts and Figures 2013* report. EPA has since released historical data, which included data for each year from 1960 through 2013. The recalculations based on these historical data resulted in changes ranging from a 1 percent increase in sequestration in 2001 to a 7 percent decrease in sequestration in 2013, and an average 0.66 percent decrease in sequestration across the 1990 through 2013 time series compared to the previous Inventory.

Planned Improvements

Future work is planned to evaluate the consistency between the estimates of C storage described in this chapter and the estimates of landfill CH_4 emissions described in the *Waste* chapter. For example, the *Waste* chapter does not distinguish landfill CH_4 emissions from yard trimmings and food scraps separately from landfill CH_4 emissions from total bulk (i.e., municipal solid) waste, which includes yard trimmings and food scraps.

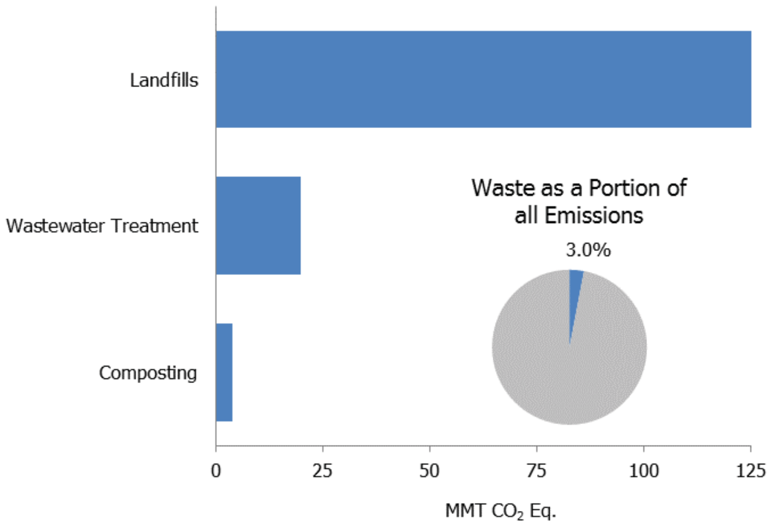
In addition, additional data will be evaluated from recent peer-reviewed literature that may modify the default C storage factors, initial C contents, and decay rates for yard trimmings and food scraps in landfills. Based upon this evaluation, changes may be made to the default values. Whether to update the weighted national average component-specific decay rate using new U.S. Census data, if any are available, will also be investigated.

The yard waste composition will also be evaluated to determine if changes need to be made based on changes in residential practices, research will be conducted to determine if there are changes in the allocation of yard trimmings. For example, leaving grass clippings in place is becoming a more common practice, thus reducing the percentage of grass clippings in yard trimmings disposed in landfills.

7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1). Landfills accounted for approximately 25.7 percent of total U.S. anthropogenic methane (CH_4) emissions in 2014, the largest contribution of any CH_4 source in the United States. Additionally, wastewater treatment and composting of organic waste accounted for approximately 2.1 percent and less than 1 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions from the discharge of wastewater treatment effluents into aquatic environments were estimated, as were N_2O emissions from the treatment process itself. N_2O emissions from composting were also estimated. Together, these waste activities account for 1.6 percent of total U.S. N_2O emissions. Nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are emitted by waste activities, and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 7-1 and Table 7-2.

Figure 7-1: 2014 Waste Chapter Greenhouse Gas Sources (MMT CO_2 Eq.)



Box 7-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and sinks presented in this report and this chapter, are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC 2006).[1] Additionally, the calculated emissions and sinks in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[2] The use of consistent methods to calculate emissions and sinks by

---

[1] See <http://www.ipcc-nggip.iges.or.jp/public/index.html>.

[2] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>.

all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard, U.S. emissions and sinks reported in this Inventory report are comparable to emissions and sinks reported by other countries. The manner that emissions and sinks are provided in this Inventory is one of many ways U.S. emissions and sinks could be examined; this Inventory report presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. Emissions and sinks provided in the current Inventory do not preclude alternative examinations,[3] but rather presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted. The UNFCCC incorporated the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* as the standard for Annex I countries at the Nineteenth Conference of the Parties (Warsaw, November 11-23, 2013). This chapter presents emission estimates calculated in accordance with the methodological guidance provided in these guidelines.

Overall, in 2014, waste activities generated emissions of 205.6 MMT CO_2 Eq., or just under 3 percent of total U.S. greenhouse gas emissions.

Table 7-1: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CH_4	**200.4**	**205.1**	**193.6**	**194.0**	**190.6**	**193.7**	**198.9**
Landfills	184.4	187.3	176.3	176.9	173.5	176.7	181.8
Wastewater Treatment	15.7	15.9	15.5	15.3	15.2	15.0	15.0
Composting	0.4	1.9	1.8	1.9	1.9	2.0	2.1
N_2O	**3.7**	**6.0**	**6.4**	**6.5**	**6.6**	**6.7**	**6.8**
Wastewater Treatment	3.4	4.3	4.7	4.8	4.9	4.9	4.9
Composting	0.3	1.7	1.6	1.7	1.7	1.8	1.8
Total	**204.1**	**211.1**	**200.0**	**200.5**	**197.2**	**200.5**	**205.6**

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (kt)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CH_4	**8,017**	**8,203**	**7,744**	**7,759**	**7,625**	**7,749**	**7,954**
Landfills	7,376	7,493	7,052	7,074	6,942	7,066	7,271
Wastewater Treatment	626	635	619	610	606	601	601
Composting	15	75	73	75	77	81	82
N_2O	**12**	**20**	**21**	**22**	**22**	**23**	**23**
Wastewater Treatment	11	15	16	16	16	17	17
Composting	1	6	5	6	6	6	6

Note: Totals may not sum due to independent rounding.

Carbon dioxide, CH_4, and N_2O emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2014 resulted in 9.7 MMT CO_2 Eq. emissions, more than half of which is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 7.4.

---

[3] For example, see < http://www.epa.gov/ghgreporting/ghgrp-methodology-and-verification >.

Box 7-2: Waste Data from the Greenhouse Gas Reporting Program

On October 30, 2009, the U.S. EPA published a rule for the mandatory reporting of greenhouse gases from large greenhouse gas emissions sources in the United States. Implementation of 40 CFR Part 98 is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP). 40 CFR part 98 applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by 41 industrial categories. Reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year.

EPA's GHGRP dataset and the data presented in this Inventory report are complementary and, as indicated in the respective planned improvements sections for source categories in this chapter, EPA is analyzing how to use facility-level GHGRP data to improve the national estimates presented in this Inventory. Most methodologies used in EPA's GHGRP are consistent with IPCC, though for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards. This may differ with the more aggregated data collected for the Inventory to estimate total, national U.S. emissions. It should be noted that the definitions for source categories in the GHGRP may differ from those used in this Inventory in meeting the UNFCCC reporting guidelines. In line with the UNFCCC reporting guidelines, the Inventory report is a comprehensive accounting of all emissions from source categories identified in the IPCC guidelines. Further information on the reporting categorizations in EPA's GHGRP and specific data caveats associated with monitoring methods in EPA's GHGRP has been provided on the EPA's GHGRP website.[4]

EPA presents the data collected by EPA's GHGRP through a data publication tool[5] that allows data to be viewed in several formats including maps, tables, charts and graphs for individual facilities or groups of facilities.

7.1 Landfills (IPCC Source Category 5A1)

In the United States, solid waste is managed by landfilling, recovery through recycling or composting, and combustion through waste-to-energy facilities. Disposing of solid waste in modern, managed landfills is the most commonly used waste management technique in the United States. More information on how solid waste data are collected and solid waste is managed in the United States is provided in Box 7-1 and Box 7-2. The municipal solid waste (MSW) and industrial waste landfills referred to in this section are all modern landfills that must comply with a variety of regulations as discussed in Box 7-3. Disposing of waste in illegal dumping sites is not considered to have occurred in years later than 1980 and these sites are not considered to contribute to net emissions in this section for the time frame of 1990 to the current inventory year. MSW landfills, or sanitary landfills, are sites where MSW is managed to prevent or minimize health, safety, and environmental impacts. Waste is deposited in different cells and covered daily with soil; many have environmental monitoring systems to track performance, collect leachate, and collect landfill gas. Industrial waste landfills are constructed in a similar way as MSW landfills, but accept waste produced by industrial activity, such as factories, mills, and mines.

After being placed in a landfill, organic waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. These methane (CH_4) producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic carbon dioxide (CO_2) and 50 percent CH_4, by volume. Landfill biogas also

---

[4] See <http://www.ccdsupport.com/confluence/display/ghgp/Detailed+Description+of+Data+for+Certain+Sources+and+Processes>.

[5] See <http://ghgdata.epa.gov>.

contains trace amounts of non-methane organic compounds (NMOC) and volatile organic compounds (VOC) that either result from decomposition by-products or volatilization of biodegradable wastes (EPA 2008).

Methane and CO_2 are the primary constituents of landfill gas generation and emissions. However, the *2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines* set an international convention to not report biogenic CO_2 released due to landfill decomposition in the Waste sector (IPCC 2006). Carbon dioxide emissions from landfills are estimated and reported under the Land Use/Land Use Change and Forestry (LULUCF) sector (see Box 7-4). Additionally, emissions of NMOC and VOC are not estimated because they are considered to be emitted in trace amounts. Nitrous oxide (N_2O) emissions from the disposal and application of sewage sludge on landfills are also not explicitly modeled as part of greenhouse gas emissions from landfills. N_2O emissions from sewage sludge applied to landfills as a daily cover or for disposal are expected to be relatively small because the microbial environment in an anaerobic landfill is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. Furthermore, the *2006 IPCC Guidelines* (IPCC 2006) did not include a methodology for estimating N_2O emissions from solid waste disposal sites "because they are not significant." Therefore, only CH_4 generation and emissions are estimated for landfills under the Waste sector.

Methane generation and emissions from landfills are a function of several factors, including: (1) the total amount of waste-in-place, which is the total waste landfilled annually over the operational lifetime of a landfill; (2) the characteristics of the landfill receiving waste (e.g., composition of waste-in-place, size, climate, cover material); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized as the landfill gas passes through the cover material into the atmosphere. Each landfill has unique characteristics, but all managed landfills practice similar operating practices, including the application of a daily and intermediate cover material over the waste being disposed of in the landfill to prevent odor and reduce risks to public health. Based on recent literature, the specific type of cover material used can affect the rate of oxidation of landfill gas (RTI 2011). The most commonly used cover materials are soil, clay, and sand. Some states also permit the use of green waste, tarps, waste derived materials, sewage sludge or biosolids, and contaminated soil as a daily cover. Methane production typically begins within the first year after the waste is disposed of in a landfill and will continue for 10 to 60 years or longer as the degradable waste decomposes over time.

In 2014, landfill CH_4 emissions were approximately 181.8 MMT CO_2 Eq. (7,271 kt), representing the largest source of CH_4 emissions in the United States, followed by enteric fermentation and natural gas systems. Emissions from MSW landfills accounted for approximately 95 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 1,900 to 2,000 operational MSW landfills exist in the United States, with the largest landfills receiving most of the waste and generating the majority of the CH_4 emitted (EPA 2015b; EPA 2015d). Conversely, there are approximately 3,200 MSW landfills in the United States that have been closed since 1980 (for which a closure data is known, EPA 2015b; WBJ 2010). While the number of active MSW landfills has decreased significantly over the past 20 years, from approximately 6,326 in 1990 to approximately 2,000 in the 2010s, the average landfill size has increased (EPA 2015c; EPA 2015d; *BioCycle* 2010; WBJ 2010). The exact number of active and closed dedicated industrial waste landfills is not known at this time, but the Waste Business Journal total for landfills accepting industrial and construction and demolition debris for 2010 is 1,305 (WBJ 2010). Only 176 facilities with industrial waste landfills reported under subpart TT (Industrial Waste Landfills) of EPA's Greenhouse Gas Reporting Program (GHGRP) since reporting began in 2011, indicating that there may be several hundreds of industrial waste landfills that are not required to report under EPA's GHGRP, or that the actual number of industrial waste landfills in the United States is relatively low compared to MSW landfills.

The estimated annual quantity of waste placed in MSW landfills increased 27 percent from approximately 234 MMT in 1990 to 299 MMT in 2000 and then decreased by 11 percent to 266 MMT in 2014 (see Annex 3.14). The annual amount of waste generated and subsequently disposed in MSW landfills varies annually and depends on several factors (e.g., the economy, consumer patterns, recycling and composting programs, inclusion in a garbage collection service). The total amount of MSW generated is expected to increase as the U.S. population continues to grow, but the percentage of waste landfilled may decline due to increased recycling and composting practices. The estimated quantity of waste placed in industrial waste landfills (from the pulp and paper, and food processing sectors) has remained relatively steady since 1990, ranging from 9.7 MMT in 1990 to 11.3 MMT in 2014.

Net CH_4 emissions have fluctuated over the time-series, with peak emissions in the late 2000's and a slowly decreasing trend since. For example, from 1990 to 2000, net CH_4 emissions from landfills decreased by approximately 4.6 percent, from 184.4 MMT to 176.0 MMT, but then increased by 8.7 percent from 2000 to 2009. From 2009 to 2014, however, net CH_4 emissions decreased by nearly 5 percent, from 191.3 MMT to 181.8 MMT (see Table 7-3). This decreasing trend can be mostly attributed to an approximately 21 percent reduction in the amount of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in MSW landfills over the time-series (EPA 2015d) and an increase in the amount of landfill gas collected and combusted (i.e., used for energy or flared) at MSW landfills, resulting in lower net CH_4 emissions from MSW landfills. For instance, in 1990, approximately 0.8 MMT of CH_4 were recovered and combusted from landfills, while in 2014, approximately 7.9 MMT of CH_4 were recovered and combusted, representing an average annual increase in the quantity of CH_4 recovered and combusted at MSW landfills from 1990 to 2014 of 11 percent (see Annex 3.14). Landfill gas collection and control is not accounted for at industrial waste landfills in this chapter (see the Methodology discussion for more information).

The quantity of recovered CH_4 that is either flared or used for energy purposes at MSW landfills has continually increased as a result of 1996 federal regulations that require large MSW landfills to collect and combust landfill gas (see 40 CFR Part 60, Subpart Cc 2005 and 40 CFR Part 60, Subpart WWW 2005). Voluntary programs that encourage CH_4 recovery and beneficial reuse, such as EPA's Landfill Methane Outreach Program (LMOP) and federal and state incentives that promote renewable energy (e.g., tax credits, low interest loans, and Renewable Portfolio Standards), have also contributed to increased interest in landfill gas collection and control. In 2014, an estimated 10 new landfill gas-to-energy (LFGTE) projects (EPA 2015a; EPA 2015b) and 3 new flares began operation. While the amount of landfill gas collected and combusted continues to increase every year, the rate of increase in collection and combustion no longer exceeds the rate of additional CH_4 generation from the amount of organic MSW landfilled as the U.S. population grows.

Table 7-3: CH_4 Emissions from Landfills (MMT CO_2 Eq.)

Activity	1990		2005		2010	2011	2012	2013	2014
MSW Landfills	212.7		329.6		366.1	370.7	375.0	379.1	383.5
Industrial Landfills	12.1		15.9		16.4	16.4	16.5	16.5	16.6
Recovered									
Gas-to-Energy	(7.1)		(86.8)		(125.9)	(129.3)	(135.7)	(136.0)	(134.7)
Flared	(12.8)		(50.6)		(60.7)	(61.3)	(62.9)	(63.4)	(63.4)
Oxidized[a]	(20.5)		(20.8)		(19.6)	(19.7)	(19.3)	(19.6)	(20.2)
Total	**184.4**		**187.3**		**176.3**	**176.9**	**173.5**	**176.7**	**181.8**

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.
[a] Includes oxidation at municipal and industrial landfills.

Table 7-4: CH_4 Emissions from Landfills (kt)

Activity	1990		2005		2010	2011	2012	2013	2014
MSW Landfills	8,508		13,185		14,642	14,828	15,001	15,163	15,338
Industrial Landfills	484		636		656	657	659	661	665
Recovered									
Gas-to-Energy	(285)		(3,471)		(5,035)	(5,172)	(5,430)	(5,438)	(5,387)
Flared	(512)		(2,024)		(2,428)	(2,428)	(2,517)	(2,535)	(2,537)
Oxidized[a]	(820)		(833)		(784)	(786)	(771)	(785)	(808)
Total	**7,376**		**7,493**		**7,052**	**7,074**	**6,942**	**7,066**	**7,271**

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.
[a] Includes oxidation at municipal and industrial landfills.

Methodology

CH_4 emissions from landfills were estimated as the CH_4 produced from MSW landfills, plus the CH_4 produced by industrial waste landfills, minus the CH_4 recovered and combusted from MSW landfills, minus the CH_4 oxidized before being released into the atmosphere:

$$\mathrm{CH_{4,Solid\ Waste}} = [\mathrm{CH_{4,MSW}} + \mathrm{CH_{4,Ind}} - \mathrm{R}] - \mathrm{Ox}$$

where,

$CH_{4,\text{Solid Waste}}$ = CH_4 emissions from solid waste
$CH_{4,MSW}$ = CH_4 generation from MSW landfills,
$CH_{4,Ind}$ = CH_4 generation from industrial landfills,
R = CH_4 recovered and combusted (only for MSW landfills), and
Ox = CH_4 oxidized from MSW and industrial waste landfills before release to the atmosphere.

The methodology for estimating CH_4 emissions from landfills is based on the first order decay (FOD) model described by the IPCC (IPCC 2006). Methane generation is based partly on nationwide waste disposal data (for years prior to 1983) and partly on facility-specific waste acceptance data (for 1983 and later). The amount of CH_4 recovered is landfill-specific for all years in the time-series, but only for MSW landfills due to a lack of data specific to industrial waste landfills. Values for the CH_4 generation potential (L_0) and the decay rate constant (k) used in the first order decay model were obtained from an analysis of CH_4 recovery rates for a database of 52 landfills and from published studies of other landfills (RTI 2004; EPA 1998; SWANA 1998; Peer, Thorneloe, and Epperson 1993). The decay rate constant was found to increase with average annual rainfall; consequently, values of k were developed for three ranges of rainfall, or climate types (wet, arid, and temperate). The annual quantity of waste placed in landfills was apportioned to the three ranges of rainfall based on the percent of the U.S. population in each of the three ranges. Historical census data were used to account for the shift in population to more arid areas over time (U.S. Census Bureau, 2015). An overview of the data sources and methodology used to calculate CH_4 generation and recovery is provided below, while a more detailed description of the methodology used to estimate CH_4 emissions from landfills can be found in Annex 3.14.

States and local municipalities across the United States do not consistently track and report quantities of MSW generated or collected for management, nor are end-of-life disposal methods reported to a centralized system. The GHGRP, however, requires landfills meeting or exceeding a threshold of 25,000 metric tons of CH_4 generation per year to report a variety of facility-specific information, including historical and current waste disposal quantities by year, CH_4 generation, gas collection system details, CH_4 recovery, and CH_4 emissions. The landfills reporting to the GHGRP are considered the largest emitters, but not all landfills are required to report. However, when this dataset is supplemented with others, such as the EPA LMOP data (incorporated into the Inventory through the Landfill Gas-to-energy [LFGTE] database), or the Waste Business Journal data, a complete data set of the annual quantity of waste landfilled is represented. A bottom-up approach has been taken with the current inventory whereby the GHGRP data, supplemented with the LFGTE database, provides the annual waste disposal data needed for the FOD model. In previous inventories, a top-down approach was used to estimate national MSW landfill waste generation (i.e., the State of Garbage [SOG] surveys). The SOG survey is a nationwide survey of waste disposed in landfills and relies on 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* 2010; Shin 2014). The SOG survey data was used to estimate nationwide MSW generation by state, and then a waste disposal factor was applied to estimate the quantity of waste landfilled. Switching from the SOG survey data to the GHGRP and LFGTE data provides a higher tier and quality of data, and improves the accuracy of landfill CH_4 emissions in the U.S.

Estimates of the annual quantity of waste landfilled for 1960 through 1982 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. For calculations in the current Inventory, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in landfills (Methane Conversion Factor, MCF, of 1) and those disposed in dumps (MCF of 0.6). All calculations after 1980 assume waste is disposed in managed, modern landfills. Please see Annex 3.14 for more details.

Methane recovery is currently only accounted for at MSW landfills. Data collected through EPA’s GHGRP for industrial waste landfills (subpart TT) show that only 2 of the 176 facilities, or 1 percent of facilities, reporting have active gas collection systems (EPA 2015b). EPA’s GHGRP is not a national database and no comprehensive data regarding gas collection systems have been published for industrial waste landfills. Assumptions regarding a percentage of landfill gas collection systems, or a total annual amount of landfill gas collected for the non-reporting industrial waste landfills, have not been made for the Inventory methodology.

The estimated landfill gas recovered per year (R) at MSW landfills was based on a combination of four databases and grouped into recovery from flares and recovery from landfill gas-to-energy projects:

- the flare vendor database (contains updated sales data collected from vendors of flaring equipment)
- a database of LFGTE projects that is primarily based on information compiled by EPA LMOP (EPA 2015a)
- a database developed by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007), and
- EPA's GHGRP dataset for MSW landfills (EPA 2015b).

EPA's GHGRP MSW landfills database was first introduced as a data source for the previous Inventory. EPA's GHGRP MSW landfills database contains facility-reported data that undergoes rigorous verification, thus it is considered to contain the least uncertain data of the four databases. However, as mentioned earlier, this database is unique in that it only contains a portion of the landfills in the U.S. (although, presumably the highest emitters since only those landfills that meet a certain CH_4 generation threshold must report) and only contains data for 2010 and later. Methane generation can be estimated for prior years based on reported annual waste disposal. Methane recovery prior to 2010 can also be estimated, but it is more uncertain than the CH_4 generation because the GHGRP does not require facilities to report the year the flare(s) or gas collection system(s) were installed and fully operational.

The total amount of CH_4 recovered and destroyed was estimated using the four databases listed above. 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 as described below.

For the years 2010 to 2014, if a landfill in EPA's GHGRP MSW landfills database was also in the EIA, LFGTE, and/or flare vendor database, the avoided emissions were based on EPA's GHGRP MSW landfills database only to avoid double or triple counting the recovery amounts. Directly reported values for CH_4 recovery to the GHGRP database were used for years 2010 through 2014. Because these data are not reported for years prior to 2010, CH_4 recovery had to be calculated using available data (e.g., landfill gas project information) from LFGTE and the EIA databases. Methane recovery from years 1990 to 2009 was calculated for landfills in EPA's GHGRP database using the known values of CH_4 recovery from the years 2010 to 2014. If a landfill was also in the LFGTE or EIA databases, the landfill gas project information, specifically the project start year, was used as the cutoff years for the estimated CH_4 recovery in the EPA's GHGRP database. For example, if a landfill reporting under EPA's GHGRP was also included in the LFGTE database under a project that started in 2002 and is still operational, the CH_4 recovery in EPA's GHGRP database was back-calculated to the year 2002. This method, although somewhat uncertain, can be refined in future Inventory years after further investigating the landfill gas project start years for landfills in EPA's GHGRP database.

If a landfill in the EIA database was also in the LFGTE and/or the flare vendor database, the CH_4 recovery was based on the EIA data because landfill owners or operators directly reported the amount of CH_4 recovered using gas flow concentration and measurements, and because the reporting accounted for changes over time. However, as the EIA database only includes data through 2006, the amount of CH_4 recovered for years 2007 and later were assumed to be the same as in 2006 for landfills that are in the EIA database, but not in EPA's GHGRP or the LFGTE databases. This quantity likely underestimates flaring because the EIA database does not have information on all flares in operation for the years after 2006. If both the flare data and LFGTE recovery data were available for any of the remaining landfills (i.e., not in the EIA or EPA's GHGRP databases), then the avoided emissions were based on the LFGTE data, which provides reported landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The flare vendor database, on the other hand, estimates CH_4 combusted by flares using the midpoint of a flare's reported capacity.

Given that each LFGTE project is likely to also have a flare, double counting reductions from flares and LFGTE projects in the LFGTE database was avoided by subtracting emission reductions associated with LFGTE projects for which a flare had not been identified from the emission reductions associated with flares (referred to as the flare correction factor). A further explanation of the methodology used to estimate the landfill gas recovered can be found in Annex 3.14.

The amount of landfill gas recovered and combusted is also presented in terms of avoided emissions by flaring and avoided emissions by LFGTE. The amount combusted by flaring was directly determined using information provided by the EIA and flare vendor databases and indirectly determined using information in EPA's GHGRP dataset for MSW landfills. Information provided by the EIA and LFGTE databases were used to directly estimate methane combusted in LFGTE projects over the time-series. EPA's GHGRP MSW landfills database provides a total amount of CH_4 recovered at the facility-level and was indirectly used to estimate methane combusted in LFGTE projects. Unlike the three other databases, EPA's GHGRP dataset does not identify whether the amount of CH_4 recovered is combusted by a flare versus an LFGTE project. Therefore, a mapping exercise was performed between EPA's GHGRP MSW landfills database and the three other databases to make a distinction between landfills contained in both EPA's GHGRP MSW landfills database and one or more of the other databases. The CH_4 recovered by landfills matched to the EIA (and marked as LFGTE) and LFGTE databases was allocated as CH_4 recovered and combusted by LFGTE projects. The remaining CH_4 recovered from EPA's GHGRP dataset was allocated as CH_4 recovered and combusted by flares.

The destruction efficiencies reported through EPA's GHGRP were applied to the landfills in EPA's GHGRP MSW landfills database. The median value of the reported destruction efficiencies was 99 percent for all reporting years (2010 through 2013). A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions avoided due to the combusting of CH_4 in destruction devices (i.e., flares) in the EIA, LFGTE, and flare vendor databases. The 99 percent destruction efficiency value 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-CH_4 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 shutdown flares used by the EPA LMOP.

Emissions from industrial waste landfills were estimated from industrial production data (ERG 2014), waste disposal factors, and the FOD model. As over 99 percent of the organic waste placed in industrial waste landfills originated from the food processing (meat, vegetables, fruits) and pulp and paper sectors, estimates of industrial landfill emissions focused on these two sectors (EPA 1993). There are currently no data sources that track and report the amount and type of waste disposed of in industrial waste landfills in the United States. Therefore, the amount of waste landfilled is assumed to be a fraction of production that is held constant over the time-series as explained in Annex 3.14. The composition of waste disposed of in industrial waste landfills is expected to be more consistent in terms of composition and quantity than that disposed of in MSW landfills.

The amount of CH_4 oxidized by the landfill cover at both municipal and industrial waste landfills was assumed to be 10 percent of the CH_4 generated that is not recovered (IPCC 2006, Mancinelli and McKay 1985, Czepiel et al. 1996). To calculate net CH_4 emissions, both CH_4 recovered and CH_4 oxidized were subtracted from CH_4 generated at municipal and industrial waste landfills.

Uncertainty and Time-Series Consistency

Several types of uncertainty are associated with the estimates of CH_4 emissions from MSW and industrial waste landfills. The primary uncertainty concerns the characterization of landfills. Information is not available on two fundamental factors affecting CH_4 production: the amount and composition of waste placed in every MSW and industrial waste landfill for each year of a landfill's operation. EPA's GHGRP allows facilities to report annual quantities of waste disposed by composition, but most MSW landfills report annual waste disposed as bulk MSW versus the detailed waste composition data. Some MSW landfills have conducted detailed waste composition studies, but the data are scarce over the time-series and across the country. EPA is currently compiling the waste composition studies and data that have been performed in the past decade and may revise the default waste composition applied to MSW landfilled in the FOD model in future inventory estimates.

The approach used here assumes that the CH_4 generation potential (L_o) and the rate of decay that produces CH_4 from MSW, as determined from several studies of CH_4 recovery at MSW landfills, are representative of conditions at U.S. MSW landfills. When this top-down approach is applied at the nationwide level, the uncertainties are assumed to be less than when applying this approach to individual landfills and then aggregating the results to the national level. In other words, this approach may over- and under-estimate CH_4 generation at some landfills if used at the facility-level, but the end result is expected to balance out because it is being applied nationwide. There is also a high degree of uncertainty and variability associated with the first order decay model, particularly when a homogeneous waste composition and hypothetical decomposition rates are applied to heterogeneous landfills (IPCC 2006).

Additionally, there is a lack of landfill-specific information regarding the number and type of industrial waste landfills in the United States. The approach used here assumes that the majority (99 percent) of industrial waste disposed of in industrial waste landfills consists of waste from the pulp and paper and food processing sectors. However, because waste generation and disposal data are not available in an existing data source for all U.S. industrial waste landfills, we apply a straight disposal factor over the entire time-series to the amount of waste generated to determine the amounts disposed. Industrial waste facilities reporting under EPA's GHGRP do report detailed waste stream information, and these data have been used to improve, for example, the DOC value used in the inventory methodology for the pulp and paper sector. Additional improvements to reduce the uncertainty in CH_4 emissions estimates are being investigated for both MSW and industrial waste landfills.

Aside from the uncertainty in estimating landfill CH_4 generation, uncertainty also exists in the estimates of the landfill gas oxidized. A constant oxidation factor of 10 percent as recommended by the Intergovernmental Panel on Climate Change (IPCC) for managed landfills is used for both MSW and industrial waste landfills regardless of climate, the type of cover material, and/or presence of a gas collection system. The number of field studies measuring the rate of oxidation has increased substantially since the *2006 IPCC Guidelines* were published and, as discussed in the Potential Improvements section, efforts are being made to review the literature and revise this value based on recent, peer-reviewed studies.

Another significant source of uncertainty lies with the estimates of CH_4 that are recovered by flaring and gas-to-energy projects at MSW landfills. The EPA's GHGRP MSW landfills database was added as a fourth recovery database in the previous Inventory. Relying on multiple databases for a complete picture introduces uncertainty because the coverage and characteristics of each database differs, which increases the chance of double counting avoided emissions. Additionally, the methodology and assumptions that go into each database differ. For example, the flare database assumes the midpoint of each flare capacity at the time it is sold and installed at a landfill; in reality, the flare may be achieving a higher capacity, in which case the flare database would underestimate the amount of CH_4 recovered.

The LFGTE database and the flare vendor databases are updated annually. The EIA database has not been updated since 2005 and has, for the most part, been replaced by EPA's GHGRP MSW landfills database. To avoid double counting and to use the most relevant estimate of CH_4 recovery for a given landfill, a hierarchical approach is used among the four databases. EPA's GHGRP data are given precedence because CH_4 recovery is directly reported by landfills and undergoes a rigorous verification process; the EIA data are given second priority because facility data were directly reported; the LFGTE data are given third priority because CH_4 recovery is estimated from facility-reported LFGTE system characteristics; and the flare data are given fourth priority because this database contains minimal information about the flare and no site-specific operating characteristics (Bronstein et al. 2012). The coverage provided across the databases most likely represents the complete universe of landfill CH_4 gas recovery, however the number of unique landfills between the four databases does differ.

The IPCC default value of 10 percent for uncertainty in recovery estimates was used for 2 of the 4 recovery databases in the uncertainty analysis where metering of landfill gas was in place (for about 64 percent of the CH_4 estimated to be recovered). This 10 percent uncertainty factor applies to the LFGTE database; 12 percent to the EIA database; and 1 percent for the GHGRP MSW landfills dataset because of the supporting information provided and rigorous verification process. For flaring without metered recovery data (the flare database), a much higher uncertainty value of 50 percent is used. The compounding uncertainties associated with the 4 databases in addition to the uncertainties associated with the FOD model and annual waste disposal quantities leads to the large upper and lower bounds for MSW landfills presented in Table 7-5. Industrial waste landfills are shown with a lower range of uncertainty due to the smaller number of data sources and associated uncertainty involved. For example, 3 data sources are used to generate the annual quantities of MSW waste disposed over the 1940 to current year, while industrial waste landfills rely on 2 data sources.

The results of the *2006 IPCC Guidelines* Approach 2 quantitative uncertainty analysis are summarized in Table 7-5. In 2014, landfill CH_4 emissions were estimated to be between 119.4 and 278.7 MMT CO_2 Eq., which corresponds to a range of 34 percent below to 53 percent above the 2014 emission estimate of 181.8 MMT CO_2 Eq.

Table 7-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills ($MMT CO_2$ Eq. and Percent)

Source	Gas	2014 Emission Estimate ($MMT CO_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] ($MMT CO_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Landfills	**CH_4**	**181.8**	**119.4**	**278.7**	**-34%**	**+53%**
MSW	CH_4	166.8	106.3	261.5	-36%	+57%
Industrial	CH_4	15.0	10.4	18.8	-30%	+25%

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

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time-series are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are performed for the transcription of the published data set used to populate the Inventory data set, including the published GHGRP and LFGTE databases, but are not performed on the data itself against primary data used. A primary focus of the QA/QC checks was to ensure that CH_4 recovery estimates were not double-counted and that all LFGTE projects and flares were included in the respective project databases. Both manual and electronic checks were used to ensure that emission avoidance from each landfill was calculated only once. The primary calculation spreadsheet is tailored from the IPCC waste model and has been verified previously using the original, peer-reviewed IPCC waste model. All model input values were verified by secondary QA/QC review.

Recalculations Discussion

Five major methodological recalculations were performed for the current Inventory.

- First, the SOG survey data previously used to estimate annual waste generation and disposal was replaced by EPA's GHGRP and LFGTE data (EPA 2015c) for the inventory time-series (1990 to 2014) and years from 1983 to 1989. The waste acceptance data included in the databases in EPA (2015c) were used directly and no modifications to this data set were made. This improvement increased the annual quantities of waste disposed for each year in the time-series, and consequently, led to an increase in net CH_4 emissions compared to the previous Inventory.
- Second, a review of the flare and LFGTE projects across the 4 recovery databases was made. Several corrections were made to avoid double counting. Additionally, several facilities in the LFGTE database were removed because they were not in the past three LMOP databases. The LFGTE is an enhanced version of the LMOP database and if a landfill is no longer in the LMOP database, it was assumed to be added erroneously. These revisions resulted in larger than expected changes to the annual quantities of the annual CH_4 recovery estimates used in the net CH_4 emissions compared to the previous Inventory and are the second primary driver for the increase in net CH_4 emissions after the change to EPA's GHGRP waste acceptance data.
- Third, the GHGRP CH_4 recovery data were back-calculated for landfills in EPA's GHGRP database for years prior to the first GHGRP reporting year (typically 2010 for most landfills). In the previous Inventory, there was a significant change in the total recovery between years 2009 and 2010. This methodological change was made to smooth the recovery data for years prior to 2009.
- Fourth, the flare correction factor was revised. This effort included reviewing the 27 flare projects included in the flare correction factor to identify them with landfills in EPA's GHGRP, the LFGTE, or EIA databases, or match them to existing operational or closed landfills through and Internet search (RTI 2015a). The number of flares included in the flare correction factor decreased from 27 to 19. The impact on CH_4 recovery varies by year and is a modest amount.

- Fifth, the DOC value for landfilled pulp and paper waste was revised from 0.20 to 0.15 based a literature review of pulp and paper waste characterization studies (RTI 2015b) and data reported under the GHGRP. This conservative approach allows for a revision to the DOC value and will be re-assessed in future Inventories as more information becomes available.

The overall impact from these changes resulted in an average increase in emissions of nearly 14 percent across the time-series. A significant increase in net CH_4 emissions for the years 2010 through 2013 ranging from 20 to 52 percent higher in the current Inventory compared to the previous inventory. The drivers for this large increase are the increased quantities of annual waste disposal, which results in higher CH_4 generation, and corrections to the landfill matching across the recovery databases.

Planned Improvements

Improvements being examined for future Inventory estimates include (1) incorporating additional data from recent peer-reviewed literature to modify the default oxidation factor applied to MSW and industrial waste landfills (currently 10 percent); (2) either modifying the bulk waste DOC value or estimating emissions using a waste-specific approach in the first order decay model using data from EPA’s GHGRP and peer-reviewed literature; and (3) reviewing waste-stream specific DOC and decay rate constant (k) value data reported for industrial waste landfills as reported under EPA’s GHGRP.

A standard CH_4 oxidation factor of 10 percent has been used for both industrial and MSW landfills in prior Inventory reports and is currently recommended as the default for well-managed landfills in the latest IPCC guidelines (2006). Recent comments received on the Inventory methodology indicated that a default oxidation factor of 10 percent may be less than oxidation rates achieved at well-managed landfills with gas collection and control. As a first step toward revising this oxidation factor, a literature review was conducted in 2011 (RTI 2011). In addition, facilities reporting under EPA’s GHGRP have the option to use an oxidation factor other than 10 percent (e.g., 0, 25, or 35 percent) if the calculated result of methane flux calculations warrants it. Various options are being investigated to incorporate this facility-specific data for landfills reporting under EPA’s GHGRP and or the remaining facilities.

The standard oxidation factor (10 percent) is applied to the total amount of waste generated nationwide. Changing the oxidation factor and calculating the amount of CH_4 oxidized from landfills with gas collection and control requires the estimation of waste disposed in these types of landfills over the entire time-series. Although EPA’s GHGRP does not capture every landfill in the United States, larger landfills are expected to meet the reporting thresholds and are reporting waste disposal information by year. At this time, data are available to calculate the amount of waste disposed of at landfills with and without gas collection systems in the United States for landfills reporting under EPA’s GHGRP. After investigating the landfills not reporting under EPA’s GHGRP to determine the presence of a landfill gas collection and control system and waste disposal data, a modification to the Inventory waste model to apply different oxidation factors depending on the presence of a gas collection system may be possible.

Other potential improvements to the methodology may be made in the future using other portions of EPA’s GHGRP dataset, specifically for inputs to the first order decay equation. The approach used in the Inventory to estimate CH_4 generation assumes a bulk waste-specific DOC value that may not accurately capture the changing waste composition over the time-series (e.g., the reduction of organics entering the landfill environment due to increased composting, see Box 7-2). Using data obtained from EPA’s GHGRP and any publicly available landfill-specific waste characterization studies in the United States, the methodology may be modified to incorporate a waste composition approach, or revisions may be made to the bulk waste DOC value currently used. Additionally, EPA’s GHGRP data could be analyzed and a weighted average for the CH_4 correction factor (MCF), fraction of CH_4 (F) in the landfill gas, the destruction efficiency of flares, and the decay rate constant (k) could replace the values currently used in the Inventory. At this time, the majority of landfills reporting under EPA’s GHGRP select bulk MSW for their waste composition.

In addition to MSW landfills, industrial waste landfills at facilities emitting CH_4 in amounts equivalent to 25,000 metric tons or more of CO_2 Eq. were required to report their greenhouse gas emissions beginning in September 2012 through EPA’s GHGRP. Similar data for industrial waste landfills as is required for the MSW landfills are being reported. Any additions or improvements to the Inventory using reported GHGRP data will be made for the industrial waste landfill source category. One potential improvement includes a revision to the waste disposal factor currently used in the Inventory for the pulp and paper sector using production data from pulp and paper facilities that reported annual production and annual disposal data under EPA's GHGRP. Another possible improvement is the addition of emission estimates from landfills at industrial sectors other than pulp and paper, and food and beverage (e.g., metal foundries, petroleum refineries, and chemical manufacturing facilities) to the Inventory.

Box 7-3: Nationwide Municipal Solid Waste Data Sources

Municipal solid waste generated in the United States can be managed through landfilling, recycling, composting, and combustion with or without energy recovery. There are three main sources for nationwide solid waste management data in the United States,

- The *BioCycle* and Earth Engineering Center of Columbia University's State of Garbage (SOG) in America surveys
- The EPA's Municipal Solid Waste in The United States: Facts and Figures reports, and
- The EPA's Greenhouse Gas Reporting Program (GHGRP).

The SOG surveys collect state-reported data on the amount of waste generated and the amount of waste managed via different management options: landfilling, recycling, composting, and combustion. The survey asks for actual tonnages instead of percentages in each waste category (e.g., residential, commercial, industrial, construction and demolition, organics, tires) for each waste management option. If such a breakdown is not available, the survey asks for total tons landfilled. The data are adjusted for imports and exports across state lines so that the principles of mass balance are adhered to, whereby the amount of waste managed does not exceed the amount of waste generated. The SOG reports present survey data aggregated to the state level.

The EPA Facts and Figures reports use a materials flow methodology, which relies heavily on a mass balance approach. Data are gathered from industry associations, key businesses, similar industry sources, and government agencies (e.g., the Department of Commerce and the U.S. Census Bureau) and are used to estimate tons of materials and products generated, recycled, or discarded nationwide. The amount of MSW generated is estimated by adjusting the imports and exports of produced materials to other countries. MSW that is not recycled, composted, or combusted is assumed to be landfilled. The data presented in the report are nationwide totals.

The EPA GHGRP is a mandatory reporting program to which facilities meeting specific definitions and methane generation and other greenhouse gas emission thresholds are required to report. If eligible, facilities that operate a MSW landfill must report a variety of information, including calculated annual methane generation and emissions using a prescribed methodology, annual waste disposal since the first year of waste acceptance, disposed waste characteristics (where available), landfill gas collection and control system details (if applicable), including landfill gas characteristics (e.g., methane concentration, annual volumetric flow).

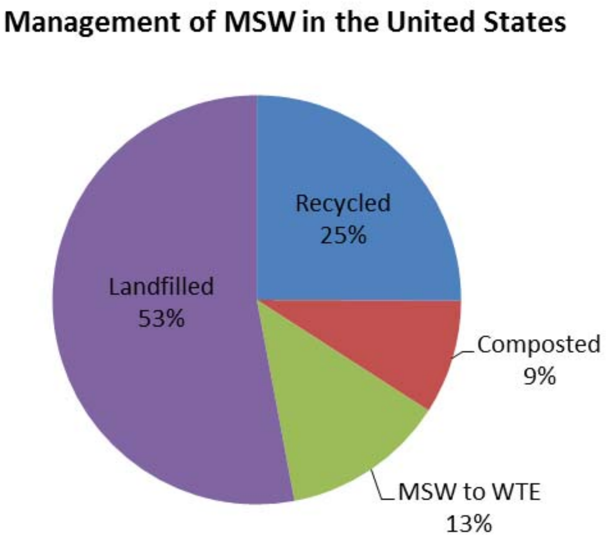
EPA's GHGRP data are the preferred data source for municipal solid waste disposal amounts in the Inventory because they are directly reported by facilities using a similar methodology and undergo a rigorous quality assurance and verification review by the EPA. Supplementary data on the quantity of waste disposed by landfills not subject to EPA's GHGRP was sourced from the EPA's Landfill Methane Outreach Program (LMOP) and direct information from state agencies for select landfills that began accepting waste in, or after 2013 for the current Inventory year (EPA 2015c). In future Inventories, supplementary waste disposal data may be sourced from the Waste Business Journal, or SOG surveys. The EPA Facts and Figures reports are useful when investigating waste management trends at the nationwide level and for typical waste composition data, which the State of Garbage surveys do not request and the GHGRP does not require. The EPA Facts and Figures reports have never been used as the source for annual waste disposal data in the Inventory.

In this Inventory, emissions from solid waste management are presented separately by waste management option, except for recycling of waste materials. Emissions from recycling are attributed to the stationary combustion of fossil fuels that may be used to power on-site recycling machinery, and are presented in the stationary combustion chapter in the Energy sector, although the emissions estimates are not called out separately. Emissions from solid waste disposal in landfills and the composting of solid waste materials are presented in the Landfills and Composting chapters in the Waste sector of this report. In the United States, almost all incineration of MSW occurs at waste-to-energy (WTE) facilities or industrial facilities where useful energy is recovered, and thus emissions from waste incineration are accounted for in the Incineration of Waste chapter of the Energy sector of this report.

Box 7-4: Overview of the Waste Sector

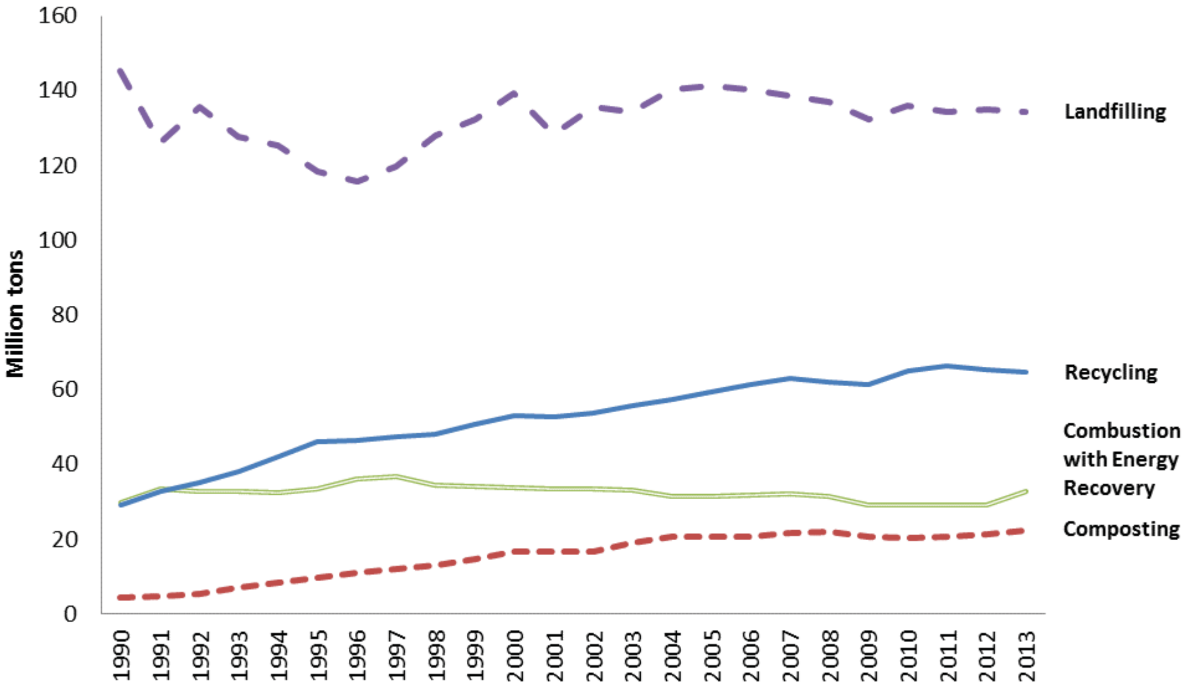
As shown in Figure 7-2 and Figure 7-3, landfilling of MSW is currently and has been the most common waste management practice. A large portion of materials in the waste stream are recovered for recycling and composting, which is becoming an increasingly prevalent trend throughout the country. Materials that are composted and recycled would have normally been disposed of in a landfill.

Figure 7-2: Management of Municipal Solid Waste in the United States, 2013



Source: EPA (2015d)

Figure 7-3: MSW Management Trends from 1990 to 2013 (Million Tons)



Source: EPA (2015d)

Table 7-6 presents a typical composition of waste disposed of at a typical MSW landfill in the United States over time. It is important to note that the actual composition of waste entering each landfill will vary from that presented in Table 7-6. Understanding how the waste composition changes over time, specifically for the degradable waste types, is important for estimating greenhouse gas emissions. For certain degradable waste types (i.e., paper and paperboard), the amounts discarded have decreased over time due to an increase in waste recovery, including recycling and composting (see Table 7-6 and Figure 7-4). Landfill ban legislation affecting yard trimmings resulted in an increase of composting from 1990 to 2008. Table 7-6 and Figure 7-4 do not reflect the impact of backyard composting on yard trimming generation and recovery estimates. The recovery of food trimmings has been consistently low. Increased recovery of degradable materials reduces the CH_4 generation potential and CH_4 emissions from landfills.

Table 7-6: Materials Discarded in the Municipal Waste Stream by Waste Type from 1990 to 2013 (Percent)

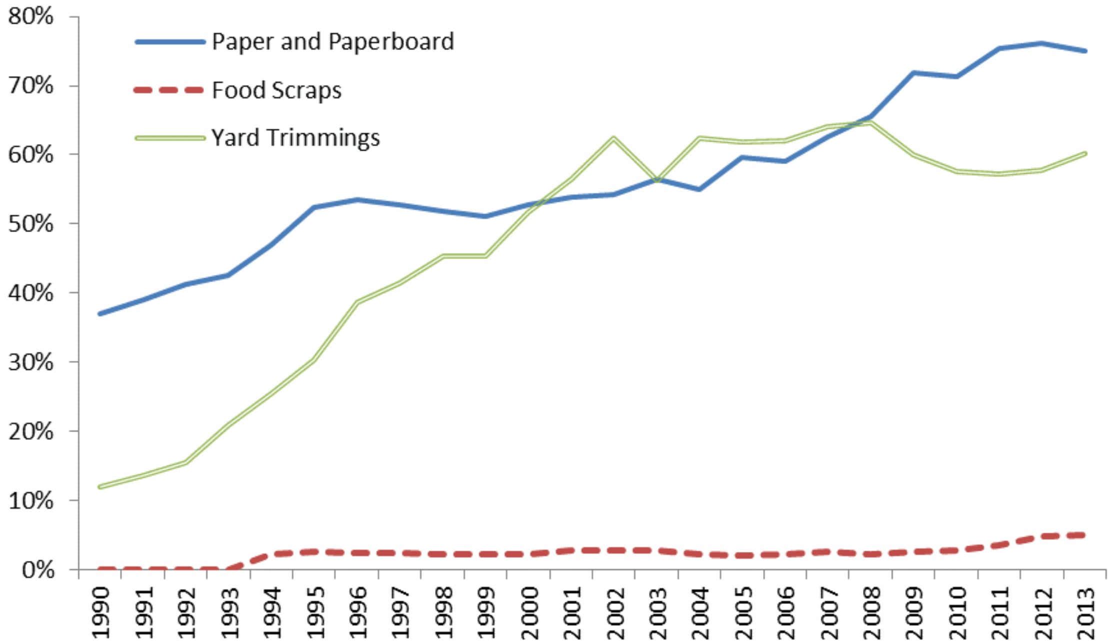
Waste Type	1990	2005	2009	2010	2011	2012	2013
Paper and Paperboard	30.0%	24.5%	14.8%	16.2%	14.8%	14.8%	15.1%
Glass	6.0%	5.7%	5.0%	5.1%	5.1%	5.1%	5.0%
Metals	7.2%	7.7%	8.0%	8.8%	8.9%	9.0%	9.1%
Plastics	9.6%	15.7%	15.8%	17.4%	17.8%	17.6%	17.7%
Rubber and Leather	3.1%	3.5%	3.7%	3.7%	3.8%	3.8%	3.9%
Textiles	2.9%	5.5%	6.3%	6.7%	6.8%	7.4%	7.7%
Wood	6.9%	7.4%	7.7%	8.1%	8.2%	8.2%	8.0%
Other[a]	1.4%	1.8%	1.9%	2.0%	2.0%	2.0%	2.0%
Food Scraps[b]	13.6%	17.9%	19.1%	21.0%	21.4%	21.1%	21.1%
Yard Trimmings[c]	17.6%	7.0%	7.6%	8.6%	8.8%	8.7%	8.1%
Miscellaneous Inorganic Wastes	1.7%	2.1%	2.2%	2.3%	2.4%	2.4%	2.4%

[a] Includes electrolytes in batteries and fluff pulp, feces, and urine in disposable diapers. Details may not add to totals due to rounding. Source: EPA (2015d).

[b] Data for food scraps were estimated using sampling studies in various parts of the country in combination with demographic data on population, grocery store sales, restaurant sales, number of employees, and number of prisoners, students, and patients in institutions. Source: EPA (2015d).

[c] Data for yard trimmings were estimated using sampling studies, population data, and published sources documenting legislation affecting yard trimmings disposal in landfills. Source: EPA (2015d).

Figure 7-4: Percent of Recovered Degradable Materials from 1990 to 2013 (Percent)



Source: EPA (2015d)

Box 7-5: Description of a Modern, Managed Landfill

Modern, managed landfills are well-engineered facilities that are located, designed, operated, and monitored to ensure compliance with federal, state, and tribal regulations. Municipal solid waste (MSW) landfills must be designed to protect the environment from contaminants which may be present in the solid waste stream. Additionally, many new landfills collect and destroy landfill gas through flares or landfill gas-to-energy projects. Requirements for affected MSW landfills may include:

- Siting requirements to protect sensitive areas (e.g., airports, floodplains, wetlands, fault areas, seismic impact zones, and unstable areas)
- Design requirements for new landfills to ensure that Maximum Contaminant Levels (MCLs) will not be exceeded in the uppermost aquifer (e.g., composite liners and leachate collection systems)
- Leachate collection and removal systems
- Operating practices (e.g., daily and intermediate cover, receipt of regulated hazardous wastes, use of landfill cover material, access options to prevent illegal dumping, use of a collection system to prevent stormwater run-on/run-off, record-keeping)
- Air monitoring requirements (explosive gases)
- Groundwater monitoring requirements
- Closure and post-closure care requirements (e.g., final cover construction), and
- Corrective action provisions.

Specific federal regulations that affected MSW landfills must comply with include the 40 CFR Part 258 (Subtitle D of RCRA), or equivalent state regulations and the New Source Performance Standards (NSPS) 40 CFR Part 60 Subpart WWW. Additionally, state and tribal requirements may exist.[6]

Box 7-6: Biogenic Wastes in Landfills

Regarding the depositing of wastes of biogenic origin in landfills (i.e., all degradable waste), empirical evidence shows that some of these wastes degrade very slowly in landfills, and the C they contain is effectively sequestered in landfills over a period of time (Barlaz 1998, 2006). Estimates of C removals from landfilling of forest products, yard trimmings, and food scraps are further described in the Land Use, Land-Use Change, and Forestry chapter, based on methods presented in IPCC (2003) and IPCC (2006).

7.2 Wastewater Treatment (IPCC Source Category 5D) (TO BE UPDATED)

Due to circumstances, the wastewater treatment section was not updated for the current Inventory. The numbers are currently being updated using the same methodology as the previous Inventory, with no significant improvements. Minimal impacts on the emission estimates are expected as a result of the update.

Wastewater treatment processes can produce anthropogenic CH_4 and N_2O emissions. Wastewater from domestic[7] and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants. Treatment may either occur on site, most commonly through septic systems or package plants, or off site at centralized treatment systems. Centralized wastewater treatment systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients. In the United States, approximately 20 percent of domestic wastewater is treated in septic systems or other on-site systems, while the rest is collected and treated centrally (U.S. Census Bureau 2011).

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. The generation of N_2O may also result from the treatment of domestic wastewater during both nitrification and denitrification of the N present, usually in the form of urea, ammonia, and proteins. These compounds are converted to nitrate (NO_3) through the aerobic process of nitrification. Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas (N_2). N_2O can be an intermediate product of both processes, but has typically been associated with denitrification. Recent research suggests that higher emissions of N_2O may in fact originate from nitrification (Ahn et al. 2010). Other more recent research suggests that N_2O may also result from other types of wastewater treatment operations (Chandran 2012).

The principal factor in determining the CH_4 generation potential of wastewater is the amount of degradable organic material in the wastewater. Common parameters used to measure the organic component of the wastewater are the Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). Under the same conditions,

---

[6] For more information regarding federal MSW landfill regulations, see <http://www.epa.gov/osw/nonhaz/municipal/landfill/msw_regs.htm>.

[7] Throughout the inventory, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

wastewater with higher COD (or BOD) concentrations will generally yield more CH_4 than wastewater with lower COD (or BOD) concentrations. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes, while COD measures the total material available for chemical oxidation (both biodegradable and non-biodegradable). Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH_4 production. The principal factor in determining the N_2O generation potential of wastewater is the amount of N in the wastewater. The variability of N in the influent to the treatment system, as well as the operating conditions of the treatment system itself, also impact the N_2O generation potential.

In 2013, CH_4 emissions from domestic wastewater treatment were 9.2 MMT CO_2 Eq. (368 kt CH_4). Emissions remained fairly steady from 1990 through 1997, but have decreased since that time due to decreasing percentages of wastewater being treated in anaerobic systems, including reduced use of on-site septic systems and central anaerobic treatment systems (EPA 1992, 1996, 2000, and 2004, U.S. Census 2011). In 2013, CH_4 emissions from industrial wastewater treatment were estimated to be 5.8 MMT CO_2 Eq. (233 kt CH_4). Industrial emission sources have generally increased across the time series through 1999 and then fluctuated up and down with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries. Table 7-7 and Table 7-8 provide CH_4 and N_2O emission estimates from domestic and industrial wastewater treatment.

With respect to N_2O, the United States identifies two distinct sources for N_2O emissions from domestic wastewater: emissions from centralized wastewater treatment processes, and emissions from effluent from centralized treatment systems that has been discharged into aquatic environments. The 2013 emissions of N_2O from centralized wastewater treatment processes and from effluent were estimated to be 0.3 MMT CO_2 Eq. (1 kt N_2O) and 4.6 MMT CO_2 Eq. (15 kt N_2O), respectively. Total N_2O emissions from domestic wastewater were estimated to be 4.9 MMT CO_2 Eq. (17 kt N_2O). N_2O emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption.

Table 7-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (MMT CO_2 Eq.)

Activity	1990	2005	2009	2010	2011	2012	2013
CH_4	**15.7**	**15.9**	**15.6**	**15.5**	**15.3**	**15.2**	**15.0**
Domestic	10.5	10.0	9.8	9.6	9.4	9.3	9.2
Industrial[a]	5.1	5.8	5.8	5.9	5.9	5.8	5.8
N_2O	**3.4**	**4.3**	**4.6**	**4.7**	**4.8**	**4.9**	**4.9**
Domestic	3.4	4.3	4.6	4.7	4.8	4.9	4.9
Total	**19.1**	**20.2**	**20.2**	**20.2**	**20.1**	**20.1**	**19.9**

[a] Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.
Note: Totals may not sum due to independent rounding.

Table 7-8: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (kt)

Activity	1990	2005	2009	2010	2011	2012	2013
CH_4	**626**	**635**	**623**	**619**	**610**	**606**	**601**
Domestic	421	401	392	384	375	373	368
Industrial[a]	206	234	231	235	235	233	233
N_2O	**11**	**15**	**16**	**16**	**16**	**16**	**17**
Domestic	11	15	16	16	16	16	17

[a] Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.
Note: Totals may not sum due to independent rounding.

Methodology

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems, such as publicly owned treatment works (POTWs). Within these centralized systems, CH_4 emissions can arise from aerobic systems that are not well managed or that are designed to have periods of anaerobic activity (e.g., constructed wetlands), anaerobic systems (anaerobic lagoons and facultative lagoons), and from anaerobic digesters when the captured biogas is not completely combusted. CH_4 emissions from septic systems were estimated by multiplying the United States population by the percent of wastewater treated in septic systems (about 20 percent) and an emission factor (10.7 g CH_4/capita/day), and then converting the result to kt/year. CH_4emissions from POTWs were estimated by multiplying the total BOD_5 produced in the United States by the percent of wastewater treated centrally (about 80 percent), the relative percentage of wastewater treated by aerobic and anaerobic systems, the relative percentage of wastewater facilities with primary treatment, the percentage of BOD_5 treated after primary treatment (67.5 percent), the maximum CH_4-producing capacity of domestic wastewater (0.6), and the relative MCFs for well-managed aerobic (zero), not well managed aerobic (0.3), and anaerobic (0.8) systems with all aerobic systems assumed to be well-managed. CH_4emissions from anaerobic digesters were estimated by multiplying the amount of biogas generated by wastewater sludge treated in anaerobic digesters by the proportion of CH_4 in digester biogas (0.65), the density of CH_4 (662 g CH_4/m^3 CH_4), and the destruction efficiency associated with burning the biogas in an energy/thermal device (0.99). The methodological equations are:

Emissions from Septic Systems = A

$$= US_{POP} \times (\text{\% onsite}) \times (EF_{SEPTIC}) \times 1/10^{\wedge}9 \times \text{Days}$$

Emissions from Centrally Treated Aerobic Systems = B

$$= [(\text{\% collected}) \times (\text{total } BOD_5 \text{ produced}) \times (\text{\% aerobic}) \times (\text{\% aerobic w/out primary}) + (\text{\% collected}) \times (\text{total } BOD_5 \text{ produced}) \times (\text{\% aerobic}) \times (\text{\% aerobic w/primary}) \times (1\text{-\% BOD removed in prim. treat.})] \times (\text{\% operations not well managed}) \times (B_o) \times (\text{MCF-aerobic\_not\_well\_man})$$

Emissions from Centrally Treated Anaerobic Systems = C

$$= [(\text{\% collected}) \times (\text{total } BOD_5 \text{ produced}) \times (\text{\% anaerobic}) \times (\text{\% anaerobic w/out primary}) + (\text{\% collected}) \times (\text{total } BOD_5 \text{ produced}) \times (\text{\% anaerobic}) \times (\text{\% anaerobic w/primary}) \times (1\text{-\%BOD removed in prim. treat.})] \times (B_o) \times (\text{MCF-anaerobic})$$

Emissions from Anaerobic Digesters = D

$$= [(\text{POTW\_flow\_AD}) \times (\text{digester gas})/ (\text{per capita flow})] \times \text{conversion to } m^3 \times (\text{FRAC\_}CH_4) \times (365.25) \times (\text{density of } CH_4) \times (1\text{-DE}) \times 1/10^{\wedge}9$$

$$\text{Total } CH_4 \text{ Emissions (kt)} = A + B + C + D$$

where,

US_{POP} = U.S. population
% onsite = Flow to septic systems / total flow
% collected = Flow to POTWs / total flow
% aerobic = Flow to aerobic systems / total flow to POTWs
% anaerobic = Flow to anaerobic systems / total flow to POTWs
% aerobic w/out primary = Percent of aerobic systems that do not employ primary treatment
% aerobic w/primary = Percent of aerobic systems that employ primary treatment
% BOD removed in prim. treat. = 32.5%
% operations not well managed = Percent of aerobic systems that are not well managed and in which some anaerobic degradation occurs
% anaerobic w/out primary = Percent of anaerobic systems that do not employ primary treatment
% anaerobic w/primary = Percent of anaerobic systems that employ primary treatment
EF_{SEPTIC} = Methane emission factor (10.7 g CH_4/capita/day) – septic systems
Days = days per year (365.25)

Total BOD$_5$ produced = kg BOD/capita/day × U.S. population × 365.25 days/yr
B$_o$ = Maximum CH$_4$-producing capacity for domestic wastewater (0.60 kg CH$_4$/kg BOD)
1/10^6 = Conversion factor, kg to kt
MCF-aerobic_not_well_man. = CH$_4$ correction factor for aerobic systems that are not well managed (0.3)
MCF-anaerobic = CH$_4$ correction factor for anaerobic systems (0.8)
DE = CH$_4$ destruction efficiency from flaring or burning in engine (0.99 for enclosed flares)
POTW_flow_AD = Wastewater influent flow to POTWs that have anaerobic digesters (MGD)
digester gas = Cubic feet of digester gas produced per person per day (1.0 ft^3/person/day)
per capita flow = Wastewater flow to POTW per person per day (100 gal/person/day)
conversion to m^3 = Conversion factor, ft^3 to m^3 (0.0283)
FRAC_CH$_4$ = Proportion CH$_4$ in biogas (0.65)
density of CH$_4$ = 662 (g CH$_4$/m^3 CH$_4$)
1/10^9 = Conversion factor, g to kt

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2014) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. Table 7-9 presents U.S. population and total BOD$_5$ produced for 1990 through 2013, while Table 7-10 presents domestic wastewater CH$_4$ emissions for both septic and centralized systems in 2013. The proportions of domestic wastewater treated onsite versus at centralized treatment plants were based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, and 2011 American Housing Surveys conducted by the U.S. Census Bureau (U.S. Census 2011), with data for intervening years obtained by linear interpolation and data for 2013 forecasted using 1990-2012 data. The percent of wastewater flow to aerobic and anaerobic systems, the percent of aerobic and anaerobic systems that do and do not employ primary treatment, and the wastewater flow to POTWs that have anaerobic digesters were obtained from the 1992, 1996, 2000, and 2004 Clean Watershed Needs Survey (EPA 1992, 1996, 2000, and 2004). Data for intervening years were obtained by linear interpolation and the years 2004 through 2013 were forecasted from the rest of the time series. The BOD$_5$ production rate (0.09 kg/capita/day) and the percent BOD$_5$ removed by primary treatment for domestic wastewater were obtained from Metcalf and Eddy (2003). The maximum CH$_4$-producing capacity (0.6 kg CH$_4$/kg BOD$_5$) and both MCFs used for centralized treatment systems were taken from IPCC (2006), while the CH$_4$ emission factor (10.7 g CH$_4$/capita/day) used for septic systems were taken from Leverenz et al. (2010). The CH$_4$ destruction efficiency for methane recovered from sludge digestion operations, 99 percent, was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in AP-42 Compilation of Air Pollutant Emission Factors, Chapter 2.4 (EPA 1998), efficiencies used to establish New Source Performance Standards (NSPS) for landfills, along with data from CAR (2011), Sullivan (2007), Sullivan (2010), and UNFCCC (2012). The cubic feet of digester gas produced per person per day (1.0 ft^3/person/day) and the proportion of CH$_4$ in biogas (0.65) come from Metcalf and Eddy (2003). The wastewater flow to a POTW (100 gal/person/day) was taken from the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, "Recommended Standards for Wastewater Facilities (Ten-State Standards)" (2004).

Table 7-9: U.S. Population (Millions) and Domestic Wastewater BOD$_5$ Produced (kt)

Year	Population	BOD$_5$
1990	253	8,333
2005	300	9,853
2009	311	10,220
2010	313	10,303
2011	316	10,377
2012	318	10,452
2013	320	10,534

Sources: U.S. Census Bureau (2014); Metcalf & Eddy (2003).

Table 7-10: Domestic Wastewater CH_4 Emissions from Septic and Centralized Systems (2013)

	CH_4 Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater CH_4
Septic Systems	6.0	65.5%
Centralized Systems (including anaerobic sludge digestion)	3.2	34.5%
Total	**9.2**	**100%**

Note: Totals may not sum due to independent rounding.

Industrial Wastewater CH_4 Emission Estimates

Methane emission estimates from industrial wastewater were developed according to the methodology described in IPCC (2006). Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified and included in the Inventory. The main criteria used to identify these industries are whether they generate high volumes of wastewater, whether there is a high organic wastewater load, and whether the wastewater is treated using methods that result in CH_4 emissions. The top five industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; and petroleum refining. Wastewater treatment emissions for these sectors for 2013 are displayed in Table 7-11 below. Table 7-12 contains production data for these industries.

Table 7-11: Industrial Wastewater CH_4 Emissions by Sector (2013)

	CH_4 Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater CH_4
Meat & Poultry	4.4	75%
Pulp & Paper	1.1	18%
Fruit & Vegetables	0.1	2%
Petroleum Refineries	0.1	2%
Ethanol Refineries	0.1	2%
Total	**5.8**	**100%**

Note: Totals may not sum due to independent rounding.

Table 7-12: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, and Petroleum Refining Production (MMT)

Year	Pulp and Paper[a]	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices	Ethanol	Petroleum Refining
1990	128.9	27.3	14.6	38.7	2.5	702.4
2005	138.5	31.4	25.1	42.9	11.7	818.6
2009	120.4	33.8	25.2	46.5	32.7	822.4
2010	128.6	33.7	25.9	43.2	39.7	848.6
2011	127.5	33.8	26.2	44.3	41.6	858.8
2012	127.0	33.8	26.1	45.3	39.5	856.1
2013	131.5	33.6	26.5	43.9	39.8	875.9

[a] Pulp and paper production is the sum of woodpulp production plus paper and paperboard production.

Sources: Lockwood-Post (2002); FAO (2014); USDA (2014a); RFA (2014); EIA (2014).

CH_4 emissions from these categories were estimated by multiplying the annual product output by the average outflow, the organics loading (in COD) in the outflow, the maximum CH_4 producing potential of industrial wastewater (B_o), and the percentage of organic loading assumed to degrade anaerobically in a given treatment system (MCF). Ratios of BOD:COD in various industrial wastewaters were obtained from EPA (1997a) and used to estimate COD loadings. The B_o value used for all industries is the IPCC default value of 0.25 kg CH_4/kg COD (IPCC 2006).

For each industry, the percent of plants in the industry that treat wastewater on site, the percent of plants that have a primary treatment step prior to biological treatment, and the percent of plants that treat wastewater anaerobically were defined. The percent of wastewater treated anaerobically onsite (TA) was estimated for both primary treatment ($\%TA_p$) and secondary treatment ($\%TA_s$). For plants that have primary treatment in place, an estimate of COD that is removed prior to wastewater treatment in the anaerobic treatment units was incorporated. The values used in the %TA calculations are presented in Table 7-13 below.

The methodological equations are:

where,

CH_4 (industrial wastewater) = Total CH_4 emissions from industrial wastewater (kg/year)
P = Industry output (metric tons/year)
W = Wastewater generated (m^3/metric ton of product)
COD = Organics loading in wastewater (kg/m^3)
$\%TA_p$ = Percent of wastewater treated anaerobically on site in primary treatment
$\%TA_s$ = Percent of wastewater treated anaerobically on site in secondary treatment
$\%Plants_o$ = Percent of plants with onsite treatment
$\%WW_{a,p}$ = Percent of wastewater treated anaerobically in primary treatment
$\%COD_p$ = Percent of COD entering primary treatment
$\%Plants_a$ = Percent of plants with anaerobic secondary treatment
$\%Plants_t$ = Percent of plants with other secondary treatment
$\%WW_{a,s}$ = Percent of wastewater treated anaerobically in anaerobic secondary treatment
$\%WW_{a,t}$ = Percent of wastewater treated anaerobically in other secondary treatment
$\%COD_s$ = Percent of COD entering secondary treatment
B_o = Maximum CH_4 producing potential of industrial wastewater (default value of 0.25 kg CH_4/kg COD)
MCF = CH_4 correction factor, indicating the extent to which the organic content (measured as COD) degrades anaerobically

Alternate methodological equations for calculating %TA were used for secondary treatment in the pulp and paper industry to account for aerobic systems with anaerobic portions. These equations are:

$$\%TA_a = [\%Plants_a \times \%WW_{as} \times \%COD_s]+[\%Plant_{st} \times \%WW_{at} \times COD_s]$$

$$\%TA_{at} = [\%Plants_{at} \times \%WW_{as} \times \%COD_s]$$

where,

$\%TA_a$ = Percent of wastewater treated anaerobically on site in secondary treatment
$\%TA_{at}$ = Percent of wastewater treated in aerobic systems with anaerobic portions on site in secondary treatment
$\%Plants_a$ = Percent of plants with anaerobic secondary treatment
$\%Plants_{a,t}$ = Percent of plants with partially anaerobic secondary treatment
$\%WW_{a,s}$ = Percent of wastewater treated anaerobically in anaerobic secondary treatment
$\%WW_{a,t}$ = Percent of wastewater treated anaerobically in other secondary treatment

$\%COD_s$ = Percent of COD entering secondary treatment

As described below, the values presented in Table 7-13 were used in the emission calculations and are described in detail in ERG (2008), ERG (2013a), and ERG (2013b).

Table 7-13: Variables Used to Calculate Percent Wastewater Treated Anaerobically by Industry (percent)

	Industry						
Variable	**Pulp and Paper**	**Meat Processing**	**Poultry Processing**	**Fruit/ Vegetable Processing**	**Ethanol Production – Wet Mill**	**Ethanol Production – Dry Mill**	**Petroleum Refining**
$\%TA_p$	0	0	0	0	0	0	0
$\%TA_s$	0	33	25	4.2	33.3	75	23.6
$\%TA_a$	2.2	0	0	0	0	0	0
$\%TA_{a,t}$	11.8	0	0	0	0	0	0
$\%Plants_o$	0	100	100	11	100	100	100
$\%Plants_a$	5	33	25	5.5	33.3	75	23.6
$\%Plants_{a,t}$	28	0	0	0	0	0	0
$\%Plants_t$	35	67	75	5.5	66.7	25	0
$\%WW_{a,p}$	0	0	0	0	0	0	0
$\%WW_{a,s}$	100	100	100	100	100	100	100
$\%WW_{a,t}$	0	0	0	0	0	0	0
$\%COD_p$	100	100	100	100	100	100	100
$\%COD_s$	42	100	100	77	100	100	100

Sources: ERG (2008); ERG (2013a); and ERG (2013b).

Pulp and Paper. Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999, Nemerow and Dasgupta 1991). Secondary treatment (storage, settling, and biological treatment) mainly consists of lagooning. In determining the percent that degrades anaerobically, both primary and secondary treatment were considered. In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993). The vast majority of pulp and paper mills with on-site treatment systems use mechanical clarifiers to remove suspended solids from the wastewater. About 10 percent of pulp and paper mills with treatment systems use settling ponds for primary treatment and these are more likely to be located at mills that do not perform secondary treatment (EPA 1993). However, because the vast majority of primary treatment operations at U.S. pulp and paper mills use mechanical clarifiers, and less than 10 percent of pulp and paper wastewater is managed in primary settling ponds that are not expected to have anaerobic conditions, negligible emissions are assumed to occur during primary treatment.

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. Based on EPA's OAQPS Pulp and Paper Sector Survey, 5.3 percent of pulp and paper mills reported using anaerobic secondary treatment for wastewater and/or pulp condensates (ERG 2013a). Twenty-eight percent (28 percent) of mills also reported the use of quiescent settling ponds. Using engineering judgment, these systems were determined to be aerobic with possible anaerobic portions. For the truly anaerobic systems, an MCF of 0.8 is used, as these are typically deep stabilization basins. For the partially anaerobic systems, an MCF of 0.2 is used, which is the IPCC suggested MCF for shallow lagoons.

A time series of CH_4 emissions for 1990 through 2001 was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post 2002). Data from the Food and Agricultural Organization of the United Nations (FAO) database FAOSTAT were used for 2002 through 2013 (FAO 2014). The overall wastewater outflow varies based on a time series outlined in ERG (2013a) to reflect historical and current industry wastewater flow, and the average BOD concentrations in raw wastewater was estimated to be 0.4 gram BOD/liter (EPA 1997b, EPA 1993, World Bank 1999). The COD:BOD ratio used to convert the organic loading to COD for pulp and paper mills was 2 (EPA 1997a).

Meat and Poultry Processing. The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps, and dissolved air flotation when treating wastewater on site. About 33 percent of meat processing operations (EPA 2002) and 25 percent of poultry processing operations (U.S. Poultry 2006) perform on-site treatment in anaerobic lagoons. The IPCC default B_o of 0.25 kg CH_4/kg COD and default MCF of 0.8 for anaerobic lagoons were used to estimate the CH_4 produced from these on-site treatment systems. Production data, in carcass weight and live weight killed for the meat and poultry industry, were obtained from the USDA Agricultural Statistics Database and the Agricultural Statistics Annual Reports (USDA 2014a). Data collected by EPA's Office of Water provided estimates for wastewater flows into anaerobic lagoons: 5.3 and 12.5 m^3/metric ton for meat and poultry production (live weight killed), respectively (EPA 2002). The loadings are 2.8 and 1.5 g BOD/liter for meat and poultry, respectively. The COD:BOD ratio used to convert the organic loading to COD for both meat and poultry facilities was 3 (EPA 1997a).

Vegetables, Fruits, and Juices Processing. Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling, and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. Effluent is suitable for discharge to the sewer. This industry is likely to use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta 1991). Consequently, 4.2 percent of these wastewater organics are assumed to degrade anaerobically. The IPCC default B_o of 0.25 kg CH_4/kg COD and default MCF of 0.8 for anaerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems. The USDA National Agricultural Statistics Service (USDA 2014a) provided production data for potatoes, other vegetables, citrus fruit, non-citrus fruit, and grapes processed for wine. Outflow and BOD data, presented in Table 7-14, were obtained from EPA (1974) for potato, citrus fruit, and apple processing, and from EPA (1975) for all other sectors. The COD:BOD ratio used to convert the organic loading to COD for all fruit, vegetable, and juice facilities was 1.5 (EPA 1997a).

Table 7-14: Wastewater Flow (m^3/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits, and Juices Production

Commodity	Wastewater Outflow (m^3/ton)	BOD (g/L)
Vegetables		
Potatoes	10.27	1.765
Other Vegetables	8.67	0.791
Fruit		
Apples	3.66	1.371
Citrus	10.11	0.317
Non-citrus	12.42	1.204
Grapes (for wine)	2.78	1.831

Sources: EPA 1974, EPA 1975.

Ethanol Production. Ethanol, or ethyl alcohol, is produced primarily for use as a fuel component, but is also used in industrial applications and in the manufacture of beverage alcohol. Ethanol can be produced from the fermentation of sugar-based feedstocks (e.g., molasses and beets), starch- or grain-based feedstocks (e.g., corn, sorghum, and beverage waste), and cellulosic biomass feedstocks (e.g., agricultural wastes, wood, and bagasse). Ethanol can also be produced synthetically from ethylene or hydrogen and carbon monoxide. However, synthetic ethanol comprises only about 2 percent of ethanol production, and although the Department of Energy predicts cellulosic ethanol to greatly increase in the coming years, currently it is only in an experimental stage in the United States. Currently, ethanol is mostly made from sugar and starch crops, but with advances in technology, cellulosic biomass is increasingly used as ethanol feedstock (DOE 2013).

Ethanol is produced from corn (or other starch-based feedstocks) primarily by two methods: wet milling and dry milling. Historically, the majority of ethanol was produced by the wet milling process, but now the majority is produced by the dry milling process. The dry milling process is cheaper to implement, and has become more efficient in recent years (Rendleman and Shapouri 2007). The wastewater generated at ethanol production facilities is handled in a variety of ways. Dry milling facilities often combine the resulting evaporator condensate with other process wastewaters, such as equipment wash water, scrubber water, and boiler blowdown and anaerobically treat this wastewater using various types of digesters. Wet milling facilities often treat their steepwater condensate in anaerobic systems followed by aerobic polishing systems. Wet milling facilities may treat the stillage (or processed stillage) from the ethanol fermentation/distillation process separately or together with steepwater and/or wash water. CH_4 generated in anaerobic digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006).

Available information was compiled from the industry on wastewater generation rates, which ranged from 1.25 gallons per gallon ethanol produced (for dry milling) to 10 gallons per gallon ethanol produced (for wet milling) (Ruocco 2006a,b; Merrick 1998; Donovan 1996; and NRBP 2001). COD concentrations were also found to be about 3 g/L (Ruocco 2006a; Merrick 1998; White and Johnson 2003). The amount of wastewater treated anaerobically was estimated, along with how much of the CH_4 is recovered through the use of biomethanators. Biomethanators are anaerobic reactors that use microorganisms under anaerobic conditions to reduce COD and organic acids and recover biogas from wastewater (ERG 2006). Methane emissions were then estimated as follows:

$$\text{Methane} = [\text{Production} \times \text{Flow} \times \text{COD} \times 3.785 \times ([\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p] + [\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s] + [\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s]) \times B_o \times \text{MCF} \times \%\text{ Not Recovered}] + [\text{Production} \times \text{Flow} \times 3.785 \times \text{COD} \times ([\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p] + [\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s] + [\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s]) \times B_o \times \text{MCF} \times (\%\text{ Recovered}) \times (1\text{-}\text{DE})] \times 1/10\text{\^{}}9$$

where,

Production = gallons ethanol produced (wet milling or dry milling)
Flow = gallons wastewater generated per gallon ethanol produced (1.25 dry milling, 10 wet milling)
COD = COD concentration in influent (3 g/l)
3.785 = conversion, gallons to liters
$\%Plants_o$ = percent of plants with onsite treatment (100%)
$\%WW_{a,p}$ = percent of wastewater treated anaerobically in primary treatment (0%)
$\%COD_p$ = percent of COD entering primary treatment (100%)
$\%Plants_a$ = percent of plants with anaerobic secondary treatment (33.3% wet, 75% dry)
$\%Plants_t$ = percent of plants with other secondary treatment (66.7% wet, 25% dry)
$\%WW_{a,s}$ = percent of wastewater treated anaerobically in anaerobic secondary treatment (100%)
$\%WW_{a,t}$ = percent of wastewater treated anaerobically in other secondary treatment (0%)
$\%COD_s$ = percent of COD entering secondary treatment (100%)
B_o = maximum methane producing capacity (0.25 g CH_4/g COD)
MCF = methane conversion factor (0.8 for anaerobic systems)
% Recovered = percent of wastewater treated in system with emission recovery
% Not Recovered = 1 - percent of wastewater treated in system with emission recovery
DE = destruction efficiency of recovery system (99%)
1/10^9 = conversion factor, g to kt

A time series of CH_4 emissions for 1990 through 2013 was developed based on production data from the Renewable Fuels Association (RFA 2014).

Petroleum Refining. Petroleum refining wastewater treatment operations have the potential to produce CH_4 emissions from anaerobic wastewater treatment. EPA's Office of Air and Radiation performed an Information Collection Request (ICR) for petroleum refineries in 2011.[8] Of the responding facilities, 23.6 percent reported using non-aerated surface impoundments or other biological treatment units, both of which have the potential to lead to anaerobic conditions (ERG 2013b). In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product (ERG 2013b). An average COD value in the wastewater was estimated at 0.45 kg/m^3 (Benyahia et al. 2006).

The equation used to calculate CH_4 generation at petroleum refining wastewater treatment systems is presented below:

$$\text{Methane} = \text{Flow} \times \text{COD} \times \text{TA} \times B_o \times \text{MCF}$$

where,

Flow = Annual flow treated through anaerobic treatment system (m^3/year)
COD = COD loading in wastewater entering anaerobic treatment system (kg/m^3)
TA = Percent of wastewater treated anaerobically on site

---

[8] Available online at <https://refineryicr.rti.org/>.

B_o = maximum methane producing potential of industrial wastewater (default value of 0.25 kg CH_4 /kg COD)
MCF = methane conversion factor (0.3)

A time series of CH_4 emissions for 1990 through 2013 was developed based on production data from the Energy Information Association (EIA 2014).

Domestic Wastewater N_2O Emission Estimates

N_2O emissions from domestic wastewater (wastewater treatment) were estimated using the IPCC (2006) methodology, including calculations that take into account N removal with sewage sludge, non-consumption and industrial/commercial wastewater N, and emissions from advanced centralized wastewater treatment plants:

- In the United States, a certain amount of N is removed with sewage sludge, which is applied to land, incinerated, or landfilled (N_{SLUDGE}). The N disposal into aquatic environments is reduced to account for the sewage sludge application.
- The IPCC methodology uses annual, per capita protein consumption (kg protein/person-year). For this inventory, the amount of protein available to be consumed is estimated based on per capita annual food availability data and its protein content, and then adjusts that data using a factor to account for the fraction of protein actually consumed.
- Small amounts of gaseous nitrogen oxides are formed as byproducts in the conversion of nitrate to N gas in anoxic biological treatment systems. Approximately 7 g N_2O is generated per capita per year if wastewater treatment includes intentional nitrification and denitrification (Scheehle and Doorn 2001). Analysis of the 2004 CWNS shows that plants with denitrification as one of their unit operations serve a population of 2.4 million people. Based on an emission factor of 7 g per capita per year, approximately 21.2 metric tons of additional N_2O may have been emitted via denitrification in 2004. Similar analyses were completed for each year in the Inventory using data from CWNS on the amount of wastewater in centralized systems treated in denitrification units. Plants without intentional nitrification/denitrification are assumed to generate 3.2 g N_2O per capita per year.

N_2O emissions from domestic wastewater were estimated using the following methodology:

$$N_2O_{TOTAL} = N_2O_{PLANT} + N_2O_{EFFLUENT}$$

$$N_2O_{PLANT} = N_2O_{NIT/DENIT} + N_2O_{WOUT\ NIT/DENIT}$$

$$N_2O_{NIT/DENIT} = [(US_{POPND}) \times EF_2 \times F_{IND\text{-}COM}] \times 1/10\text{\^{}}9$$

$$N_2O_{WOUT\ NIT/DENIT} = \{[(US_{POP} \times WWTP) - US_{POPND}] \times F_{IND\text{-}COM} \times EF_1\} \times 1/10\text{\^{}}9$$

$$N_2O_{EFFLUENT} = \{[(((US_{POP} \times WWTP) - (0.9 \times US_{POPND})) \times Protein \times F_{NPR} \times F_{NON\text{-}CON} \times F_{IND\text{-}COM}) - N_{SLUDGE}] \times EF_3 \times 44/28\} \times 1/10\text{\^{}}6$$

where,

N_2O_{TOTAL} = Annual emissions of N_2O (kt)
N_2O_{PLANT} = N_2O emissions from centralized wastewater treatment plants (kt)
$N_2O_{NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants with nitrification/denitrification (kt)
$N_2O_{WOUT\ NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants without nitrification/denitrification (kt)
$N_2O_{EFFLUENT}$ = N_2O emissions from wastewater effluent discharged to aquatic environments (kt)
US_{POP} = U.S. population
US_{POPND} = U.S. population that is served by biological denitrification (from CWNS)
WWTP = Fraction of population using WWTP (as opposed to septic systems)
EF_1 = Emission factor (3.2 g N_2O/person-year) – plant with no intentional denitrification
EF_2 = Emission factor (7 g N_2O/person-year) – plant with intentional denitrification
Protein = Annual per capita protein consumption (kg/person/year)
F_{NPR} = Fraction of N in protein, default = 0.16 (kg N/kg protein)

$F_{NON\text{-}CON}$ = Factor for non-consumed protein added to wastewater (1.4)
$F_{IND\text{-}COM}$ = Factor for industrial and commercial co-discharged protein into the sewer system (1.25)
N_{SLUDGE} = N removed with sludge, kg N/yr
EF_3 = Emission factor (0.005 kg N_2O -N/kg sewage-N produced) – from effluent
0.9 = Amount of nitrogen removed by denitrification systems
44/28 = Molecular weight ratio of N_2O to N_2

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2014) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. The fraction of the U.S. population using wastewater treatment plants is based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, and 2011 American Housing Survey (U.S. Census 2011). Data for intervening years were obtained by linear interpolation and data from 2012 and 2013 were forecasted using 1990-2011 data. The emission factor (EF_1) used to estimate emissions from wastewater treatment for plants without intentional denitrification was taken from IPCC (2006), while the emission factor (EF_2) used to estimate emissions from wastewater treatment for plants with intentional denitrification was taken from Scheehle and Doorn (2001). Data on annual per capita protein intake were provided by the U.S. Department of Agriculture Economic Research Service (USDA 2014b). Protein consumption data for 2010 through 2013 were extrapolated from data for 1990 through 2006. An emission factor to estimate emissions from effluent (EF_3) has not been specifically estimated for the United States, thus the default IPCC value (0.005 kg N_2O-N/kg sewage-N produced) was applied (IPCC 2006). The fraction of N in protein (0.16 kg N/kg protein) was also obtained from IPCC (2006). The factor for non-consumed protein and the factor for industrial and commercial co-discharged protein were obtained from IPCC (2006). Sludge generation was obtained from EPA (1999) for 1988, 1996, and 1998 and from Beecher et al. (2007) for 2004. Intervening years were interpolated, and estimates for 2005 through 2012 were forecasted from the rest of the time series. The amount of nitrogen removed by denitrification systems was taken from EPA (2008). An estimate for the N removed as sludge (N_{SLUDGE}) was obtained by determining the amount of sludge disposed by incineration, by land application (agriculture or other), through surface disposal, in landfills, or through ocean dumping (US EPA 1993b, Beecher et al. 2007, McFarland 2001, US EPA 1999). In 2013, 286 kt N was removed with sludge. Table 7-15 presents the data for U.S. population, population served by biological denitrification, population served by wastewater treatment plants, available protein, protein consumed, and nitrogen removed with sludge.

Table 7-15: U.S. Population (Millions), Population Served by Biological Denitrification (Millions), Fraction of Population Served by Wastewater Treatment (percent), Available Protein (kg/person-year), Protein Consumed (kg/person-year), and Nitrogen Removed with Sludge (kt-N/year)

Year	Population	$Population_{ND}$	WWTP Population	Available Protein	Protein Consumed	N Removed
1990	253	2.0	75.6	38.4	29.5	214.1
2005	300	2.7	78.8	39.8	30.7	261.1
2009	311	2.9	79.3	40.9	31.5	273.4
2010	313	3.0	80.0	41.0	31.6	276.4
2011	316	3.0	80.6	41.1	31.7	279.5
2012	318	3.0	80.4	41.2	31.8	282.6
2013	320	3.1	80.7	41.3	31.9	285.6

Sources: Beecher et al. 2007, McFarland 2001, U.S. Census 2011, U.S. Census 2014, USDA 2014b, US EPA 1992, US EPA 1993b, US EPA 1996, US EPA 1999, US EPA 2000, US EPA 2004.

Uncertainty and Time-Series Consistency

The overall uncertainty associated with both the 2013 CH_4 and N_2O emission estimates from wastewater treatment and discharge was calculated using the *2006 IPCC Guidelines* Approach 2 methodology (2006). Uncertainty associated with the parameters used to estimate CH_4 emissions include that of numerous input variables used to model emissions from domestic wastewater, and wastewater from pulp and paper manufacture, meat and poultry processing, fruits and vegetable processing, ethanol production, and petroleum refining. Uncertainty associated with the parameters used to estimate N_2O emissions include that of sewage sludge disposal, total U.S. population, average protein consumed per person, fraction of N in protein, non-consumption nitrogen factor, emission factors per capita and per mass of sewage-N, and for the percentage of total population using centralized wastewater treatment plants.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 7-16. Methane emissions from wastewater treatment were estimated to be between 9.2 and 15.3 MMT CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 39 percent below to 2 percent above the 2013 emissions estimate of 15.0 MMT CO_2 Eq. N_2O emissions from wastewater treatment were estimated to be between 1.2 and 10.2 MMT CO_2 Eq., which indicates a range of approximately 76 percent below to 107 percent above the 2013 emissions estimate of 4.9 MMT CO_2 Eq.

Table 7-16: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Wastewater Treatment (MMT CO_2 Eq. and Percent)

Source	Gas	2013 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Wastewater Treatment	**CH_4**	**15.0**	**9.2**	**15.3**	**-39%**	**+2%**
Domestic	CH_4	9.2	5.7	9.9	-38%	+7%
Industrial	CH_4	5.8	2.4	6.9	-59%	+18%
Wastewater Treatment	**N_2O**	**4.9**	**1.2**	**10.2**	**-76%**	**+107%**

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

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed on activity data, documentation, and emission calculations. This effort included a Tier 1 analysis, including the following checks:

- Checked for transcription errors in data input;
- Ensured references were specified for all activity data used in the calculations;
- Checked a sample of each emission calculation used for the source category;
- Checked that parameter and emission units were correctly recorded and that appropriate conversion factors were used;
- Checked for temporal consistency in time series input data for each portion of the source category;
- Confirmed that estimates were calculated and reported for all portions of the source category and for all years;
- Investigated data gaps that affected emissions estimates trends; and
- Compared estimates to previous estimates to identify significant changes.

All transcription errors identified were corrected. The QA/QC analysis did not reveal any systemic inaccuracies or incorrect input values.

Recalculations Discussion

Production data were updated to reflect revised USDA NASS datasets. In addition, the most recent USDA ERS data were used to update percent protein values from 1990 through 2010. The updated ERS data also resulted in small changes in forecasted values from 2011. The factor for sewage sludge production change per year was updated to include all available data. This change resulted in updated 1990 through 1995 values for total N in sludge along with a change in forecasted values from 2005 through 2012.

Workbooks were also updated to show emissions in kilotons and MMT CO_2 Eq. In addition, global warming potentials for N_2O and CH_4 were updated with the AR4 100-year values (IPCC 2007).

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for N_2O. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

Planned Improvements

The methodology to estimate CH_4 emissions from domestic wastewater treatment currently utilizes estimates for the percentage of centrally treated wastewater that is treated by aerobic systems and anaerobic systems. These data come from the 1992, 1996, 2000, and 2004 CWNS. The question of whether activity data for wastewater treatment systems are sufficient across the time series to further differentiate aerobic systems with the potential to generate small amounts of CH_4 (aerobic lagoons) versus other types of aerobic systems, and to differentiate between anaerobic systems to allow for the use of different MCFs for different types of anaerobic treatment systems, continues to be explored. The CWNS data for 2008 were evaluated for incorporation into the Inventory, but due to significant changes in format, this dataset is not sufficiently detailed for inventory calculations. However, additional information and other data continue to be evaluated to update future years of the Inventory, including anaerobic digester data compiled by the North East Biosolids and Residuals Association (NEBRA) in collaboration with several other entities. While NEBRA is no longer involved in the project, the Water Environment Federation (WEF) now hosts and manages the dataset which has been relocated to www.wef.org/biosolids. WEF will complete the second phase of their data collection and by late fall. They are currently collecting additional data on a Region by Region basis which should add to the quality of the database by decreasing uncertainty and data gaps (ERG 2014a). EPA will continue to monitor the status of these data as a potential source of digester, sludge, and biogas data from POTWs.

Data collected under the EPA's Greenhouse Gas Reporting Program Subpart II, Industrial Wastewater Treatment (GHGRP) is being investigated for use in improving the emission estimates for the industrial wastewater category. Ensuring time series consistency has been the focus, as the reporting data from EPA's GHGRP are not available for all inventory years. Whether EPA's GHGRP reporters sufficiently represent U.S. emissions is being investigated to determine if moving to a facility-level implementation of GHGRP data is warranted, or whether the GHGRP data will allow update of activity data for certain industry sectors, such as use of biogas recovery systems or update of waste characterization data. Since EPA's GHGRP only includes reporters that have met a certain threshold and because EPA is unable to review whether the reporters represent the majority of U.S. production, GHGRP data are not believed to be sufficiently representative to move toward facility-level estimates in the Inventory. However, the GHGRP data continues to be evaluated for improvements to activity data, and in verifying methodologies currently in use in the Inventory to estimate emissions (ERG 2014b). In implementing any improvements and integration of data from EPA's GHGRP, EPA will follow the latest guidance from the IPCC on the use of facility-level data in national inventories.[9]

For industrial wastewater emissions, EPA is also working with the National Council of Air and Stream Improvement (NCASI) to determine if there are sufficient data available to update the estimates of organic loading in pulp and paper wastewaters treated on site. These data include the estimates of wastewater generated per unit of production, the BOD and/or COD concentration of these wastewaters, and the industry-level production basis used in the Inventory. EPA has received data on the industry-level production basis to date and intends to incorporate these data once a full evaluation of the production basis is made in relation to the wastewater generation rate and the organic

---

[9] See: <http://www.ipcc-nggip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

content of the wastewater. In this way, EPA plans to make a coordinated update to the three values that are used to estimate the total organic industry load to wastewater treatment plants, rather than multiple changes over time.

In addition to this investigation, any reports based on international research will be investigated to inform potential updates to the Inventory. The Global Water Research Coalition report has been evaluated, regarding wastewater collection and treatment systems (GWRC 2011). The report included results of studies from Australia, France, the Netherlands, and the United States. Since each dataset was taken from a variety of wastewater treatment plant types using different methodologies and protocols, it was determined that it was not representative enough to include in the Inventory at this time (ERG 2014a). In addition, wastewater inventory submissions from other countries have been investigated to determine if there are any emission factors, specific methodologies, or additional industries that could be used to inform the U.S. inventory calculations. Although no comparable data have been found, other countries' submissions will continue to be investigated for potential improvements to the inventory.

IPCC's 2013 wetlands supplement has also been investigated regarding the inclusion of constructed and semi-natural treatment wetlands in Inventory calculations (IPCC 2014). Methodologies are presented for estimating both CH_4 and N_2O. Next, the use of CWNS treatment system data will be investigated to determine if these data can be used to estimate the amount of wastewater treated in constructed wetlands for potential implementation in future Inventory reports.

Currently, for domestic wastewater, it is assumed that all aerobic wastewater treatment systems are well managed and produce no CH_4 and that all anaerobic systems have an MCF of 0.8. Efforts to obtain better data reflecting emissions from various types of municipal treatment systems are currently being pursued by researchers, including the Water Environment Research Federation (WERF). This research includes data on emissions from partially anaerobic treatment systems which was reviewed (Willis et al. 2013). It was determined that the emissions were too variable and the sample size too small to include in the Inventory at this time. In addition, information on flare efficiencies was reviewed and it was determined that they were not suitable for use in updating the Inventory because the flares used in the study are likely not comparable to those used at wastewater treatment plants (ERG 2014a). The status of this and similar research will continue to be monitored for potential inclusion in the Inventory in the future.

With respect to estimating N_2O emissions, the default emission factors for indirect N_2O from wastewater effluent and direct N_2O from centralized wastewater treatment facilities have a high uncertainty. Research is being conducted by WERF to measure N_2O emissions from municipal treatment systems and is periodically reviewed for its utility for the Inventory. The Phase I report from WERF on N_2O emissions was recently reviewed and EPA concluded, along with the author, that there were not enough data to create an emission factor for N_2O (Chandran 2012). While the authors suggested a facility-level approach, there are not enough data available to estimate N_2O emissions on a facility-level for the more than 16,000 POTWs in the United States (ERG 2014a). In addition, a literature review has been conducted focused on N_2O emissions from wastewater treatment to determine the state of such research and identify data to develop a country-specific N_2O emission factor or alternate emission factor or method (ERG 2011). Such data will continue to be reviewed as they are available to determine if a country-specific N_2O emission factor can or should be developed, or if alternate emission factors should be used. EPA will also follow up with the authors of any relevant studies, including those from WERF, to determine if there is additional information available on potential methodological revisions.

There is the potential for N_2O emissions associated with on-site industrial wastewater treatment operations; however, the methodology provided in IPCC (2006) only addresses N_2O emissions associated with domestic wastewater treatment. A literature review was initiated to assess other Annex I countries' wastewater inventory submissions for additional data and methodologies that could be used to inform the U.S. wastewater inventory calculations, in particular to determine if any countries have developed industrial wastewater N_2O emission estimates (ERG 2014a). Currently, there are insufficient data to develop a country-specific methodology; however, available data will continue to be reviewed, and will consider if indirect N_2O emissions associated with on-site industrial wastewater treatment using the IPCC default factor for domestic wastewater (0.005 kg N_2O-N/kg N) would be appropriate.

Previously, a new measurement data from WERF was used to develop a U.S.-specific emission factor for CH_4 emissions from septic systems, and these were incorporated into the inventory emissions calculation. Due to the high uncertainty of the measurements for N_2O from septic systems, estimates of N_2O emissions were not included. Appropriate emission factors for septic system N_2O emissions will continue to be investigated as the data collected by WERF indicate that septic soil systems are a source of N_2O emissions.

In addition, the estimate of N entering municipal treatment systems is under review. The factor that accounts for non-sewage N in wastewater (bath, laundry, kitchen, industrial components) also has a high uncertainty. Obtaining data on the changes in average influent N concentrations to centralized treatment systems over the time series would improve the estimate of total N entering the system, which would reduce or eliminate the need for other factors for non-consumed protein or industrial flow. The dataset previously provided by the National Association of Clean Water Agencies (NACWA) was reviewed to determine if it was representative of the larger population of centralized treatment plants for potential inclusion into the Inventory. However, this limited dataset was not representative of the number of systems by state or the service populations served in the United States, and therefore could not be incorporated into the inventory methodology. Additional data sources will continue to be researched with the goal of improving the uncertainty of the estimate of N entering municipal treatment systems. Unfortunately, NACWA's suggestion of using National Pollution Discharge Elimination System (NPDES) permit data to estimate nitrogen loading rates is not feasible as influent concentration are not available. EPA is also evaluating whether available effluent nitrogen concentrations reported under POTW NPDES permits would support a more robust analysis of nitrogen contributing to indirect nitrous oxide emissions. Not every POTW is required to measure for effluent nitrogen so the database is not a complete source. Often, only those POTWs that are required to reduce nutrients are monitoring effluent nitrogen, so the database may reflect lower N effluent loadings than that typical throughout the United States. However, EPA is continuing to evaluate the utility of these data in future inventories.

The value used for N content of sludge continues to be investigated. This value is driving the N_2O emissions for wastewater treatment and is static over the time series. To date, new data have not been identified that would be able to establish a time series for this value. The amount of sludge produced and sludge disposal practices will also be investigated. In addition, based on UNFCCC review comments, the transparency of the fate of sludge produced in wastewater treatment will continue to be improved.

A review of other industrial wastewater treatment sources for those industries believed to discharge significant loads of BOD and COD has been ongoing. Food processing industries have the highest potential for CH_4 generation due to the waste characteristics generated, and the greater likelihood to treat the wastes anaerobically. However, in all cases there is dated information available on U.S. wastewater treatment operations for these industries. Previously, organic chemicals, the seafood processing industry, and coffee processing were investigated to estimate their potential to generate CH_4. Due to the insignificant amount of CH_4 estimated to be emitted and the lack of reliable, up-to-date activity data, these industries were not selected for inclusion in the Inventory. Analyses of breweries and dairy products processing facilities have been performed. While the amount of COD present in brewery wastewater is substantial, it is likely that the majority of the industry utilizes aerobic treatment or anaerobic treatment with biogas recovery. As a result, breweries will not be included in the Inventory at this time. There are currently limited data available on the wastewater characteristics and treatment of dairy processing wastewater, but EPA will continue to investigate this and other industries as necessary for inclusion in future years of the Inventory.

7.3 Composting (IPCC Source Category 5B1)

Composting of organic waste, such as food waste, garden (yard) and park waste, and wastewater treatment sludge and/or biosolids, is common in the United States. Advantages of composting include reduced volume of the waste, stabilization of the waste, and destruction of pathogens in the waste. The end products of composting, depending on its quality, can be recycled as a fertilizer and soil amendment, or be disposed of in a landfill.

Composting is an aerobic process and a large fraction of the degradable organic carbon in the waste material is converted into carbon dioxide (CO_2). Methane (CH_4) is formed in anaerobic sections of the compost, which are created when there is excessive moisture or inadequate aeration (or mixing) of the compost pile. This CH_4 is then oxidized to a large extent in the aerobic sections of the compost. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few percent of the initial C content in the material (IPCC 2006). Depending on how well the compost pile is managed, nitrous oxide (N_2O) emissions can be produced. The formation of N_2O depends on the initial nitrogen content of the material and is mostly due to nitrogen oxide (NO_x) denitrification during the later composting stages. Emissions vary and range from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006). Animal manures are typically expected to generate more N_2O than, for example, yard waste, however data are limited.

From 1990 to 2014, the amount of waste composted in the United States has increased from 3,810 kt to 20,533 kt, an increase of approximately 439 percent. The amount of material composted in the United States in the last decade has increased by approximately 11 percent. Emissions of CH_4 and N_2O from composting have increased by the same percentage. In 2014, CH_4 emissions from composting (see Table 7-17 and Table 7-18) were 2.1 MMT CO_2 Eq. (82 kt), and N_2O emissions from composting were 1.8 MMT CO_2 Eq. (6 kt). The wastes composted primarily include yard trimmings (grass, leaves, and tree and brush trimmings) and food scraps from the residential and commercial sectors (such as grocery stores; restaurants; and school, business, and factory cafeterias). The composted waste quantities reported here do not include backyard composting or agricultural composing.

The growth in composting since the 1990s and specifically over the past decade is attributable to primarily two factors: (1) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings in landfills, (2) yard trimming collection and yard trimming drop off sites provided by local solid waste management districts/divisions, and (3) an increased awareness of the environmental benefits of composting. Most bans on the disposal of yard trimmings were initiated in the early 1990s by state or local governments (U.S. Composting Council 2010). By 2010, 25 states, representing about 50 percent of the nation's population, had enacted such legislation (BioCycle 2010). An additional 16 states are known to have commercial-scale composting facilities (Shin 2014). Despite these factors, the total amount of waste composted exhibited a downward trend after peaking in 2008 (see Table 7-17 and Figure 7-5), but has been increasing since 2010 and the annual quantity composted is now on par with the 2008 quantity composted. While there is no definitive reason for the decreasing trend in the amount of waste composted, it is most likely a result of the recession and the fact that the quantities composted are estimated using a mass balance approach on the municipal waste stream across the entire United States. As presented in Figure 7-5, the quantity of CH_4 and N_2O emitted from composting operations across the time-series parallels the trends for the quantities composted, although the trend in emissions has a much lower slope compared to the quantities composted.

Table 7-17: CH_4 and N_2O Emissions from Composting (MMT CO_2 Eq.)

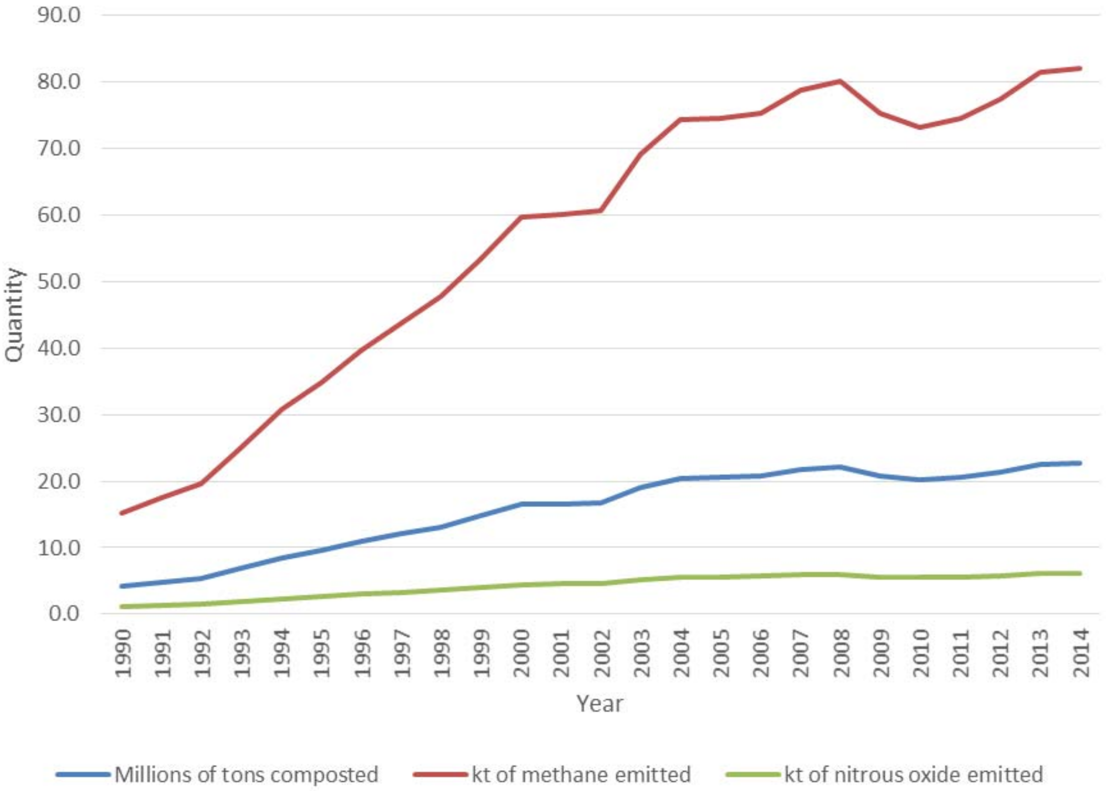
Activity	1990		2005		2010	2011	2012	2013	2014
CH_4	0.4		1.9		1.8	1.9	1.9	2.0	2.1
N_2O	0.3		1.7		1.6	1.7	1.7	1.8	1.8
Total	**0.7**		**3.5**		**3.5**	**3.5**	**3.7**	**3.9**	**3.9**

Note: Totals may not sum due to independent rounding.

Table 7-18: CH_4 and N_2O Emissions from Composting (kt)

Activity	1990		2005		2010	2011	2012	2013	2014
CH_4	15		75		73	75	77	81	82
N_2O	1		6		5	6	6	6	6

Figure 7-5: CH_4 and N_2O Emitted from Composting Operations Between 1990 and 2014 (kt)



Methodology

Methane and N_2O emissions from composting depend on factors such as the type of waste composted, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), and aeration during the composting process.

The emissions shown in Table 7-17 and Table 7-18 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006), which is the product of an emission factor and the mass of organic waste composted (note: no CH_4 recovery is expected to occur at composting operations in the emission estimates presented):

$$E_i = M \times EF_i$$

where,

E_i = CH_4 or N_2O emissions from composting, kt CH_4 or N_2O,
M = mass of organic waste composted in kt,
EF_i = emission factor for composting, 4 t CH_4/kt of waste treated (wet basis) and 0.3 t N_2O/kt of waste treated (wet basis) (IPCC 2006), and
i = designates either CH_4 or N_2O.

Estimates of the quantity of waste composted (M) are presented in Table 7-19. Estimates of the quantity composted for 1990, 2005 and 2007 through 2009 were taken from *Municipal Solid Waste in the United States: 2010 Facts and Figures* (EPA 2011); estimates of the quantity composted for 2006 were taken from EPA's *Municipal Solid Waste In The United States: 2006 Facts and Figures* (EPA 2007); estimates of the quantity composted for 2011 through 2012 were taken from EPA's *Municipal Solid Waste In The United States: 2012 Facts and Figures* (EPA 2014); estimates of the quantity composted for 2013 was taken from EPA's *Advancing Sustainable Materials Management: Facts and Figures 2013* (EPA 2015); estimates of the quantity composted for 2014 were extrapolated using the 2013 quantity composted and a ratio of the U.S. population in 2013 and 2014 (U.S. Census Bureau 2015).

Table 7-19: U.S. Waste Composted (kt)

Activity	1990		2005		2010	2011	2012	2013	2014
Waste Composted	3,810		18,643		18,298	18,661	19,351	20,358	20,533

Uncertainty and Time-Series Consistency

The estimated uncertainty from the *2006 IPCC Guidelines* is ±50 percent for the Approach 1 methodology. Emissions from composting in 2014 were estimated to be between 1.9 and 5.8 MMT CO_2 Eq., which indicates a range of 50 percent below to 50 percent above the actual 2014 emission estimate of 3.9 MMT CO_2 Eq. (see Table 7-20).

Table 7-20: Approach 1 Quantitative Uncertainty Estimates for Emissions from Composting (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Composting	CH_4, N_2O	3.9	1.9	5.8	-50%	+50%

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time-series are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. A primary focus of the QA/QC checks was to ensure that the amount of waste composted annually was correct according to the latest EPA *Advancing Sustainable Materials Management: Facts and Figures* report.

Recalculations Discussion

The estimated amount of waste composted in 2013 was updated based on new data contained in EPA's *Advancing Sustainable Materials Management: Facts and Figures 2013* report (EPA 2015). The amounts of CH_4 and N_2O emissions estimates presented in Table 7-17 and Table 7-18 were revised accordingly.

Planned Improvements

For future Inventories, additional efforts will be made to improve the estimates of CH_4 and N_2O emissions from composting. For example, a literature search on emission factors and their drivers (e.g., the type of composting system, material composition, management technique, impact of varying climatic regions) is underway. The purpose of this literature review is to compile all published emission factors to determine whether the emission factors used in the current methodology should be revised, or expanded to account for various composting system, material composition, management techniques, and/or geographical/climatic differences. For example, composting systems that primarily compost food waste may generate CH_4 at different rates than composting yard trimmings because the food waste may have a higher moisture content and more readily degradable material. Further cooperation with estimating emissions in the LULUCF Other section will also be investigated.

7.4 Waste Incineration (IPCC Source Category 5C1)

As stated earlier in this chapter, CO_2, N_2O, and CH_4 emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2014 resulted in 9.7 MMT CO_2 Eq. emissions, over half of which (4.9 MMT CO_2 Eq.) is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 3.3 of the Energy chapter.

Additional sources of emissions from waste incineration include non-hazardous industrial waste incineration and medical waste incineration. As described in Annex 5 of this report, data are not readily available for these sources and emission estimates are not provided. An analysis of the likely level of emissions was conducted based on a 2009 study of hospital/ medical/ infectious waste incinerator (HMIWI) facilities in the United States (RTI 2009). Based on that study's information of waste throughput and an analysis of the fossil-based composition of the waste, it was determined that annual greenhouse gas emissions for medical waste incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of Inventory reporting under the UNFCCC. More information on this analysis is provided in Annex 5.

7.5 Waste Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of indirect greenhouse gas emissions. Total emissions of NO_x, CO, and NMVOCs from waste sources for the years 1990 through 2014 are provided in Table 7-21.

Table 7-21: Emissions of NO_x, CO, and NMVOC from Waste (kt)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
NO_x	**+**	**2**	**1**	**1**	**1**	**1**	**1**
Landfills	+	2	1	1	1	1	1
Wastewater Treatment	+	0	0	0	0	0	0
Miscellaneous[a]	+	0	0	0	0	0	0
CO	**1**	**7**	**5**	**5**	**5**	**5**	**5**
Landfills	1	6	5	4	4	4	4
Wastewater Treatment	+	+	+	+	+	+	+
Miscellaneous[a]	+	0	0	0	0	0	0
NMVOCs	**673**	**114**	**44**	**38**	**38**	**38**	**39**
Wastewater Treatment	57	49	19	17	17	17	17
Miscellaneous[a]	557	43	17	15	15	15	15
Landfills	58	22	8	7	7	7	7

[a] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.5 kt.

Methodology

Emission estimates for 1990 through 2014 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2015), and disaggregated based on EPA (2003). Emission estimates for 2014 for non-EGU and non-mobile sources are held constant from 2011 in EPA (2015). Emission estimates of these gases were provided by sector, using a “top down” estimating procedure—emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Uncertainty and Time-Series Consistency

No quantitative estimates of uncertainty were calculated for this source category. Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

8. Other

The United States does not report any greenhouse gas emissions under the Intergovernmental Panel on Climate Change (IPCC) "Other" sector.

9. Recalculations and Improvements

Each year, emission and sink estimates are recalculated and revised for all years in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, as attempts are made to improve both the analyses themselves, through the use of better methods or data, and the overall usefulness of the report. In this effort, the United States follows the *2006 IPCC Guidelines* (IPCC 2006), which states, "Both methodological changes and refinements over time are an essential part of improving inventory quality. It is *good practice* to change or refine methods when available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; new inventory methods become available; and for correction of errors."

The results of all methodological changes and historical data updates made in the current Inventory report are presented in this section; detailed descriptions of each recalculation are contained within each source's description found in this report, if applicable. Table 9-1 summarizes the quantitative effect of these changes on U.S. greenhouse gas emissions and sinks and Table 9-2 summarizes the quantitative effect on annual net CO_2 fluxes, both relative to the previously published U.S. Inventory (i.e., the 1990 through 2013 report). These tables present the magnitude of these changes in units of million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.).

The Recalculations Discussion section of each source's description in the respective chapter of this Inventory presents the details of each recalculation. In general, when methodological changes have been implemented, the entire time series (i.e., 1990 through 2013) has been recalculated to reflect the change, per IPCC (2006). Changes in historical data are generally the result of changes in statistical data supplied by other agencies.

The following ten emission sources and sinks underwent some of the most significant methodological and historical data changes. These emission sources consider only methodological and historical data changes. A brief summary of the recalculations and/or improvements undertaken is provided for each of the ten sources.

- *Natural Gas Systems and Petroleum Systems (CH_4).* Substantial new data are available on natural gas and petroleum systems from subpart W of the EPA's greenhouse gas reporting program (GHGRP) and a number of new studies. The EPA is evaluating approaches for incorporating this new data into its emission estimates for the Inventory of U.S. GHG Emissions and Sinks: 1990-2014. The details of the revisions under consideration for this year's Inventory, and key questions for stakeholder feedback are available in segment-level memoranda at http://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html. See the Energy chapter, sections 3.7 and 3.6, for further information.

- *Landfills (CH_4).* Five major methodological recalculations were performed for the current Inventory. First, the SOG survey data previously used to estimate annual waste generation and disposal was replaced by the GHGRP and LFGTE data (EPA 2015) for the inventory time series (1990 to 2014) and years from 1983 to 1989. Second, a review of the flare and LFGTE projects across the 4 recovery databases was made. Several corrections were made to avoid double counting. Additionally, several facilities in the LFGTE database were removed because they were not in the past three LMOP databases. Third, the GHGRP CH_4 recovery data were back-calculated for landfills in EPA's GHGRP database for years prior to the first GHGRP reporting year (typically 2010 for most landfills). Fourth, the flare correction factor was revised. Fifth, the DOC value for landfilled pulp and paper waste was revised from 0.20 to 0.15 based a literature review of pulp and paper waste characterization studies (RTI 2015) and data reported under EPA's GHGRP. Overall there is a significant increase in net CH_4 emissions for the years 2010 through 2013 ranging from 20 to 52 percent higher in the current Inventory compared to the 1990 through 2013 Inventory. The drivers for this large increase are the increased quantities of annual waste disposal, which results in higher CH_4 generation, and corrections to the landfill matching across the recovery databases. These changes resulted in an average annual increase in emissions of 19.4 MMT CO_2 Eq. relative to the previous Inventory.

- *Forest Land Remaining Forest Land (CO_2 sink).* Forest ecosystem stock and stock-change estimates differ from the previous inventory report principally due to the adoption of a new accounting approach (FCAF; Woodall et al. 2015). The major differences between FCAF and past accounting approaches is the sole use of annual forest inventory data and the back casting of forest C stocks across the ~1990s based on forest C stock density and land use change information derived from the nationally consistent forest inventory (coupled with in situ observations of non-tree C pools such as soils, dead wood, and litter). The adoption of FCAF has enabled the creation of the two land use sections for forest C stocks: Forest Land Remaining Forest Land and Land Converted to Forest Land. In prior submissions (e.g., the 2015 Inventory submission), these two land use sections were combined. A second major change was the adoption of a new approach to estimating forest soil C, the largest stock in the U.S. For detailed discussion of these new approaches please refer to the Methodolgy section, Annex 3.12, Domke et al. (in preparation), and Woodall et al. 2015. In addition to these major changes, the model of Ogle et al. (in preparation) identifies some of the forest land in south central and southeastern coastal Alaska as unmanaged; this is in contrast to past assumptions of "managed" for these forest lands included in the FIADB. Therefore, the estimates for coastal Alaska as included here reflect that adjustment, which effectively reduces the forest area included here by about 5 percent.

  In addition to the creation of explicit estimates of removals and emissions by *Forest Land Remaining Forest Land* versus *Land Converted to Forest Land*, the FCAF eliminated the use of inconsistent periodic data which contributed to a data artefact in prior estimates of emissions/removals from 1990 to the present. In the 2015 submission, there was a reduction in net sequestration from 1995 to 2000 followed by an increase in net sequestration from 2000 to 2004. This artefact of comparing inconsistent inventories of the 1980s-1990s to the nationally consistent inventories of the 2000s has been removed in this 2016 submission. This has resulted in a fairly consistent estimated annual net sequestration of ~160 MMT C. Overall, there were net C additions to HWP in use and in landfills combined due, in large part, to updated data on Products in Use from 2010-present. All these changes resulted in an average annual decrease in sequestration of 144.7 MMT CO_2 Eq. relative to the previous Inventory.

- *Agricultural Soil Management (N_2O).* Methodological recalculations in the current Inventory are associated with the following improvements: 1) driving the DAYCENT simulations with updated input data for land management from the National Resources Inventory extending the time series through 2010; 2) accounting for N inputs from residues associated with additional crops not simulated by DAYCENT including most vegetable crops; 3) modifying the number of experimental study sites used to quantify model uncertainty for direct N_2O emissions; and 4) using DAYCENT for direct N_2O emissions from most flooded rice lands, instead of using the Tier 1 approach for all rice lands. These changes resulted in an increase in emissions of approximately 24 percent on average relative to the previous Inventory and a decrease in the upper bound of the 95 percent confidence interval for direct N_2O emissions from 26 to 24 percent. The differences are mainly due to increasing the number of study sites used to quantify model uncertainty and correct bias. These changes resulted in an average annual increase in emissions of 59.8 MMT CO_2 Eq. relative to the previous Inventory.

- *Cropland Remaining Cropland (CO_2 sink).* Methodological recalculations in the current Inventory are associated with the following improvements: 1) incorporation of updated NRI data for 1990 through 2010; 2) inclusion of federal croplands; and 3) improving the simulation of hydric soil. These changes in SOC stocks resulted in an average annual increase in sequestration of 8.4 MMT CO_2 Eq. relative to the previous Inventory.

- *Land Converted to Cropland (CO_2 sink).* Methodological recalculations in the current Inventory are associated with the following improvements: 1) incorporation of updated NRI data for 1990 through 2010; 2) inclusion of federal croplands; and 3) improving the simulation of hydric soils in DAYCENT. These changes in SOC stocks resulted in an average annual decrease in emissions of 4.3 MMT CO_2 Eq. relative to the previous Inventory.

- *Grassland Remaining Grassland (CO_2 sink).* Methodological recalculations in the current Inventory are associated with the following improvements, including 1) incorporation of updated NRI data for 1990 through 2010; 2) inclusion of federal grasslands in the Tier 2 analysis; and 3) improving the simulation of hydric soils in

DAYCENT. These changes in SOC stocks resulted in an average annual decrease in emissions of 4.3 MMT CO_2 Eq. relative to the previous Inventory.

- *Land Converted to Grassland (CO_2 sink).* Methodological recalculations in the current Inventory are associated with the following improvements, including 1) incorporation of updated NRI data for 1990-2010; 2) inclusion of federal grasslands in the Tier 2 analysis; and 3) improving the simulation of hydric soils in DAYCENT. As a result of these improvements to the Inventory, changes in SOC stocks increased by an average of 0.2 MMT CO_2 eq. annually over the time series. These changes resulted in an average annual increase in sequestration of 3.4 MMT CO_2 Eq. relative to the previous Inventory.

- *Substitution of Ozone Depleting Substances (HFCs).* For the current Inventory, a review of the large retail food end-use resulted in revisions to the Vintaging Model since the previous Inventory. In addition, a vending machine end-use was added to the Vintaging Model since the previous Inventory. Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. For the large retail food end-use, assumptions regarding new installations by system type and refrigerant transitions were revised based on a review of data collected by EPA's GreenChill Partnership and the California Air Resources Board's Refrigerant Management Program. The vending machine end-use was added based on a review of technical reports and sales data. Combined, these assumption changes and additions decreased GHG emissions on average by 3 percent between 1990 and 2002 and increased GHG emissions on average by 4 percent between 2003 and 2014. These changes resulted in an average annual increase in emissions of 2.1 MMT CO_2 Eq. relative to the previous Inventory.

- *Forest Fires (CH_4).* The current non-CO_2 emissions estimates are based on the calculation described in *Forest Land Remaining Forest Land* (see Section 6.2) and in IPCC (2006), which is a very similar form to the basic calculation of previous Inventory reports (i.e., this report, last year and previous). However, some of the data summarized and applied to the calculation are now very different. The use of the MTBS data summaries is the most prominent example (see Planned Improvements discussion in previous Inventories). Annual burned areas on managed forest lands were identified according to Ruefenacht et al. (2008) and Ogle et al. (in preparation). The other change with this year’s estimates is in the use of the underlying plot level carbon densities based on forest inventory plots. Although the base data are similar to past years, the current uncertainty estimates are based on an assumption that plot-to-plot variability is a greater influence on uncertainty than the uncertainty in the forest-inventory to carbon conversions factors (as employed for uncertainty in the past). See Annex 3.13 for additional details. These changes resulted in an average annual decrease in emissions of 1.5 MMT CO_2 Eq. relative to the previous Inventory.

Table 9-1: Revisions to U.S. Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	Average Annual Change
CO_2	**0.3**	**(1.4)**	**(6.3)**	**(0.3)**	**2.7**	**8.1**	**(0.6)**
Fossil Fuel Combustion	+	(0.5)	(8.9)	(3.7)	(1.3)	(0.1)	(1.1)
Electricity Generation	*NC*	*NC*	*NC*	*NC*	*NC*	*(1.6)*	*(0.1)*
Transportation	*NC*	*(0.8)*	*(3.7)*	*(3.9)*	*(4.0)*	*(5.4)*	*(1.5)*
Industrial	+	*0.2*	*(0.1)*	*(0.8)*	*(1.3)*	*(5.0)*	*(0.2)*
Residential	*NC*	+	*(0.1)*	*(0.4)*	*(0.6)*	*0.1*	+
Commercial	*NC*	+	*(0.1)*	*(0.3)*	*(0.4)*	*0.3*	+
U.S. Territories	*NC*	*NC*	*(4.8)*	*1.7*	*5.0*	*11.6*	*0.6*
Non-Energy Use of Fuels	0.5	+	(0.5)	0.2	0.7	1.8	0.1
Natural Gas Systems[a]	-	-	-	-	-	-	-
Cement Production	NC	NC	NC	NC	NC	+	+
Lime Production	+	+	+	+	+	+	+
Other Process Uses of Carbonates	NC	NC	NC	NC	NC	6.0	0.2
Glass Production	NC	NC	NC	NC	NC	0.2	+
Soda Ash Production and Consumption	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Carbon Dioxide Consumption	NC	NC	3.2	3.3	3.2	3.3	0.5
Incineration of Waste	NC	NC	NC	NC	+	(0.7)	+
Titanium Dioxide Production	NC	NC	NC	NC	NC	0.1	+
Aluminum Production	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Ammonia Production	NC	NC	NC	NC	NC	(0.2)	+
Urea Consumption for Non-Agricultural Purposes	NC	NC	NC	NC	NC	(0.5)	+
Phosphoric Acid Production	(0.1)	(0.1)	+	+	+	(0.1)	(0.1)
Petrochemical Production	+	(0.7)	(0.1)	(0.1)	+	(0.1)	(0.2)
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	+	+
Lead Production	NC	NC	NC	NC	NC	+	+
Zinc Production	NC	NC	NC	NC	NC	NC	NC
Liming	NC	NC	NC	+	0.2	(2.0)	(0.1)
Peatlands Remaining Peatlands	NC	NC	NC	NC	NC	NC	NC
Petroleum Systems[b]	-	-	-	-	-	-	-
Magnesium Production and Processing	NC	NC	NC	NC	NC	NC	NC
Urea Fertilization	NC	NC	NC	NC	NC	0.3	+
LULUCF Total Net Flux[c]	*71.6*	*275.8*	*188.5*	*197.4*	*199.6*	*199.4*	*NC*
Biomass – Wood[c]	*NC*	*NC*	*NC*	*NC*	*NC*	*3.0*	*0.1*
International Bunker Fuels[c]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
Biomass – Ethanol[c]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
CH_4	**(0.2)**	**27.5**	**53.6**	**50.8**	**56.2**	**67.7**	**19.4**
Stationary Combustion	+	+	+	+	+	+	+
Mobile Combustion	+	(0.3)	+	+	+	+	(0.1)
Coal Mining	NC	NC	NC	NC	NC	NC	NC
Abandoned Underground Coal Mines	NC	NC	NC	NC	NC	NC	NC
Natural Gas Systems[a]	-	-	-	-	-	-	-
Petroleum Systems[b]	-	-	-	-	-	-	-
Petrochemical Production	+	(0.1)	+	+	+	+	+
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	(1.1)	(0.8)	(0.6)	(0.7)	(0.7)	(0.7)	(0.9)
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Enteric Fermentation	NC	NC	0.2	0.2	0.4	0.9	0.1

Manure Management	NC	NC	+	0.1	+	+	+
Rice Cultivation	2.1	5.2	1.1	3.7	2.9	3.9	2.5
Field Burning of Agricultural Residues	(0.1)	+	+	+	+	+	+
Forest Fires	0.8	1.6	(1.5)	(8.0)	(4.6)	1.5	(1.5)
Peatlands Remaining Peatlands	NC	NC	NC	NC	NC	NC	NC
Landfills	(1.9)	21.8	54.5	55.6	58.3	62.0	19.4
Wastewater Treatment	NC	NC	NC	NC	NC	NC	NC
Composting	NC	NC	NC	NC	NC	0.1	+
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
International Bunker Fuels[c]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
N_2O	**79.6**	**50.5**	**55.2**	**51.9**	**53.8**	**55.8**	**57.5**
Stationary Combustion	+	+	+	+	+	+	+
Mobile Combustion	+	(3.7)	(0.1)	(0.1)	(0.2)	(0.2)	(1.4)
Adipic Acid Production	NC	NC	NC	NC	NC	NC	NC
Nitric Acid Production	+	+	+	+	+	NC	+
Manure Management	0.2	0.1	0.1	0.1	0.2	0.2	0.1
Agricultural Soil Management	78.9	53.1	56.1	57.1	56.9	54.7	59.8
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Wastewater Treatment	NC	NC	NC	NC	NC	NC	NC
N_2O from Product Uses	NC	NC	NC	NC	NC	NC	NC
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
Settlement Soils	NC	+	+	+	+	+	+
Forest Fires	0.5	1.1	(1.0)	(5.2)	(3.1)	1.0	(1.0)
Forest Soils	NC	NC	NC	NC	NC	NC	NC
Composting	NC	NC	NC	NC	NC	0.1	+
Peatlands Remaining Peatlands	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC	NC
International Bunker Fuels[c]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
HFCs	**NC**	**1.9**	**9.1**	**8.7**	**7.8**	**6.6**	**2.1**
Substitution of Ozone Depleting Substances	NC	1.9	9.1	8.7	7.8	6.6	2.1
HCFC-22 Production	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC	NC
Magnesium Production and Processing	NC	NC	NC	NC	NC	NC	NC
PFCs	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**
Aluminum Production	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC	NC
SF_6	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**
Electrical Transmission and Distribution	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC	NC
Magnesium Production and Processing	NC	NC	NC	NC	NC	NC	NC
NF_3	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC	NC
Net Change in Total Emissions[d]	**71.6**	**275.8**	**188.5**	**197.4**	**199.6**	**199.4**	
Percent Change	**9.2%**	**30.2%**	**21.6%**	**22.4%**	**22.7%**	**22.6%**	

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

NC (No Change)

+ Absolute value does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent

[a] The values presented in this table for Natural Gas Systems are from the previous Inventory and do not reflect updates to emission estimates for this category. Please see the Energy Chapter, Section 3.7, Natural Gas Systems.

[b] The values presented in this table for Petroleum Systems are from the previous Inventory and do not reflect updates to the emission estimates for this category. Please see the Energy Chapter, Section 3.6, Petroleum Systems.

[c] Not included in emissions total.

[d] Excludes net CO_2 flux from Land Use, Land-Use Change, and Forestry, and emissions from International Bunker Fuels.

Table 9-2: Revisions to Total Net Flux from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Component: Total Net Flux from Land Use, Land-Use Change, and Forestry[a]	**1990**	**2005**	**2010**	**2011**	**2012**	**2013**	**Average Annual Change**
Forest Land Remaining Forest Land	63.4	274.7	180.4	195.8	196.4	195.6	144.7
Land Converted to Forest Land	NC*	NC*	NC*	NC*	NC*	NC*	NC*
Cropland Remaining Cropland	22.0	11.5	21.2	5.7	6.3	6.6	8.4
Land Converted to Cropland	(1.7)	(5.2)	(0.6)	(2.0)	(1.6)	(1.4)	(4.3)
Grassland Remaining Grassland	(11.0)	(1.3)	(9.1)	(0.4)	0.2	(0.2)	(4.3)
Land Converted to Grassland	(1.1)	(3.8)	(3.5)	(2.1)	(2.1)	(2.2)	(3.4)
Settlements Remaining Settlements	NC	NC	NC	NC	NC	NC	NC
Other (Landfilled Yard Trimmings and Food Scraps)	NC	NC	+	0.5	0.5	0.9	0.1
Net Change in LULUCF Total Net Flux[a]	**71.6**	**275.8**	**188.5**	**197.4**	**199.6**	**199.4**	
Percent Change	**9.2%**	**30.2%**	**21.6%**	**22.4%**	**22.7%**	**22.6%**	

NC (No Change)

Note: Numbers in parentheses indicate an increase in C sequestration.

\+ Absolute value does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent

* Indicates a new source for the current Inventory year

[a] Total net flux from LULUCF includes the positive C sequestration reported for *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Other Land* plus the loss in C sequestration reported for *Land Converted to Cropland* and *Grassland Remaining Grassland*.

Note: Totals may not sum due to independent rounding.

10. References

Executive Summary

BEA (2015) *2014 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2014*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. Available online at <http://www.bea.gov/national/index.htm#gdp>.

Carbon Dioxide Information Analysis Center (CDIAC) (2014) Recent Greenhouse Gas Concentrations. February 2014. Available online at: <http://cdiac.ornl.gov/pns/current_ghg>.

EIA (2015a) *Electricity Generation*. *Monthly Energy Review, December 2015*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

EIA (2015b) *Electricity in the United States*. *Electricity Explained*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at <http://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states>.

EIA (2013) *International Energy Statistics 2013*. Energy Information Administration (EIA), U.S. Department of Energy. Washington, D.C. Available online at <http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm>. 30 November 2014.

EPA (2015a) *1970 - 2014 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 March 2015. Available online at <http://www.epa.gov/ttn/chief/trends/index.html>.

EPA (2015b) Advancing Sustainable Materials Management: Facts and Figures 2013. June 2015. Available online at <http://www.epa.gov/sites/production/files/2015-09/documents/2013_advncng_smm_rpt.pdf>.

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 (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 (2001) *Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change*. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.). Cambridge University Press. Cambridge, United Kingdom.

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.

NOAA/ESRL (2016) *Trends in Atmospheric Carbon Dioxide*. Available online at <http://www.esrl.noaa.gov/gmd/ccgg/trends/>. 5 February 2016.

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>.

U.S. Census Bureau (2015) U.S. Census Bureau International Database (IDB). Available online at <http://www.census.gov/ipc/www/idbnew.html>.

Introduction

CDIAC (2014) Recent Greenhouse Gas Concentrations. T.J. Blasing; DOI: 10.3334/CDIAC/atg.032. Available online at <http://cdiac.ornl.gov/pns/current_ghg.html>. 11 November 2014.

EPA (2009) Technical Support Document for the Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act. U.S. Environmental Protection Agency. December 2009.

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 (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 (2001) *Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change*. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.). Cambridge University Press. Cambridge, United Kingdom.

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

IPCC/TEAP (2005) *Special Report: Safeguarding the Ozone Layer and the Global Climate System, Chapter 4: Refrigeration*. 2005. Available online <http://www.auto-ts.com/hcfc/technology%20option/Refrigeration/transport%20refrigeration.pdf>.

Jacobson, M.Z. (2001) “Strong Radiative Heating Due to the Mixing State of Black Carbon in Atmospheric Aerosols.” Nature, 409:695-697.

NOAA (2014) Vital Signs of the Planet. Available online at <http://climate.nasa.gov/causes/>. 12 December 2014.

NOAA/ESRL (2015) Trends in Atmospheric Carbon Dioxide. Available online at <http://www.esrl.noaa.gov/gmd/ccgg/trends/>. 6 February 2015.

UNEP/WMO (1999) Information Unit on Climate Change. Framework Convention on Climate Change. Available online at <http://unfccc.int>.

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

Trends in Greenhouse Gas Emissions

BEA (2015) *2014 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2014*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. Available online at <http://www.bea.gov/national/index.htm#gdp>.

Duffield, J. (2006) Personal communication. Jim Duffield, Office of Energy Policy and New Uses, USDA and Lauren Flinn, ICF International. December 2006.

EIA (2015) *Monthly Energy Review, December 2015.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

EPA (2015a) Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 - 2014. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at < http://www.epa.gov/otaq/fetrends-complete.htm >.

EPA (2015b) “1970 - 2014 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, March 2015. Available online at <http://www.epa.gov/ttn/chief/trends/index.html>.

FRB (2015) Industrial Production and Capacity Utilization. Federal Reserve Statistical Release, G.17, Federal Reserve Board. Available online at <http://www.federalreserve.gov/releases/G17/table1_2.htm>. July 21, 2015.

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 (2001) *Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change*. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.). Cambridge University Press. Cambridge, United Kingdom.

U.S. Census Bureau (2015) U.S. Census Bureau International Database (IDB). Available online at <http://www.census.gov/ipc/www/idbnew.html>.

Energy

EIA (2013) Indicators: CO_2 Emissions. *International Energy Statistics 2013*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available at <http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm>.

Carbon Dioxide Emissions from Fossil Fuel Combustion

AAR (2008 through 2015) *Railroad Facts.* Policy and Economics Department, Association of American Railroads, Washington, D.C. Obtained from Clyde Crimmel at AAR.

AISI (2004 through 2013) *Annual Statistical Report*, American Iron and Steel Institute, Washington, D.C.

APTA (2007 through 2015) *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 (2015) *Table 1.1.6. Real Gross Domestic Product, Chained 2009 Dollars*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. December, 2015. 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.

Coffeyville Resources Nitrogen Fertilizers (2014) Nitrogen Fertilizer Operations. Available online at <http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>.

Dakota Gasification Company (2006) *CO_2 Pipeline Route and Designation Information*. Bismarck, ND. Available online at <http://www.dakotagas.com/SafetyHealth/Pipeline_Information.html>.

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

DLA Energy (2015) Unpublished data from the Fuels Automated System (FAS). Defense Logistics Agency Energy, U.S. Department of Defense. Washington, D.C.

DOC (1991 through 2015) 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 2015) *Transportation Energy Data Book*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. ORNL-6978.

DOE (2012) *2010 Worldwide Gasification Database*. National Energy Technology Laboratory and Gasification Technologies Council. Available online at <http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html>. Accessed on 15 March 2012.

DOT (1991 through 2015) Airline *Fuel Cost and Consumption*. U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, D.C. DAI-10. http://www.transtats.bts.gov/fuel.asp.

Eastman Gasification Services Company (2011) Project Data on Eastman Chemical Company's Chemicals-from-Coal Complex in Kingsport, TN. Available online at <http://www.netl.doe.gov/coal/gasification/pubs/pdf/Eastman%20Chemicals%20from%20Coal%20Complex.pdf>.

EIA (2015a) *Monthly Energy Review, December 2015*, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2015/12).

EIA (2015b) *Natural Gas Annual 2014.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0131(06).

EIA (2015c) *Quarterly Coal Report: January – March 2015*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0121.

EIA (2015d) *U.S. Energy-Related Carbon Dioxide Emissions, 2013.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. October 2014. Available online at <http://www.eia.gov/environment/emissions/carbon/>.

EIA (1991 through 2015) *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/>.

EIA (2014) Indicators: CO_2 Emissions. *International Energy Statistics 2014*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available at: <http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm>.

EIA (2013) *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 (2009a) *Emissions of Greenhouse Gases in the United States 2008, Draft Report.* Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE-EIA-0573(2009).

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

EIA (2008) *Historical Natural Gas Annual, 1930 – 2008*. Energy Information Administration, U.S. Department of Energy. Washington, D.C.

EIA (2007) Personal Communication. Joel Lou, Energy Information Administration. and Aaron Beaudette, ICF International. *Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island*. October 24, 2007.

EIA (2001) *U.S. Coal, Domestic and International Issues*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. March 2001.

EPA (2015a) Acid Rain Program Dataset 1996-2014. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2015a) Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 - 2015. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at < http://www.epa.gov/otaq/fetrends-complete.htm >.

EPA (2015b*). Motor Vehicle Emissions Simulator (Moves) 2014*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at < http://www.epa.gov/otaq/models/moves/index.htm>.

EPA (2010a) 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.

Erickson, T. (2003) *Plains* CO_2 *Reduction (PCOR) Partnership*. Presented at the Regional Carbon Sequestration Partnership Meeting Pittsburgh, Pennsylvania, Energy and Environmental Research Center, University of North Dakota. November 3, 2003. Available online at <http://www.netl.doe.gov/publications/proceedings/03/carbon-seq/Erickson.pdf>.

FAA (2016) Personal Communication between FAA and Leif Hockstad for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). February 2016.

FHWA (1996 through 2015) *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>.

Fitzpatrick, E. (2002) *The Weyburn Project: A Model for International Collaboration*. Available online at <http://www.netl.doe.gov/coalpower/sequestration/pubs/mediarelease/mr-101102.pdf>.

FRB (2015) *Industrial Production and Capacity Utilization*. Federal Reserve Statistical Release, G.17, Federal Reserve Board. Available online at <http://www.federalreserve.gov/releases/G17/table1_2.htm>. March 28, 2014.

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

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, 1990–2013.* Unpublished. U.S. Energy Information Administration. Washington, D.C.

Marland, G. and A. Pippin (1990) "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity." *Energy Systems and Policy,* 14(4):323.

SAIC/EIA (2001) *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emission Estimates*. *Final Report*. Prepared by Science Applications International Corporation (SAIC) for Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. June 22, 2001.

U.S. Census Bureau (2011) *Current Industrial Reports Fertilizer Materials and Related Products: 2010 Summary.* Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

USAA (2014) *U.S. Primary Aluminum Production 2013.* U.S. Aluminum Association, Washington, D.C. January, 2014.

USAF (1998) Fuel Logistics Planning. U.S. Air Force: AFPAM23-221. May 1, 1998.

United States Geological Survey (USGS) (1994 through 2011) *Minerals Yearbook: Lead Annual Report.* U.S. Geological Survey, Reston, VA.

USGS (1991 through 2011) *Minerals Yearbook: Manufactured Abrasives Annual Report.* U.S. Geological Survey, Reston, VA.

USGS (2011) *2010 Mineral Yearbook; Aluminum [Advanced Release]*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2010a) *Minerals Yearbook: Silicon Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2010b) *Mineral Yearbook: Titanium Annual Report.* U.S. Geological Survey, Reston, VA.

USGS (2010) *2009 Mineral Commodity Summaries: Aluminum*. U.S. Geological Survey, Reston, VA.

USGS (2009) *2008 Mineral Yearbook: Aluminum*. U.S. Geological Survey, Reston, VA.

USGS (2007) *2006 Mineral Yearbook: Aluminum*. U.S. Geological Survey, Reston, VA.

USGS (1995, 1998, 2000 through 2002) *Mineral Yearbook: Aluminum Annual Report.* U.S. Geological Survey, Reston, VA.

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

Stationary Combustion (excluding CO_2)

EIA (2015a) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, December 2015,* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

EIA (2015b) Electricity in the United States. *Electricity Explained.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at <http://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states>.

EPA (2015) "1970 - 2014 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 <http://www.epa.gov/ttn/chief/trends/index.html>.

EPA (2003) E-mail correspondance. 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 (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, 1990–2009.* Unpublished. U.S. Energy Information Administration. Washington, D.C.

SAIC/EIA (2001) *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emission Estimates*. *Final Report*. Prepared by Science Applications International Corporation (SAIC) for Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. June 22, 2001.

Mobile Combustion (excluding CO_2)

AAR (2008 through 2015) *Railroad Facts.* Policy and Economics Department, Association of American Railroads, Washington, D.C. Obtained from Clyde Crimmel at AAR.

ANL (2006) Argonne National Laboratory (2006) GREET model Version 1.7. June 2006.

ANL (2015) *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET_1_2015)*. Argonne National Laboratory. October 2015. Available at <https://greet.es.anl.gov>.

APTA (2007 through 2015) *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>.

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

BEA (1991 through 2015) Unpublished BE-36 survey data. Bureau of Economic Analysis, U.S. Department of Commerce. Washington, D.C.

Browning, L. (2015) “Methodology for Highway Vehicle Alternative Fuel GHG Estimates”. Technical Memo, December 2015.

Browning, L. (2009) Personal communication with Lou Browning, “Suggested New Emission Factors for Marine Vessels.”, ICF International.

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

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

DLA Energy (2015) 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 2015) 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 2015) *Transportation Energy Data Book*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. ORNL-6978.

DOT (1991 through 2015) 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.>.

EDTA (2015) *Electric Drive Sales Dashboard*. Electric Drive Transportation Association, Washington, D.C. Available at: <http://electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952>.

EIA (2015). *Monthly Energy Review, December 2015,* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

EIA (1991 through 2015) *Fuel Oil and Kerosene Sales.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available at: http://www.eia.gov/petroleum/fueloilkerosene/

EIA (2007 through 2015) *Natural Gas Annual*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0131(11).

EIA (2011) *Annual Energy Review 2010*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0384(2011). October 19, 2011.

EIA (2015a) "Table 3.1: World Petroleum Supply and Disposition." *International Energy Annual.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at <https://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=5&pid=66&aid=13 >.

EIA (2007) Personal Communication. Joel Lou, Energy Information Administration and Aaron Beaudette, ICF International. *Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island*. October 24, 2007.

EIA (2002) *Alternative Fuels Data Tables*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at <http://www.eia.doe.gov/fuelrenewable.html>.

EPA (2015b*). Motor Vehicle Emissions Simulator (Moves) 2014*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at <http://www.epa.gov/otaq/models/moves/index.htm>.

EPA (2015c) Annual Certification Test Results Report. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at <http://www.epa.gov/otaq/crttst.htm>.

EPA (2015d) Confidential Engine Family Sales Data Submitted To EPA By Manufacturers. Office of Transportation and Air Quality, U.S. Environmental Protection Agency.

EPA (2015) "1970 - 2014 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 <http://www.epa.gov/ttn/chief/trends/index.html>.

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

EPA (1999a) *Emission Facts: The History of Reducing Tailpipe Emissions.* Office of Mobile Sources. May 1999. EPA 420-F-99-017. Available online at <http://www.epa.gov/oms/consumer/f99017.pdf>.

EPA (1999b) Regulatory Announcement: EPA's Program for Cleaner Vehicles and Cleaner Gasoline. Office of Mobile Sources. December 1999. EPA420-F-99-051. Available online at <http://www.epa.gov/otaq/regs/ld-hwy/tier-2/frm/f99051.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.

EPA (1997) *Mobile Source Emission Factor Model (MOBILE5a)*. Office of Mobile Sources, U.S. Environmental Protection Agency, Ann Arbor, Michigan.

EPA (1994a) *Automobile Emissions: An Overview.* Office of Mobile Sources. August 1994. EPA 400-F-92-007. Available online at <http://www.epa.gov/otaq/consumer/05-autos.pdf>.

EPA (1994b) *Milestones in Auto Emissions Control.* Office of Mobile Sources. August 1994. EPA 400-F-92-014. Available online at <http://www.epa.gov/otaq/consumer/12-miles.pdf>.

EPA (1993) *Automobiles and Carbon Monoxide.* Office of Mobile Sources. January 1993. EPA 400-F-92-005. Available online at <http://www.epa.gov/otaq/consumer/03-co.pdf>.

Esser, C. (2003 through 2004) Personal Communication with Charles Esser, Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island.

FAA (2016) Personal Communication between FAA and Leif Hockstad for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). February 2016.

FHWA (1996 through 2015) *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>.

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

ICF (2006a) *Revised Gasoline Vehicle EFs for LEV and Tier 2 Emission Levels.* Memorandum from ICF International to John Davies, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2006.

ICF (2006b) *Revisions to Alternative Fuel Vehicle (AFV) Emission Factors for the U.S. Greenhouse Gas Inventory.* Memorandum from ICF International to John Davies, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2006.

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

Lipman, T. and M. Delucchi (2002) "Emissions of Nitrous Oxide and Methane from Conventional and Alternative Fuel Motor Vehicles." *Climate Change,* 53:477-516.

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.

U.S. Census Bureau (2000) *Vehicle Inventory and Use Survey*. U.S. Census Bureau, Washington, D.C. Database CD-EC97-VIUS.

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

Carbon Emitted from Non-Energy Uses of Fossil Fuels

ACC (2015) "PIPS Year-End Resin Statistics for 2014 vs. 2013: Production, Sales and Captive Use." Available online at <http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf>.

ACC (2014a) "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 (2014b) "*Guide to the Business of Chemistry, 2014*," American Chemistry Council.

ACC (2012) "*Guide to the Business of Chemistry, 2012*," American Chemistry Council.

ACC (2003-2011) "PIPS Year-End Resin Statistics for 2010: Production, Sales and Captive Use." Available online at <http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf>.

Bank of Canada (2014) Financial Markets Department Year Average of Exchange Rates. Available online at <http://www.bankofcanada.ca/stats/assets/pdf/nraa-2013.pdf>.

Bank of Canada (2013) Financial Markets Department Year Average of Exchange Rates. Available online at <http://www.bankofcanada.ca/stats/assets/pdf/nraa-2012.pdf>.

Bank of Canada (2012) Financial Markets Department Year Average of Exchange Rates. Available online at <http://www.bankofcanada.ca/stats/assets/pdf/nraa-2011.pdf>.

EIA (2015a) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, December 2015.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

EIA (2015b) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, December 2015.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

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

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.

EPA (2015a) "1970 - 2014 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, March 2015. Available online at <http://www.epa.gov/ttn/chief/trends/index.html>.

EPA (2015b). *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2-Onsite Management) and WR Form.

EPA (2014a) Municipal Solid Waste in the United States: 2012 Facts and Figures. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at <http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm>.

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

EPA (2013a) Municipal Solid Waste in the United States: 2011 Facts and Figures. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at <http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm>.

EPA (2013b). *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2-Onsite Management) and WR Form.

EPA (2011) EPA's Pesticides Industry Sales and Usage, 2006 and 2007 Market Estimates. Available online at <http://www.epa.gov/oppbead1/pestsales/. Accessed January 2012>.

EPA (2009) Biennial Reporting System (BRS) Database. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, D.C. Available online at <http://www.epa.gov/enviro/html/brs/>. Data for 2001-2007 are current as of Sept. 9, 2009.

EPA (2004) EPA's Pesticides Industry Sales and Usage, 2000 and 2001 Market Estimates. Available online at <http://www.epa.gov/oppbead1/pestsales/. Accessed September 2006>.

EPA (2002) EPA's Pesticides Industry Sales and Usage, 1998 and 1999 Market Estimates, table 3.6. Available online at <http://www.epa.gov/oppbead1/pestsales/99pestsales/market_estimates1999.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 <http://www.epa.gov/enviro/html/brs/>.

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. Available online at <http://www.epa.gov/oppbead1/pestsales/97pestsales/market_estimates1997.pdf>.

EPA (1998) EPA's Pesticides Industry Sales and Usage, 1994-1995 Market Estimates. Available online at <http://www.epa.gov/oppbead1/pestsales/95pestsales/market_estimates1995.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.

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, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

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. Available online at <http://www.npra.org/members/publications/papers/lubes/LW-02-126.pdf>.

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.

U.S. Bureau of the Census (2015) U.S International Trade Commission (USITC) Trade Dataweb. Available online at: < http://dataweb.usitc.gov>.

U.S. Census Bureau (2014) 2012 Economic Census. Available online at: <http://www.census.gov/econ/census/schedule/whats_been_released.html>. Accessed November 2014.

U.S. Census Bureau (2009) *Soap and Other Detergent Manufacturing: 2007*. Available online at <http://smpbff1.dsd.census.gov/TheDataWeb_HotReport/servlet/HotReportEngineServlet?emailname=vh@boc&filename=mfg1.hrml&20071204152004.Var.NAICS2002=325611&forward=20071204152004.Var.NAICS2002>.

U.S. Census Bureau (2004) *Soap and Other Detergent Manufacturing: 2002*, Issued December 2004, EC02-31I-325611 (RV). Available online at <http://www.census.gov/prod/ec02/ec0231i325611.pdf>.

U.S. Census Bureau (1999) *Soap and Other Detergent Manufacturing: 1997*, Available online at <http://www.census.gov/epcd/www/ec97stat.htm>.

U.S. International Trade Commission (1990-2015) “Interactive Tariff and Trade DataWeb: Quick Query.” Available online at <http://dataweb.usitc.gov/>. Accessed December 2015.

Incineration of Waste

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.

Berenyi, E. B. (2014) “A Compatibility Study: Recycling and Waste-to-Energy Work in Concert”. Governmental Advisory Associates, Inc. Available online at http://www.energyrecoverycouncil.org/userfiles/files/2014-Berenyi-recycling-study.pdf

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.

Energy Recovery Council (2009) “2007 Directory of Waste-to-Energy Plants in the United States.” Accessed September 29, 2009.

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 http://www3.epa.gov/epawaste/nonhaz/municipal/pubs/2013_advncng_smm_rpt.pdf.

EPA (2007, 2008, 2011, 2013, 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 <http://www.epa.gov/osw/nonhaz/municipal/msw99.htm>.

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.

Goldstein, N. and C. Madtes (2001) “13th Annual BioCycle Nationwide Survey: The State of Garbage in America.” BioCycles, 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 (2014) “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>.

RMA (2012a) "Rubber FAQs." Rubber Manufacturers Association. Available online at <http://www.rma.org/about-rma/rubber-faqs/>. Accessed 19 November 2014.

RMA (2012b) “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 18 January 2012.

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>.

RTI (2009) Updated Hospital/Medical/Infectious Waste Incinerator (HMIWI) Inventory Database. Memo dated July 6, 2009. Available online at: <http://www.epa.gov/ttnatw01/129/hmiwi/hmiwi_inventory.pdf>.

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.

Shin and Themelis. (2014) “U.S. Survey of Generation and Disposition of Municipal Solid Waste”. January 2016. Available online at: <http://www.americanchemistry.com/Policy/Energy/Energy-Recovery/2014-Update-of-Potential-for-Energy-Recovery-from-Municipal-Solid-Waste-and-Non-Recycled-Plastics.pdf>

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.

van Haaren, Rob, Themelis, N., and Goldstein, N. (2010) "The State of Garbage in America." BioCycle, October 2010. Volume 51, Number 10, pg. 16-23.

Coal Mining (TO BE UPDATED)

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

CAR (2014) *Project Database.* Climate Action Reserve. Available at <http://www.climateactionreserve.org/>.

Consol (2014) Ruby Canyon Summary 2013. *CONSOL Energy Inc. excel spreadsheet*

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

EIA (2014) *Annual Coal Report 1991-2013 (*Formerly called *Coal Industry Annual).* Table 1. Energy Information Administration, U.S. Department of Energy, Washington, D.C.

EPA (2014) *Greenhouse Gas Reporting Program (GHGRP): Underground Coal Mines.* Retrieved from http://www.epa.gov/ghgreporting/ghgdata/reported/coalmines.html

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

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.

GSA (2014) *Well Records Database.* Geological Survey of Alabama State Oil and Gas Board. Retrieved from <http://www.gsa.state.al.us/ogb/database.aspx>.

IEA (2014) *Key World Energy Statistics.* Coal Production, International Energy Agency.

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., Pub. IGES, Japan 2011.

JWR (2014) Wells Intercepted 2013. *Jim Walter Resources excel spreadsheet*.

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

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

MSHA (2014) *Data Transparency at MSHA.* Mine Safety and Health Administration. Retrieved from <http://www.msha.gov>.

Mutmansky, Jan M. and Yanbei Wang (2000) “Analysis of Potential Errors in Determination of Coal Mine Annual Methane Emissions.” *Mineral Resources Engineering,* 9(4). December 2000.

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) (2014) *Oil & Gas Production Data*. Retrieved from <http://www.wvgs.wvnet.edu/www/datastat/datastat.htm>.

Abandoned Underground Coal Mines (TO BE UPDATED)

EPA (2004) *Methane Emissions Estimates & Methodology for Abandoned Coal Mines in the U.S.* Draft Final Report. Washington, D.C. April 2004.

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.

U.S. Department of Labor, Mine Health & Safety Administration (2014) *Data Retrieval System*. Available online at <http://www.msha.gov/drs/drshome.htm>.

Petroleum Systems (TO BE UPDATED)

Allen et al. (2014) Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers. ES&T. December 9, 2014. Available online at: <http://pubs.acs.org/doi/pdf/10.1021/es5040156>.

API (2009) Compendium of Greenhouse gas Emissions Methodologies for the Oil and Gas Industry. American Petroleum Institute. Austin, TX, August 2009.

BOEM (2011a) *OCS Platform Activity*. Bureau of Ocean Energy Management, U.S. Department of Interior. Available online at <http://www.boem.gov/uploadedFiles/BOEM/Newsroom/Offshore_Stats_and_Facts/Gulf_of_Mexico_Region/OCSPlatformActivity.pdf>.

BOEM (2011b) *Platform Information and Data*. Bureau of Ocean Energy Management, U.S. Department of Interior. Available online at <https://www.data.boem.gov/homepg/data_center/platform/platform.asp>.

BOEM (2011c) *Pacific OCS Region*. Bureau of Ocean Energy Management, U.S. Department of Interior. Available online at <http://www.data.boem.gov/homepg/data_center/platform/PacificFreePlat.asp>.

BOEM (2014) *Year 2011 Gulfwide Emission Inventory Study*. Bureau of Ocean Energy Management, U.S. Department of Interior. OCS Study BOEM 2014-666. Available online at <http://www.data.boem.gov/PI/PDFImages/ESPIS/5/5440.pdf>

DrillingInfo (2014) December 2014 Download. DI Desktop® DrillingInfo, Inc.

EIA (1990 through 2014) *Refinery Capacity Report*. Energy Information Administration, U.S. Department of Energy. Washington, DC. Available online at < http://www.eia.gov/petroleum/refinerycapacity/ >.

EIA (1995 through 2014a) *Annual Energy Review*. Energy Information Administration, U.S. Department of Energy. Washington, DC. Available online at < http://www.eia.gov/totalenergy/data/annual/index.cfm >.

EIA (1995 through 2014b) *Monthly Energy Review*. Energy Information Administration, U.S. Department of Energy. Washington, DC. Available online at < http://www.eia.gov/totalenergy/data/monthly/index.cfm >.

EIA (1995 through 2014c) *Petroleum Supply Annual. Volume 1*. U.S Department of Energy Washington, DC. Available online at: < http://www.eia.gov/petroleum/supply/annual/volume1/>.

EPA (2015a) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Data Source for Well Counts. Available at http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html.

EPA (2015b) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Offshore Oil and Gas Platforms Emissions Estimate. Available at http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html.

EPA (2015c) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Refineries Emissions Estimate. Available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>.

EPA (2015d) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Potential Updates to Pneumatic Controller Emissions Estimate. Available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>.

EPA (2014) *Greenhouse Gas Reporting Program*. Environmental Protection Agency. Data reported as of August 18, 2014.

EPA (2005) *Incorporating the Mineral Management Service Gulfwide Offshore Activities Data System (GOADS) 2000 data into the methane emissions inventories*. Prepared by ICF International. U.S. Environmental Protection Agency. 2005.

EPA (1999a) *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 (1999b) *Methane Emissions from the U.S. Petroleum Industry*. Prepared by Radian International. U.S. Environmental Protection Agency. February 1999.

EPA/GRI (1996a) *Methane Emissions from the Natural Gas Industry, V7: Blow and Purge Activities*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

EPA/GRI (1996b) *Methane Emissions from the Natural Gas Industry, V11: Compressor Driver Exhaust*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

EPA/GRI (1996c) *Methane Emissions from the Natural Gas Industry, V12: Pneumatic Devices*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

EPA/GRI (1996d) *Methane Emissions from the Natural Gas Industry, V13: Chemical Injection Pumps*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

HPDI (2011) Production and Permit Data, October 2009.

IOGCC (2011) *Marginal Wells: fuel for economic growth 2010 Report*. Interstate Oil & Gas Compact Commission. Available online at <http://iogcc.myshopify.com/collections/frontpage/products/2010-marginal-well-report>.

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 (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Pachauri, R.K and Reisinger, A. eds.; IPCC, Geneva, Switzerland.

OGJ (2014a) *Oil and Gas Journal 1990-2013*. Pipeline Economics Issue, September 2014.

OGJ (2013b) *Oil and Gas Journal 1990-2013*. Worldwide Refining Issue, January 2013.

United States Army Corps of Engineers (1995 through 2012) *Waterborne Commerce of the United States, Part 5: National Summaries*. U.S. Army Corps of Engineers. Washington, DC.

Natural Gas Systems (TO BE UPDATED)

AGA (1991 through 1998) Gas Facts. American Gas Association. Washington, DC.

Alabama (2014) Alabama State Oil and Gas Board. Available online at <http://www.ogb.state.al.us>.

Allen et al. (2014a) Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Liquids Unloading. ES&T. December 9, 2014. Available online at: <http://pubs.acs.org/doi/abs/10.1021/es504016r>.

Allen et al. (2014b) Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers. ES&T. December 9, 2014. Available online at: <http://pubs.acs.org/doi/pdf/10.1021/es5040156>.

Allen et al. (2013) Measurements of methane emissions at natural gas production sites in the United States. doi: 10.1073/pnas.1304880110 PNAS September 16, 2013. Available online at <http://www.pnas.org/content/early/2013/09/10/1304880110.abstract>.

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.

BOEMRE (2011a) Gulf of Mexico Region Offshore Information. Bureau of Ocean Energy Management, Regulation and Enforcement, U.S. Department of Interior.

BOEMRE (2011b) Pacific OCS Region Offshore Information. Bureau of Ocean Energy Management, Regulation and Enforcement, U.S. Department of Interior.

BOEMRE (2011c) GOM and Pacific OCS Platform Activity. Bureau of Ocean Energy Management, Regulation and Enforcement, U.S. Department of Interior.

BOEMRE (2011d) Pacific OCS Region. Bureau of Ocean Energy Management, Regulation and Enforcement, U.S. Department of Interior.

DrillingInfo (2014) December 2014 Download. DI Desktop® DrillingInfo, Inc.

EIA (2014a) “Table 1— Summary of natural gas supply and disposition in the United States, 2009-2014.” Natural Gas Monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov>.

EIA (2014b) “Table 2—Natural Gas Consumption in the United States, 2009-2014.” Natural Gas Monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov>.

EIA (2014c) “Table 7 - Marketed production of natural gas in selected states and the Federal Gulf of Mexico, 2009-2014.” Natural Gas Monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov>.

EIA (2014d) U.S. Natural Gas Imports by Country. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov>.

EIA (2014e) Natural Gas Gross Withdrawals and Production. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov>.

EIA (2012a) Formation crosswalk. Energy Information Administration, U.S. Department of Energy, Washington, DC. Provided July 7.

EIA (2012b) Lease Condensate Production, 1979-2012, 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 (2005) “Table 5—U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 1977-2003.” Energy Information Administration, Department of Energy, Washington, DC.

EIA (2004) *US LNG Markets and Uses*. Energy Information Administration, U.S. Department of Energy, Washington, DC. June 2004.

EIA (2001) “Documentation of the Oil and Gas Supply Module (OGSM).” Energy Information Administration, U.S. Department of Energy, Washington, DC.

EPA (2015a) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Data Source for Well Counts. Available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>.

EPA (2015b) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Offshore Oil and Gas Platform Emission Estimates. Available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>.

EPA (2015c) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Hydraulically Fractured Gas Well Completions and Workover Estimate. Available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>.

EPA (2015d) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Potential Updates to Pneumatic Controller Emissions Estimate. Available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>.

EPA (2015e) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Potential Updates to Liquids Unloading Emissions Estimate. Available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>.

EPA (2014) *Greenhouse Gas Reporting Program- Subpart W – Petroleum and Natural Gas Systems*. Environmental Protection Agency. Data reported as of August 18, 2014.

EPA (2013a) *Oil and Natural Gas Sector: Standards of Performance for Crude Oil and Natural Gas Production, Transmission, and Distribution. Background Supplemental Technical Support Document for the Final New Source Performance Standards*. Environmental Protection Agency. September 2013.

EPA (2013b) *Oil and Natural Gas Sector: New Source Performance Standards and National Emission Standards for Hazardous Air Pollutants Reviews*. Environmental Protection Agency, 40 CFR Parts 60 and 63, [EPA-HQ-OAR-2010-0505; FRL-9665-1], RIN 2060-AP76.

EPA (2013c) Natural Gas STAR Reductions 1990-2012. Natural Gas STAR Program. September 2013.

EPA (2013d) 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 (1999) *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report).* Prepared by ICF-Kaiser, Office of Air and Radiation, U.S. Environmental Protection Agency. October 1999.

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.

FERC (2014) *North American LNG Terminals*. Federal Energy Regulatory Commission, Washington, D.C.

GTI (2001) Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. GRI-01/0136.

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.

Jackson et al., (2014) *Natural Gas Pipeline Leaks Across Washington, D.C.*, 48 Environ. Science Technology 2051-2058, January 16, 2014. Available online at <http://pubs.acs.org/doi/abs/10.1021/es404474x>. March 24, 2014.

McGeehan et al., (2014) *Beneath Cities, a Decaying Tangle of Gas Pipes*, N.Y. Times, March 24, 2014. Available online at <http://www.nytimes.com/2014/03/24/nyregion/beneath-cities-a-decaying-tangle-of-gas-pipes.html?hp&_r=0>.

Miller et al. (2013) Anthropogenic emissions of methane in the United States. November 25, 2013, doi: 10.1073/pnas.1314392110. Available online at <http://www.pnas.org/content/early/2013/11/20/1314392110.abstract>.

OGJ (1997-2013) “Worldwide Gas Processing.” *Oil & Gas Journal*, PennWell Corporation, Tulsa, OK. Available online at <http://www.ogj.com/>.

Payne, B & Ackley, R., (2013a) “Extended Report and Preliminary Investigation of Ground-Level Ambient Methane Levels in Manhattan, New York, NY” (11 March 2013).

Payne, B. & Ackley, R., (2013b) “Report on a Survey of Ground-Level Ambient Methane Levels in the Vicinity of Wyalusing, Bradford County, PA,” (Nov. 2013).

Payne, B. & Ackley, R., (2012) “Report to the Clean Air Council on 8 June, 2012 Field Inspection and Methane Sampling Survey of Parts of Leroy, Granville and Franklin Townships, Bradford County, PA,” (2012).

Peischl, J. et al., (2013) “Quantifying Sources of Methane Using Light Alkenes in the Los Angeles Basin, CA,” J. Geophys. Res. Atmos. 118, 4974-4990, doi: 10.1002/jgrd.50413

Petron, Gabrielle, et al. (2012) Hydrocarbon Emissions Characterization in the Colorado Front Range: A Pilot Study, Journal of Geophysical Research doi:10.1029/2011JD016360.

Phillips, N.G., et al., (2012) “Mapping Urban Pipeline Leaks: Methane Levels Across Boston,” Environmental Pollution Available online at <http://www.ncbi.nlm.nih.gov/pubmed/23174345>.

PHMSA (2013a) Transmission Annuals Data. 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 (2013b) Gas Distribution Annual Data. Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, Washington, DC. Available online at <http://phmsa.dot.gov/pipeline/library/data-stats>.

Wyoming (2013) Wyoming Oil and Gas Conservation Commission. Available online at <http://wogcc.state.wy.us/coalbedchart.cfm>.

Energy Sources of Indirect Greenhouse Gases

EPA (2015) “1970 - 2014 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, March 2015. Available online at <http://www.epa.gov/ttn/chief/trends/index.html>.

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.

International Bunker Fuels

Anderson, B.E., et al., *Alternative Aviation Fuel Experiment (AAFEX)*, NASA Technical Memorandum, in press, 2011.

ASTM (1989) *Military Specification for Turbine Fuels, Aviation, Kerosene Types*, NATO F-34 (JP-8) and NATO F-35. February 10, 1989. Available online at <http://test.wbdg.org/ccb/FEDMIL/t_83133d.pdf>.

Chevron (2000) *Aviation Fuels Technical Review (FTR-3)*. Chevron Products Company, Chapter 2. Available online at <http://www.chevron.com/products/prodserv/fuels/bulletin/aviationfuel/2_at_fuel_perf.shtm>.

DHS (2008) Personal Communication with Elissa Kay, Residual and Distillate Fuel Oil Consumption (International Bunker Fuels). Department of Homeland Security, Bunker Report. January 11, 2008.

DLA Energy (2015) 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 (2015) 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.

DOT (1991 through 2013) Fuel Cost and Consumption. Federal Aviation Administration, Bureau of Transportation Statistics, U.S. Department of Transportation. Washington, D.C. DAI-10.

EIA (2015) *Monthly Energy Review, December 2015*, Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

FAA (2016) Personal Communication between FAA and Leif Hockstad for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). February 2016.

FAA (2006) *System for assessing Aviation's Global Emission (SAGE) Model*. Federal Aviation Administration's Office of Aviation Policy, Planning, and Transportation Topics, 2006.

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.

USAF (1998) *Fuel Logistics Planning.* U.S. Air Force pamphlet AFPAM23-221, May 1, 1998.

Wood Biomass and Ethanol Consumption

EIA (2015) *Monthly Energy Review, December 2015*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0035(2015/12).

EPA (2015) Acid Rain Program Dataset 1996-2014. Office of Air and Radiation, 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.

Lindstrom, P. (2006) Personal Communication. Perry Lindstrom, Energy Information Administration and Jean Kim, ICF International.

Industrial Processes and Product Use

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., Pub. IGES, Japan 2011.

EPA (2014) *Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014*. See http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting.

Cement Production

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. Bureau of Mines (1990 through 1993) *Minerals Yearbook: Cement Annual Report.* U.S. Department of the Interior, Washington, D.C.

United States Geological Survey (USGS) (2015a) *Mineral Industry Survey: Cement in June 2015.* U.S. Geological Survey, Reston, VA. August, 2015.

USGS (2015b) *Mineral Commodity Summaries: Cement 2015.* U.S. Geological Survey, Reston, VA. January, 2015.

USGS (1995 through 2013) *Minerals Yearbook* **-** *Cement*. U.S. Geological Survey, Reston, VA.

Van Oss (2013a) 1990-2012 Clinker Production Data Provided by Hendrik van Oss (USGS) via email on November 8, 2013.

Van Oss (2013b) Personal communication. Hendrik van Oss, Commodity Specialist of the U.S. Geological Survey and Gopi Manne, Eastern Research Group, Inc. October 28, 2013.

Lime Production

Corathers (2015) Personal communication, Lisa Corathers, U.S. Geological Survey and Gopi Manne, Eastern Research Group, Inc. September 22, 2015.

EPA (2015) Greenhouse Gas Reporting Program (GHGRP). Aggregation of reported facility level data under Subpart S -National Lime production for calendar years 2010-2014. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

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

Males, E. (2003) Memorandum from Eric Males, National Lime Association to Mr. William N. Irving & Mr. Leif Hockstad, Environmental Protection Agency. March 6, 2003.

Miner, R. and B. Upton (2002) Methods for estimating greenhouse gas emissions from lime kilns at kraft pulp mills. Energy. Vol. 27 (2002), p. 729-738.

Seeger (2013) Memorandum from Arline M. Seeger, National Lime Association to Mr. Leif Hockstad, Environmental Protection Agency. March 15, 2013.

United States Geological Survey (USGS) (1992 through 2014) *Minerals Yearbook: Lime*. U.S. Geological Survey, Reston, VA.

Glass Production

EPA (2009) *Technical Support Document for the Glass Manufacturing Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases.* U.S. Environmental Protection Agency, Washington, D.C.

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

OIT (2002) *Glass Industry of the Future: Energy and Environmental Profile of the U.S. Glass Industry.* Office of Industrial Technologies, U.S. Department of Energy. Washington, D.C.

U.S. Bureau of Mines (1991 and 1993a) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Department of the Interior. Washington, D.C.

United States Geological Survey (USGS) (2015a) *Minerals Industry Surveys; Soda Ash in January 2015*. U.S. Geological Survey, Reston, VA. March, 2015.

USGS (1995 through 2015b) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995 through 2014) *Minerals Yearbook: Soda Ash Annual Report.* U.S. Geological Survey, Reston, VA.

Willett (2015) Personal communication, Jason Christopher Willett, U.S. Geological Survey and Gopi Manne, Eastern Research Group, Inc. September 9, 2015.

Willett (2014) Personal communication., Jason Christopher Willett, U.S. Geological Survey and Gopi Manne, Eastern Research Group, Inc. September 25, 2014.

Other Process Uses of Carbonates

U.S. Bureau of Mines (1991 and 1993a) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Department of the Interior. Washington, D.C.

U.S. Bureau of Mines (1990 through 1993b) *Minerals Yearbook: Magnesium and Magnesium Compounds Annual Report*. U.S. Department of the Interior. Washington, D.C.

United States Geological Survey (USGS) (2013a) *Magnesium Metal Mineral Commodity Summary for 2013*. U.S. Geological Survey, Reston, VA.

USGS (1995a through 2015) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995b through 2012) *Minerals Yearbook: Magnesium Annual Report*. U.S. Geological Survey, Reston, VA.

Willett (2015) Personal communication, Jason Christopher Willett, U.S. Geological Survey and Gopi Manne, Eastern Research Group, Inc. September 9, 2015.

Ammonia Production

ACC (2015) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

Bark (2004) *CoffeyvilleNitrogen Plant* Available online at <http://www.gasification.org/uploads/downloads/Conferences/2003/07BARK.pdf>. December 15, 2004.

Coffeyville Resources Nitrogen Fertilizers (2012) Nitrogen Fertilizer Operations. Available online at <http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>.

Coffeyville Resources Nitrogen Fertilizers (2011) Nitrogen Fertilizer Operations. Available online at <http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>.

Coffeyville Resources Nitrogen Fertilizers (2010) Nitrogen Fertilizer Operations. Available online at <http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>.

Coffeyville Resources Nitrogen Fertilizers (2009) Nitrogen Fertilizer Operations. Available online at <http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>.

Coffeyville Resources Nitrogen Fertilizers, LLC (2005 through 2007a) Business Data. Available online at <http://www.coffeyvillegroup.com/businessSnapshot.asp>.

Coffeyville Resources Nitrogen Fertilizers (2007b) Nitrogen Fertilizer Operations. Available online at <http://coffeyvillegroup.com/nitrogenMain.aspx>.

Coffeyville Resources Energy, Inc. (CVR) (2015) *CVR Energy, Inc. 2014 Annual Report.* Available online at <http://cvrenergy.com>.

CVR (2014) *CVR Energy, Inc. 2013 Annual Report.* Available online at <http://cvrenergy.com>.

CVR (2012) *CVR Energy, Inc. 2012 Annual Report.* Available online at <http://cvrenergy.com>.

EFMA (2000a) *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*. Booklet No. 1 of 8: Production of Ammonium. Available online at <http://fertilizerseurope.com/site/index.php?id=390>.

EFMA (2000b) *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*. Booklet No. 5 of 8: Production of Urea and Urea Ammonium Nitrate. Available online at <http://fertilizerseurope.com/site/index.php?id=390>.

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. Census Bureau (2011) *Current Industrial Reports Fertilizer Materials and Related Products: 2010 Summary.* Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

U.S. Census Bureau (2010) *Current Industrial Reports Fertilizer Materials and Related Products: 2009 Summary.* Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

U.S. Census Bureau (2009) *Current Industrial Reports Fertilizer Materials and Related Products: 2008 Summary*. Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

U.S. Census Bureau (2008) *Current Industrial Reports Fertilizer Materials and Related Products: 2007 Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b/mq325b075.xls.>.

U.S. Census Bureau (2007) *Current Industrial Reports Fertilizer Materials and Related Products: 2006 Summary*. Available online at <http://www.census.gov/industry/1/mq325b065.pdf>.

U.S. Census Bureau (2006) *Current Industrial Reports Fertilizer Materials and Related Products: 2005 Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2004, 2005) *Current Industrial Reports Fertilizer Materials and Related Products: Fourth Quarter Report Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (1998 through 2003) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Reports Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (1991 through 1994) *Current Industrial Reports Fertilizer Materials Annual Report.* Report No. MQ28B. U.S. Census Bureau, Washington, D.C.

United State Goelogical Survey (USGS) (2015) 2013 Minerals Yearbook: Nitrogen [Advance Release]. August 2015. Available online at < http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/myb1-2013-nitro.pdf>.

USGS (2014) 2012 Minerals Yearbook: Nitrogen [Advance Release]. September 2014. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/myb1-2012-nitro.pdf>.

USGS (1994 through 2009) Minerals Yearbook: Nitrogen. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/>.

Urea Consumption for Non-Agricultural Purposes

EFMA (2000) *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*. Booklet No. 5 of 8: Production of Urea and Urea Ammonium Nitrate.

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.

TFI (2002) *U.S. Nitrogen Imports/Exports Table.* The Fertilizer Institute. Available online at <http://www.tfi.org/statistics/usnexim.asp>. August 2002.

U.S. Census Bureau (2001 through 2011) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Summary*. Available online at < http://www.census.gov/manufacturing/cir/historical_data/index.html >.

U.S. Department of Agriculture (2012) Economic Research Service Data Sets, Data Sets, U.S. Fertilizer Imports/Exports: Standard Tables. Available online at <http://www.ers.usda.gov/data-products/fertilizer-importsexports/standard-tables.aspx>.

U.S. ITC (2002) *United States International Trade Commission Interactive Tariff and Trade DataWeb, Version 2.5.0*. Available online at <http://dataweb.usitc.gov/scripts/user_set.asp>. August 2002.

United States Geological Survey (USGS) (2014 through 2015) Minerals Yearbook: Nitrogen [Advance Release]. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/>.

USGS (1994 through 2009) Minerals Yearbook: Nitrogen. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/>.

Nitric Acid Production

Climate Action Reserve (CAR) (2013), Project Report, <https://thereserve2.apx.com/myModule/rpt/myrpt.asp?r=111>. Accessed on January 18, 2013.

Desai (2012) Personal communication. Mausami Desai, U.S. Environmental Protection Agency, January 25, 2012.

EPA (2015) Greenhouse Gas Reporting Program (GHGRP). Aggregation of reported facility level data under Subpart V -National Nitric Acid production for calendar years 2010-2014. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2013) *Draft Nitric Acid Database.* U.S. Environmental Protection Agency, Office of Air and Radiation. September, 2010.

EPA (2012) Memorandum from Mausami Desai, U.S. EPA to Mr. Bill Herz, The Fertilizer Institute. November 26, 2012.

EPA (2010) *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Nitric Acid Production Industry.* Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. December 2010. Available online at: <http://www.epa.gov/nsr/ghgdocs/nitricacid.pdf>.

EPA (1998) *Compilation of Air Pollutant Emission Factors, AP-42.* Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. February 1998.

IPCC (2007) Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, 2007: Changes in Atmospheric Constituents and in Radiative Forcing. *In: 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.

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. Census Bureau (2010a) *Current Industrial Reports. Fertilizers and Related Chemicals: 2009.* "Table 1: Summary of Production of Principle Fertilizers and Related Chemicals: 2009 and 2008." June, 2010. MQ325B(08)-5. Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

U.S. Census Bureau (2010b) Personal communication between Hilda Ward (of U.S. Census Bureau) and Caroline Cochran (of ICF International). October 26, 2010 and November 5, 2010.

U.S. Census Bureau (2009) *Current Industrial Reports. Fertilizers and Related Chemicals: 2008.* "Table 1: Shipments and Production of Principal Fertilizers and Related Chemicals: 2004 to 2008." June, 2009. MQ325B(08)-5. Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

U.S. Census Bureau (2008) *Current Industrial Reports. Fertilizers and Related Chemicals: 2007.* "Table 1: Shipments and Production of Principal Fertilizers and Related Chemicals: 2003 to 2007." June, 2008. MQ325B(07)-5. Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

Adipic Acid Production

ACC (2015) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

C&EN (1995) "Production of Top 50 Chemicals Increased Substantially in 1994." *Chemical & Engineering News*, 73(15):17. April 10, 1995.

C&EN (1994) "Top 50 Chemicals Production Rose Modestly Last Year." *Chemical & Engineering News*, 72(15):13. April 11, 1994.

C&EN (1993) "Top 50 Chemicals Production Recovered Last Year." *Chemical & Engineering News*, 71(15):11. April 12, 1993.

C&EN (1992) "Production of Top 50 Chemicals Stagnates in 1991." *Chemical & Engineering News*, 70(15): 17. April 13, 1992.

CMR (2001) "Chemical Profile: Adipic Acid." *Chemical Market Reporter*. July 16, 2001.

CMR (1998) "Chemical Profile: Adipic Acid." *Chemical Market Reporter*. June 15, 1998.

CW (2005) "Product Focus: Adipic Acid." *Chemical Week*. May 4, 2005.

CW (1999) "Product Focus: Adipic Acid/Adiponitrile." *Chemical Week*, p. 31. March 10, 1999.

Desai (2011a) Personal communication. Mausami Desai, U.S. Environmental Protection Agency and Roy Nobel, Ascend Performance Materials, October 18, 2011.

Desai (2011b) Personal communication. Mausami Desai, U.S. Environmental Protection Agency with Steve Zuiss of Invista, November 18, 2011.

Desai (2010) Personal communication. Mausami Desai, U.S. Environmental Protection Agency with Steve Zuiss of Invista, October 15, 2010.

EPA (2014 through 2015) Greenhouse Gas Reporting Program. Annual Detailed Data for Additional Industry Types (Adipic Acid Tab). Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Accessed 10/07/2015, Available online at: < http://www2.epa.gov/ghgreporting/ghg-reporting-program-data-sets>.

EPA (2012) Analysis of Greenhouse Gas Reporting Program data – Subpart E (Adipic Acid), Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

ICIS (2007) "Adipic Acid." *ICIS Chemical Business Americas*. July 9, 2007.

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.

Reimer, R.A., Slaten, C.S., Seapan, M., Koch, T.A. and Triner, V.G. (1999) "Implementation of Technologies for Abatement of N_2O Emissions Associated with Adipic Acid Manufacture." Proceedings of the 2nd Symposium on Non-CO_2 Greenhouse Gases (NCGG-2), Noordwijkerhout, The Netherlands, 8-10 Sept. 1999, Ed. J. van Ham *et al.*, Kluwer Academic Publishers, Dordrecht, pp. 347-358.

SEI (2010) *Industrial N_2O Projects Under the CDM: Adipic Acid – A Case for Carbon Leakage?* Stockholm Environment Institute Working Paper WP-US-1006. October 9, 2010.

Thiemens, M.H., and W.C. Trogler (1991) "Nylon production; an unknown source of atmospheric nitrous oxide." *Science* 251:932-934.

VA DEQ (2010) Personal communication. Stanley Faggert, Virginia Department of Environmental Quality and Joseph Herr, ICF International. March 12, 2010.

VA DEQ (2009) Personal communication. Stanley Faggert, Virginia Department of Environmental Quality and Joseph Herr, ICF International. October 26, 2009.

VA DEQ (2006) Virginia Title V Operating Permit. Honeywell International Inc. Hopewell Plant. Virginia Department of Environmental Quality. Permit No. PRO50232. Effective January 1, 2007.

Silicon Carbide Production

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.

U.S. Census Bureau (2005 through 2015) *U.S. International Trade Commission (USITC) Trade DataWeb.* Available online at <http://dataweb.usitc.gov/>.

United States Geological Survey (USGS) (2015a) *Minerals Industry Surveys: Abrasives (Manufactured) in First Quarter of 2015*. U.S. Geological Survey, Reston, VA. September 2015. Available online at < http://minerals.usgs.gov/minerals/pubs/commodity/abrasives/index.html>.

USGS (1991a through 2015b) *Minerals Yearbook: Manufactured Abrasives Annual Report.* U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/abrasives/>.

USGS (1991b through 2013) *Minerals Yearbook: Silicon Annual Report.* U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/silicon/>.

Titanium Dioxide Production

Gambogi, J. (2002) Telephone communication. Joseph Gambogi, Commodity Specialist, U.S. Geological Survey and Philip Groth, ICF International. November 2002.

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.

United States Geological Survey (USGS) (1991 through 2015b) *Minerals Yearbook: Titanium.* U.S. Geological Survey, Reston, VA.

USGS (2015a) *2015 Mineral Commodity Summary: Titanium and Titanium Dioxide* . U.S. Geological Survey, Reston, VA. January, 2015.

Soda Ash Production and Consumption

Kostick, D. S. (2012) Personal communication. Dennis S. Kostick of U.S. Department of the Interior - U.S. Geological Survey, Soda Ash Commodity Specialist with Gopi Manne and Bryan Lange of Eastern Research Group, Inc. October 2012.

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.

United States Geological Survey (USGS) (2015a) Mineral Industry Surveys: Soda Ash in July 2015. U.S. Geological Survey, Reston, VA. September, 2015.

USGS (1994 through 2015b) *Minerals Yearbook: Soda Ash Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995a) Trona Resources in the Green River Basin, Southwest Wyoming. U.S. Department of the Interior, U.S. Geological Survey. Open-File Report 95-476. Wiig, Stephen, Grundy, W.D., Dyni, John R.

Petrochemical Production

ACC (2015) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

ACC (2014a) *U.S. Chemical Industry Statistical Handbook*. American Chemistry Council, Arlington, VA.

ACC (2014b) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

ACC (2002, 2003, 2005 through 2011) *Guide to the Business of Chemistry.* American Chemistry Council, Arlington, VA.

AN (2014) *About Acrylonitrile: Production*. AN Group, Washington, D.C. Available online at: <http://www.angroup.org/about/production.cfm>

EPA Greenhouse Gas Reporting Program (2015). Aggregation of reported facility level data under Subpart X - National Petrochemical production for calendar years 2010-2014. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA Greenhouse Gas Reporting Program (2014). Aggregation of reported facility level data under Subpart X - National Petrochemical production for calendar years 2010-2013. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2008) *Technical Support Document for the Petrochemical Production Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases.* U.S. Environmental Protection Agency. September 2008.

EPA (2000) *Economic Impact Analysis for the Proposed Carbon Black Manufacturing NESHAP,* U.S. Environmental Protection Agency. Research Triangle Park, NC. EPA-452/D-00-003. May 2000.

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.

Jordan, J. (2011) Personal communication, Jim Jordan of Jordan Associates on behalf of the Methanol Institute and Pier LaFarge, ICF International. October 18, 2011

Johnson, G. L. (2005 through 2010) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Caroline Cochran, ICF International. September 2010.

Johnson, G. L. (2003) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Caren Mintz, ICF International November 2003.

HCFC-22 Production (TO BE UPDATED)

ARAP (2010) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. September 10, 2010.

ARAP (2009) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. September 21, 2009.

ARAP (2008) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. October 17, 2008.

ARAP (2007) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. October 2, 2007.

ARAP (2006) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. July 11, 2006.

ARAP (2005) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 9, 2005.

ARAP (2004) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. June 3, 2004.

ARAP (2003) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. August 18, 2003.

ARAP (2002) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 7, 2002.

ARAP (2001) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 6, 2001.

ARAP (2000) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. August 13, 2000.

ARAP (1999) Facsimile from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger Schaefer of the U.S. Environmental Protection Agency. September 23, 1999.

ARAP (1997) Letter from Dave Stirpe, Director, Alliance for Responsible Atmospheric Policy to Elizabeth Dutrow of the U.S. Environmental Protection Agency. December 23, 1997.

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 (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.

RTI (2008) "Verification of Emission Estimates of HFC-23 from the Production of HCFC-22:Emissions from 1990 through 2006." Report prepared by RTI International for the Climate Change Division. March, 2008.

RTI (1997) "Verification of Emission Estimates of HFC-23 from the Production of HCFC-22: Emissions from 1990 through 1996." Report prepared by Research Triangle Institute for the Cadmus Group. November 25, 1997; revised February 16, 1998.

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

Carbon Dioxide Consumption

Allis, R. et al. (2000) *Natural CO_2 Reservoirs on the Colorado Plateau and Southern Rocky Mountains: Candidates for CO_2 Sequestration*. Utah Geological Survey and Utah Energy and Geoscience Institute. Salt Lake City, Utah.

ARI (1990 through 2010) *CO_2 Use in Enhanced Oil Recovery*. Deliverable to ICF International under Task Order 102, July 15, 2011.

ARI (2007) *CO_2-EOR: An Enabling Bridge for the Oil Transition*. Presented at "Modeling the Oil Transition—a DOE/EPA Workshop on the Economic and Environmental Implications of Global Energy Transitions." Washington, D.C. April 20-21, 2007.

ARI (2006) *CO_2-EOR: An Enabling Bridge for the Oil Transition*. Presented at "Modeling the Oil Transition—a DOE/EPA Workshop on the Economic and Environmental Implications of Global Energy Transitions." Washington, D.C. April 20-21, 2006.

Broadhead (2003) Personal communication. Ron Broadhead, Principal Senior Petroleum Geologist and Adjunct faculty, Earth and Environmental Sciences Department, New Mexico Bureau of Geology and Mineral Resources, and Robin Pestrusak, ICF International. September 5, 2003.

COGCC (1999 through 2009) Monthly CO_2 Produced by County. Available online at <http://cogcc.state.co.us/COGCCReports/production.aspx?id=MonthlyCO2ProdByCounty>. Accessed October 2014.

Denbury Resources Inc. (2002 through 2010) Annual Report: 2001 through 2009, Form 10-K. Available online at <http://www.denbury.com/investor-relations/SEC-Filings/SEC-Filings-Details/default.aspx?FilingId=9823015>. Accessed September 2014.

EPA Greenhouse Gas Reporting Program (2015). Aggregation of reported facility level data under Subpart PP - National level CO2 transferred for food & beverage applications for calendar years 2010-2014. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

New Mexico Bureau of Geology and Mineral Resources (2006) Natural Accumulations of Carbon Dioxide in New Mexico and Adjacent Parts of Colorado and Arizona: Commercial Accumulation of CO_2. Available online at <http://geoinfo.nmt.edu/staff/broadhead/CO2.html#commercial>.

Phosphoric Acid Production

EFMA (2000) “Production of Phosphoric Acid.” *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry.* Booklet 4 of 8. European Fertilizer Manufacturers Association. Available online at <http://www.efma.org/Publications/BAT%202000/Bat04/section04.asp>.

FIPR (2003a) “Analyses of Some Phosphate Rocks.” Facsimile Gary Albarelli, the Florida Institute of Phosphate Research, Bartow, Florida, to Robert Lanza, ICF International. July 29, 2003.

FIPR (2003b) Florida Institute of Phosphate Research. Personal communication. Mr. Michael Lloyd, Laboratory Manager, FIPR, Bartow, Florida, to Mr. Robert Lanza, ICF International. August 2003.

NCDENR (2013) North Carolina Department of Environment and Natural Resources, Title V Air Permit Review for PCS Phosphate Company, Inc. – Aurora. Available online at <http://www.ncair.org/permits/permit_reviews/PCS_rev_08282012.pdf>. Accessed on January 25, 2013.

United States Geological Survey (USGS) (1994 through 2015b) *Minerals Yearbook. Phosphate Rock Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2015a) Mineral Commodity Summaries: Phosphate Rock 2015. January 2015. U.S. Geological Survey, Reston, VA. Available online at: < http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/mcs-2015-phosp.pdf>.

USGS (2012b) Personal communication between Stephen Jasinski (USGS) and Mausami Desai (EPA) on October 12, 2012.

Iron and Steel Production and Metallurgical Coke Production

AISI (2004 through 2015a) *Annual Statistical Report*, American Iron and Steel Institute, Washington, D.C.

AISI (2006 through 2014b) Personal communication, Mausami Desai, U.S. EPA, and American Iron and Steel Institute, December 8, 2014.

AISI (2008c) Personal communication, Mausami Desai, U.S. EPA, and Bruce Steiner, Technical Consultant with the American Iron and Steel Institute, October 2008.

Carroll (2015) Personal communication, Mausami Desai, U.S. EPA, and Colin P. Carroll, Director of Environment, Health and Safety, American Iron and Steel Institute, September 2015.

DOE (2000) *Energy and Environmental Profile of the U.S. Iron and Steel Industry*. Office of Industrial Technologies, U.S. Department of Energy. August 2000. DOE/EE-0229.EIA

EIA (1998 through 2014) *Quarterly Coal Report: October-December*, Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0121.

EIA (2015a) *Natural Gas Annual 2014*, Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0131(06).

EIA (2015b) *Monthly Energy Review*, *December 2015*, Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

EIA (1992) Coal and lignite production. *EIA State Energy Data Report 1992*, Energy Information Administration, U.S. Department of Energy, 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.

Fenton (2015) Personal communication. Michael Fenton, Commodity Specialist, U.S. Geological Survey and Marty Wolf, Eastern Research Group. September 16, 2015.

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/UNEP/OECD/IEA (1995) "Volume 3: Greenhouse Gas Inventory Reference Manual. Table 2-2". *IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. IPCC WG1 Technical Support Unit, United Kingdom.

United States Geological Survey (USGS) (1991 through 2014) *USGS Minerals Yearbook – Iron and Steel Scrap.* U.S. Geological Survey, Reston, VA.

Ferroalloy Production

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.

Onder, H., and E.A. Bagdoyan (1993) Everything You've Always Wanted to Know about Petroleum Coke. Allis Mineral Systems.

United States Geological Survey (USGS) (2015a) *2012 Minerals Yearbook: Ferroalloys.* U.S. Geological Survey, Reston, VA. April 2015.

USGS (2015b) *Mineral Industry Surveys: Silicon in June 2015*. U.S. Geological Survey, Reston, VA. September 2015.

USGS (2014) *Mineral Industry Surveys: Silicon in September 2014.* U.S. Geological Survey, Reston, VA. December 2014.

USGS (1996 through 2013) *Minerals Yearbook: Silicon*. U.S. Geological Survey, Reston, VA.

Aluminum Production (TO BE UPDATED)

EPA (2014) Greenhouse Gas Reporting Program (GHGRP). Envirofacts, Subpart: F Aluminum Production. Available online at <http://www.epa.gov/enviro/facts/ghg/search.html>. Accessed on: November 13, 2014.

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 (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.

USAA (2014) *U.S. Primary Aluminum Production 2013.* U.S. Aluminum Association, Washington, D.C. October, 2014.

USAA (2013) *U.S. Primary Aluminum Production 2012.* U.S. Aluminum Association, Washington, D.C. January, 2013.

USAA (2012) *U.S. Primary Aluminum Production 2011.* U.S. Aluminum Association, Washington, D.C. January, 2012.

USAA (2011) *U.S. Primary Aluminum Production 2010.* U.S. Aluminum Association, Washington, D.C.

USAA (2010) *U.S. Primary Aluminum Production 2009.* U.S. Aluminum Association, Washington, D.C.

USAA (2008, 2009) *U.S. Primary Aluminum Production.* U.S. Aluminum Association, Washington, D.C.

USAA (2004, 2005, 2006) *Primary Aluminum Statistics.* U.S. Aluminum Association, Washington, D.C.

USGS (2014) *2014 Mineral Commodity Summaries: Aluminum*. U.S. Geological Survey, Reston, VA.

USGS (2007) *2006 Mineral Yearbook: Aluminum.* U.S. Geological Survey, Reston, VA.

USGS (1995, 1998, 2000, 2001, 2002) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

Magnesium Production and Processing (TO BE UPDATED)

Bartos S., C. Laush, J. Scharfenberg, and R. Kantamaneni (2007) “Reducing greenhouse gas emissions from magnesium die casting.” *Journal of Cleaner Production*, 15: 979-987, March.

EPA (2014) Envirofacts. Greenhouse Gas Reporting Program (GHGRP), Subpart T: Magnesium Production and Processing. Available online at <http://www.epa.gov/enviro/facts/ghg/search.html>. Accessed on: November, 2014.

Gjestland, H. and D. Magers (1996) “Practical Usage of Sulphur [Sulfur] Hexafluoride for Melt Protection in the Magnesium Die Casting Industry.” #13, *1996 Annual Conference Proceedings*, International Magnesium Association. Ube City, Japan.

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.

RAND (2002) RAND Environmental Science and Policy Center, “Production and Distribution of SF_6 by End-Use Applications” Katie D. Smythe. *International Conference on* SF_6 *and the Environment: Emission Reduction Strategies*. San Diego, CA. November 21-22, 2002.

United States Geological Survey (USGS) (2002, 2003, 2005 through 2008, 2011b, 2012, and 2013) *Minerals Yearbook: Magnesium Annual Report*. U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/index.html#mis>.

USGS (2010a) *Mineral Commodity Summaries: Magnesium Metal*. U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2010-mgmet.pdf>.

Lead Production

Dutrizac, J.E., V. Ramachandran, and J.A. Gonzalez (2000) *Lead-Zinc 2000*. The Minerals, Metals, and Materials Society.

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.

Morris, D., F.R. Steward, and P. Evans (1983) *Energy Efficiency of a Lead Smelter.* Energy 8(5):337-349.

Sjardin, M. (2003) CO_2 *Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry*. Copernicus Institute. Utrecht, the Netherlands.

Ullman (1997) *Ullman’s Encyclopedia of Industrial Chemistry: Fifth Edition.* Volume A5. John Wiley and Sons.

United States Geological Survey (USGS) (2015) *2015 Mineral Commodity Summary, Lead.* U.S. Geological Survey, Reston, VA. January 2015.

USGS (2014) *Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. February 2014.

USGS (1995 through 2013) *Minerals Yearbook: Lead Annual Report.* U.S. Geological Survey, Reston, VA.

Zinc Production

Horsehead Corp. (2015) Form 10-k, Annual Report for the Fiscal Year Ended December 31, 2014. Available at: < http://www.sec.gov/Archives/edgar/data/1385544/000138554415000005/zinc-2014123110k.htm>. Submitted March 2, 2015.

Horsehead Corp. (2014) Form 10-k, Annual Report for the Fiscal Year Ended December 31, 2013. Available at: <http://www.sec.gov/Archives/edgar/data/1385544/000138554414000003/zinc-2013123110k.htm>. Submitted March 13, 2014.

Horsehead Corp. (2013) Form 10-k, Annual Report for the Fiscal Year Ended December 31, 2012. Available at: <http://www.sec.gov/Archives/edgar/data/1385544/000119312513110431/0001193125-13-110431-index.htm>. Submitted March 18, 2013.

Horsehead Corp. (2012a) Form 10-k, Annual Report for the Fiscal Year Ended December, 31, 2011. Available at: <http://www.sec.gov/Archives/edgar/data/1385544/000119312512107345/d293011d10k.htm>. Submitted March 9, 2012.

Horsehead Corp. (2012b) *Horsehead's New Zinc Plant and its Impact on the Zinc Oxide Business.* February 22, 2012. Available online at: <http://www.horsehead.net/downloadAttachmentNDO.php?ID=118>. Accessed September 10, 2015.

Horsehead Corp. (2011) 10-k Annual Report for the Fiscal Year Ended December, 31 2010. Available at: <http://google.brand.edgar-online.com/default.aspx?sym=zinc>. Submitted March 16, 2011.

Horsehead Corp. (2010a) 10-k Annual Report for the Fiscal Year Ended December, 31 2009. Available at: <http://google.brand.edgar-online.com/default.aspx?sym=zinc>. Submitted March 16, 2010.

Horsehead Corp. (2010b) *Horsehead Holding Corp. Provides Update on Operations at its Monaca, PA Plant.* July 28, 2010. Available at: <http://www.horsehead.net/pressreleases.php?showall=no&news=&ID=65>.

Horsehead Corp (2008) 10-k Annual Report for the Fiscal Year Ended December, 31 2007. Available at: <http://google.brand.edgar-online.com/default.aspx?sym=zinc>. Submitted March 31, 2008.

Horsehead Corp (2007) Registration Statement (General Form) S-1. Available at <http://google.brand.edgar-online.com/default.aspx?sym=zinc>. Submitted April 13, 2007.

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.

PIZO (2014) Available at <http://pizotech.com/index.html>. Accessed December 9, 2014.

PIZO (2012) Available at <http://pizotech.com/index.html>. Accessed October 10, 2012.

Sjardin (2003) CO_2 *Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry*. Copernicus Institute. Utrecht, the Netherlands.

Steel Dust Recycling (SDR) (2015) Personal communication. Jeremy Whitten, EHS Manager, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. September 22, 2015.

SDR (2014) Personal communication. Art Rowland, Plant Manager, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. December 9, 2014.

SDR (2013) Available at <http://steeldust.com/home.htm>. Accessed October 29, 2013.

SDR (2012) Personal communication. Art Rowland, Plant Manager, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. October 5, 2012.

United States Geological Survey (USGS) (2015) *2015 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. Jqanuary 2015.

USGS (1995 through 2014) *Minerals Yearbook: Zinc Annual Report.* U.S. Geological Survey, Reston, VA.

Viklund-White C. (2000) “The Use of LCA for the Environmental Evaluation of the Recycling of Galvanized Steel.” ISIJ International. Volume 40 No. 3: 292-299.

Semiconductor Manufacture (TO BE UPDATED)

Burton, C.S., and R. Beizaie (2001) “EPA’s PFC Emissions Model (PEVM) v. 2.14: Description and Documentation” prepared for Office of Global Programs, U. S. Environmental Protection Agency, Washington, DC. November 2001.

Citigroup Smith Barney (2005) *Global Supply/Demand Model for Semiconducto*rs. March 2005.

Doering, R. and Nishi, Y (2000) “Handbook of Semiconductor Manufacturing Technology”, Marcel Dekker, New York, USA, 2000.

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.

ISMI (2009) *Analysis of Nitrous Oxide Survey Data*. Walter Worth. June 8, 2009. Available online at <http://sematech.org/docubase/document/5015atr.pdf>

ITRS (2007, 2008, 2011, 2013) *International Technology Roadmap for Semiconductors: 2006 Update*, January 2007; *International Technology Roadmap for Semiconductors: 2007 Edition*, January 2008*; International Technology Roadmap for Semiconductors: 2011, January 2012; Update, International Technology Roadmap for Semiconductors: 2013 Edition*, Available online at <http://www.itrs.net/Links/2013ITRS/Home2013.htm>. These and earlier editions and updates are available at <http://public.itrs.net>. Information about the number of interconnect layers for years 1990–2010 is contained in Burton and Beizaie, 2001. PEVM is updated using new editions and updates of the ITRS, which are published annually.

SEMI - Semiconductor Equipment and Materials Industry (2013) *World Fab Forecast, May 2013 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2012) *World Fab Forecast, August 2012 Edition*.

Semiconductor Industry Association (SIA) (2011) SICAS Capacity and Utilization Rates Q4 2011. Available online at < http://www.semiconductors.org/industry_statistics/semiconductor_capacity_utilization_sicas_reports/>.

Semiconductor Industry Association (SIA) (2009) STATS: SICAS Capacity and Utilization Rates Q1-Q4 2008, Q1-Q4 2009, Q1-Q4 2010, Q1-Q4 2011. Available online at < http://www.semiconductors.org/industry_statistics/semiconductor_capacity_utilization_sicas_reports/ >.

U.S. EPA (2006) *Uses and Emissions of Liquid PFC Heat Transfer Fluids from the Electronics Sector*. U.S. Environmental Protection Agency, Washington, DC. EPA-430-R-06-901.

U.S. EPA Greenhouse Gas Reporting Program (GHGRP) Envirofacts. Subpart I: Electronics Manufacture. Available online at <http://www.epa.gov/enviro/facts/ghg/search.html>

VLSI Research, Inc. (2012) Worldwide Silicon Demand. August 2012.

Substitution of Ozone Depleting Substances

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.

Electrical Transmission and Distribution (TO BE UPDATED)

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 (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.

Levin et al. (2010) "The Global SF_6 Source Inferred from Long-term High Precision Atmospheric Measurements and its Comparison with Emission Inventories."*Atmospheric Chemistry and Physics*, 10: 2655–2662.

O'Connell, P., F. Heil, J. Henriot, G. Mauthe, H. Morrison, L. Neimeyer, M. Pittroff, R. Probst, J.P. Tailebois (2002) *SF_6 in the Electric Industry, Status 2000*, CIGRE. February 2002.

RAND (2004) "Trends in SF_6 Sales and End-Use Applications: 1961-2003," Katie D. Smythe. *International Conference on SF_6 and the Environment: Emission Reduction Strategies*. RAND Environmental Science and Policy Center, Scottsdale, AZ. December 1-3, 2004.

UDI (2013). *2013 UDI Directory of Electric Power Producers and Distributors,121st Edition*, Platts.

UDI (2010) *2010 UDI Directory of Electric Power Producers and Distributors, 118th Edition*, Platts.

UDI (2007) *2007 UDI Directory of Electric Power Producers and Distributors, 115th Edition*, Platts.

UDI (2004) *2004 UDI Directory of Electric Power Producers and Distributors, 112th Edition*, Platts.

UDI (2001) *2001 UDI Directory of Electric Power Producers and Distributors, 109th Edition*, Platts.

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

Nitrous Oxide from Product Use

CGA (2003) "CGA Nitrous Oxide Abuse Hotline: CGA/NWSA Nitrous Oxide Fact Sheet." Compressed Gas Association. November 3, 2003.

CGA (2002) "CGA/NWSA Nitrous Oxide Fact Sheet." Compressed Gas Association. March 25, 2002.

Heydorn, B. (1997) "Nitrous Oxide—North America." *Chemical Economics Handbook*, SRI Consulting. May 1997.

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.

Ottinger (2014) Personal communication. Deborah Ottinger (CCD, U.S. EPA) and Mausami Desai (U.S. EPA). Email received on January 29, 2014.

Tupman, M. (2003) Personal communication .Martin Tupman, Airgas Nitrous Oxide and Daniel Lieberman, ICF International. August 8, 2003.

Industrial Processes and Product Use Sources of Indirect Greenhouse Gases

EPA (2015) “1970 - 2014 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, March 2015. Available online at <http://www.epa.gov/ttn/chief/trends/index.html>.

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.

Agriculture

Enteric Fermentation

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.

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.

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, DC.

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 (2015) *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/>. Accessed August 3, 2015.

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.

Manure Management

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 (2012) AgSTAR Anaerobic Digester Database. Available online at: <http://www.epa.gov/agstar/projects/index.html#database>.

EPA (2008) *Climate Leaders Greenhouse Gas Inventory Protocol Offset Project Methodology for Project Type Managing Manure with Biogas Recovery Systems*. Available online at <http://www.epa.gov/climateleaders/documents/resources/ClimateLeaders_DraftManureOffsetProtocol.pdf>.

EPA (2006) *AgSTAR Digest*. Office of Air and Radiation, U.S. Environmental Protection Agency. Washington, D.C. Winter 2006. Available online at <http://www.epa.gov/agstar/pdf/2006digest.pdf>. Retrieved July 2006.

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 (2003) *AgSTAR Digest*. Office of Air and Radiation, U.S. Environmental Protection Agency. Washington, D.C. Winter 2003. Available online at <http://www.epa.gov/agstar/pdf/2003digest.pdf>. Retrieved July 2006.

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 (2000) *AgSTAR Digest*. Office of Air and Radiation, U.S. Environmental Protection Agency. Washington, D.C. Spring 2000. Available online at: <http://www.epa.gov/agstar/news-events/digest/2000digest.pdf>.

EPA (1992) *Global Methane Emissions from Livestock and Poultry Manure*, Office of Air and Radiation, U.S. Environmental Protection Agency. February 1992.

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_o 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 (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 (2014) *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/2008/>. (for Alaska and Hawaii). September 2014.

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 (2015a) *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 (2015b) *Chicken and Eggs 2014 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2015. Available online at <http://www.nass.usda.gov/Publications/index.asp>.

USDA (2015c) *Poultry - Production and Value 2014 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2015. Available online at <http://www.nass.usda.gov/Publications/index.asp>.

USDA (2014a) *1987, 1992, 1997, 2002, 2007, and 2012 Census of Agriculture*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at <http://www.nass.usda.gov/census/>. May 2014.

USDA (2014b) *Chicken and Eggs 2013 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2014. Available online at <http://www.nass.usda.gov/Publications/index.asp>.

USDA (2014c) *Poultry - Production and Value 2013 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2014. Available online at <http://www.nass.usda.gov/Publications/index.asp>.

USDA (2013a) *Chicken and Eggs 2012 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2013. Available online at <http://www.nass.usda.gov/Publications/index.asp>.

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 <http://www.nass.usda.gov/Publications/index.asp>.

USDA (2012a) *Chicken and Eggs 2011 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2012. Available online at <http://www.nass.usda.gov/Publications/index.asp>.

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 <http://www.nass.usda.gov/Publications/index.asp>.

USDA (2011a) *Chicken and Eggs 2010 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2011. Available online at <http://www.nass.usda.gov/Publications/index.asp>.

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 <http://www.nass.usda.gov/Publications/index.asp>.

USDA (2010a) *Chicken and Eggs 2009 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2010. Available online at <http://www.nass.usda.gov/Publications/index.asp>.

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 <http://www.nass.usda.gov/Publications/index.asp>.

USDA (2009a) *Chicken and Eggs 2008 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2009. Available online at <http://www.nass.usda.gov/Publications/index.asp>.

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 <http://www.nass.usda.gov/Publications/index.asp>.

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 <http://usda.mannlib.cornell.edu/usda/nass/SB980/sb1024.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. <http://www.aphis.usda.gov/animal_health/nahms/sheep/index.shtml#sheep2001>.

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.

Rice Cultivation (TO BE UPDATED)

Anderson, M. (2008 through 2014) Email correspondence. Monte Anderson, Oklahoma Farm Service Agency and ICF International.

Baldwin, K., E. Dohlman, N. Childs and L. Forman (2010). Consolidation and Structural Change in the U.S. Rice Sector. Economic Research Service: U.S. Department of Agriculture, Washington D.C. Available online at <http://www.ers.usda.gov/media/111364/rcs11d01_1_.pdf>. September 2013.

Baicich, P. (2013). The Birds and Rice Connection. *Bird Watcher's Digest*. Available online at <http://www.usarice.com/doclib/194/6867.pdf>.

Beighley, D. (2011 through 2012) Email correspondence. Donn Beighley, Southeast Missouri State University, Department of Agriculture and ICF International.

Bossio, D.A., W. Horwath, R.G. Mutters, and C. van Kessel (1999) "Methane pool and flux dynamics in a rice field following straw incorporation." *Soil Biology and Biochemistry*, 31:1313-1322.

Buehring, N. (2009 through 2011) Email correspondence. Nathan Buehring, Assistant Professor and Extension Rice Specialist, Mississippi State University Delta Branch Exp. Station and ICF International.

Byrd, G. T., F. M. Fisher, & R. L. Sass. (2000) Relationships between methane production and emission to lacunal methane concentrations in rice. Global biogeochemical cycles, 14(1), 73-83.

California Air Resources Board (2003) 2003 Progress Report on the Phase-down of Rice Straw Burning in the Sacremento Valley Air Basin. Available online at <http://www.arb.ca.gov/smp/rice/phsdown/rice2003.pdf>.

Cantens, G. (2004 through 2005) Personal Communication. Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company and ICF International.

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.

Environmental Defense Fund (2011) Creating and Quantifying Carbon Credits from Voluntary Practices on Rice. Available online at <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044916.pdf>.

Fife, L. (2011) Email correspondence. Les Fife, Sacramento Valley Agricultural Burning Coordinator and ICF International.

Fitzgerald, G.J., K. M. Scow & J. E. Hill (2000) "Fallow Season Straw and Rice Management Effects on Methane Emissions in California Rice." Global bigeochemical cycles, 14 (3), 767-776.

Gonzalez, R. (2007 through 2014) Email correspondence. Rene Gonzalez, Plant Manager, Sem-Chi Rice Company and ICF International.

Hardke, J. (2014) Personal Communication. Dr. Jarrod Hardke, Rice Extension Agronomist at the University of Arkansas Rice Research and Extension Center and Kirsten Jaglo, ICF International. September 11, 2014.

Hardke, J. (2013) Email correspondence. Dr. Jarrod Hardke, Rice Extension Agronomist at the University of Arkansas Rice Research and Extension Center and Cassandra Snow, ICF International. July 15, 2013.

Holzapfel-Pschorn, A., R. Conrad, and W. Seiler (1985) “Production, Oxidation, and Emissions of Methane in Rice Paddies.” *FEMS Microbiology Ecology*, 31:343-351.

IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report (AR4) of the IPCC*. The Intergovernmental Panel on Climate Change, R.K. Pachauri, A. Resinger (eds.). Geneva, Switzerland.

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/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency, Paris, France.

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.

Klosterboer, A. (1997, 1999 through 2003) Personal Communication. Arlen Klosterboer, retired Extension Agronomist, Texas A&M University and ICF International. July 7, 2003.

Kongchum, M. (2005). Effect of Plant Residue and Water Management Practices on Soil Redox Chemistry, Methane Emission, and Rice Productivity. LSU PhD Thesis.

Lee, D. (2003 through 2007) Email correspondence. Danny Lee, OK Farm Service Agency and ICF International.

Lindau, C.W. and P.K. Bollich (1993) “Methane Emissions from Louisiana First and Ratoon Crop Rice.” *Soil Science*, 156:42-48.

Lindau, C.W., P.K Bollich, and R.D. DeLaune (1995) “Effect of Rice Variety on Methane Emission from Louisiana Rice.” *Agriculture, Ecosystems and Environment*, 54:109-114.

Linscombe, S. (1999, 2001 through 2014) Email correspondence. Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center and ICF International.

McMillan, A., M. L.Goulden, and S.C. Tyler. (2007) Stoichiometry of CH_4 and CO_2 flux in a California rice paddy. Journal of Geophysical Research: Biogeosciences (2005–2012), 112(G1).

Mutters, C. (2001 through 2005) Personal Communication. Mr. Cass Mutters, Rice Farm Advisor for Butte, Glen, and Tehama Counties University of California, Cooperative Extension Service and ICF International.

Rogers, C.W., K. R. Brye, R.J. Norman, T. Gasnier, D. Frizzell, and J. Branson. (2011). Methane Emissions from a Silt-Loam Soil Under Direct-Seeded, Delayed-Flood Rice Management. B.R. Wells Rice Research Studies 2011. 306-315.

Sass, R. L. (2001). CH_4 Emissions from Rice Agriculture. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. 399-417. Available at <http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/4_7_CH4_Rice_Agriculture.pdf>.

Sass, R. L., J.A. Andrews, A. Ding and F.M. Fisher Jr. (2002a). Spatial and temporal variability in methane emissions from rice paddies: Implications for assessing regional methane budgets. Nutrient Cycling in Agroecosystems, 64(1-2), 3-7.

Sass, R. L., F.M. Fisher, and J. A. Andrews. (2002b). Spatial variability in methane emissions from a Texas rice field with some general implications. Global biogeochemical cycles, 16(1), 15-1.

Sass, R.L., F.M Fisher, P.A. Harcombe, and F.T. Turner (1991a) "Mitigation of Methane Emissions from Rice Fields: Possible Adverse Effects of Incorporated Rice Straw." *Global Biogeochemical Cycles,* 5:275-287.

Sass, R.L., F.M. Fisher, F.T. Turner, and M.F. Jund (1991b) "Methane Emissions from Rice Fields as Influenced by Solar Radiation, Temperature, and Straw Incorporation." *Global Biogeochemical Cycles,* 5:335-350.

Sass, R.L., F.M. Fisher, P.A. Harcombe, and F.T. Turner (1990) "Methane Production and Emissions in a Texas Rice Field." *Global Biogeochemical Cycles,* 4:47-68.

Schueneman, T. (1997, 1999 through 2001) Personal Communication. Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL and ICF International.

Slaton, N. (1999 through 2001) Personal Communication. Nathan Slaton, Extension Agronomist—Rice, University of Arkansas Division of Agriculture Cooperative Extension Service and ICF International.

Stansel, J. (2004 through 2005) Email correspondence. Dr. Jim Stansel, Resident Director and Professor Emeritus, Texas A&M University Agricultural Research and Extension Center and ICF International.

Street, J. (1999 through 2003) Personal Communication. Joe Street, Rice Specialist, Mississippi State University, Delta Research Center and ICF International.

Texas Agricultural Experiment Station (2007 through 2014) *Texas Rice Acreage by Variety*. Agricultural Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University System. Available online at <http://beaumont.tamu.edu/CropSurvey/CropSurveyReport.aspx>.

Texas Agricultural Experiment Station (2006) *2005 - Texas Rice Crop Statistics Report*. Agricultural Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University System, p. 8. Available online at <http://beaumont.tamu.edu/eLibrary/TRRFReport_default.htm>.

USDA (2005 through 2014) *Crop Production Summary*. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at <http://usda.mannlib.cornell.edu>.

USDA (2012) *Summary of USDA-ARS Research on the Interrelationship of Genetic and Cultural Management Factors That Impact Grain Arsenic Accumulation in Rice*. News and Events. Agricultural Research Service, U.S. Department of Agriculture, Washington, D.C. Available online at <http://www.ars.usda.gov/is/pr/2012/120919.htm>. September 2013.

USDA (2003) *Field Crops, Final Estimates 1997-2002*. Statistical Bulletin No. 982. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at <http://usda.mannlib.cornell.edu/usda/reports/general/sb/>. September 2005.

USDA (1998) *Field Crops Final Estimates 1992-1997*. Statistical Bulletin Number 947 a. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at <http://usda.mannlib.cornell.edu/>. July 2001.

USDA (1994) *Field Crops Final Estimates 1987-1992*. Statistical Bulletin Number 896. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at <http://usda.mannlib.cornell.edu/>. July 2001.

Vayssières, M. (2013). Email correspondance. Marc Vayssières, Ph.D. Cal/EPA Air Resources Board Air Quality Planning & Science Division and Rachel Steele, ICF International. January 2014.

Walker, T. (2005, 2007 through 2008) Email correspondence. Tim Walker, Assistant Research Professor, Mississippi State University Delta Branch Exp. Station and ICF International.

Wang, J.J., S.K. Dodla, S. Viator, M. Kongchum, S. Harrison, S. D. Mudi, S. Liu, Z. Tian (2013). Agriculture Field Management Practices and Greenhouse Gas Emissions from Louisiana Soils. *Louisiana Agriculture*, Spring 2013: 8-9. Available online at <http://www.lsuagcenter.com/NR/rdonlyres/78D8B61A-96A8-49E1-B2EF-BA1D4CE4E698/93016/v56no2Spring2013.pdf>.

Wilson, C. (2002 through 2007, 2009 through 2012) Personal Communication. Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service and ICF International.

Yao, H., J. Jingyan, Z. Lianggang, R. L. Sass, and F. M. Fisher. (2001). Comparison of field measurements of CH_4 emission from rice cultivation in Nanjing, China and in Texas, USA. Advances in Atmospheric Sciences, 18(6), 1121-1130.

Young, M. (2013) Rice and Ducks. Ducks Unlimited, Memphis, TN. Available online at <http://www.ducks.org/conservation/farm-bill/rice-and-ducks---by-matt-young>.

Agricultural Soil Management

AAPFCO (2008 through 2014) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

AAPFCO (1995 through 2000a, 2002 through 2007) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Kentucky. Lexington, KY.

Bateman, E. J. and E. M. Baggs (2005) "Contributions of nitrification and denitrification to N_2O emissions from soils at different water-filled pore space." Biology and Fertility of Soils 41(6): 379-388.

Cibrowski, P. (1996) Personal Communication. Peter Cibrowski, Minnesota Pollution Control Agency and Heike Mainhardt, ICF Incorporated. July 29, 1996.

CTIC (2004) 2004 Crop Residue Management Survey. Conservation Technology Information Center. Available at <http://www.ctic.purdue.edu/CRM/>.

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., 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., 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., 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., T. Wirth, S.M. Ogle, W.J. Parton (2008) Estimating agricultural nitrous oxide emissions. EOS 89, 529-530.

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.

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.

EPA (2003) Clean Watersheds Needs Survey 2000—Report to Congress, U.S. Environmental Protection Agency. Washington, D.C. Available online at <http://www.epa.gov/owm/mtb/cwns/2000rtc/toc.htm>.

EPA (1999) Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste, U.S. Environmental Protection Agency. Available online at <http://biosolids.policy.net/relatives/18941.PDF>.

EPA (1993) Federal Register. Part II. Standards for the Use and Disposal of Sewage Sludge; Final Rules. U.S. Environmental Protection Agency, 40 CFR Parts 257, 403, and 503.

Firestone, M. K., and E.A. Davidson, Ed. (1989). Microbiological basis of NO and N_2O production and consumption in soil. Exchange of trace gases between terrestrial ecosystems and the atmosphere. New York, John Wiley & Sons.

H. Berbery, M. B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi (2006) North American regional reanalysis. Bulletin of the American Meteorological Society 87:343-360.

ILENR (1993) Illinois Inventory of Greenhouse Gas Emissions and Sinks: 1990. Office of Research and Planning, Illinois Department of Energy and Natural Resources. Springfield, IL.

IPCC (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.

Kessavalou, A., A.R. Mosier, J.W. Doran, R.A. Drijber, D.J. Lyon, and O. Heinemeyer (1998). "Fluxes of carbon dioxide, nitrogen oxide, and methane in grass sod and winter wheat -fallow tillage management." Journal of Environmental Quality 27: 1094-1104.

McFarland, M.J. (2001) Biosolids Engineering, New York: McGraw-Hill, p. 2.12.

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.

Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, E. Rogers, E.

Mosier, A. R., J.M. Duxbury, J.R. Freney, O. Heinemeyer, K. Minami (1998) "Assessing and mitigating N_2O emissions from agricultural soils." Climatic Change 40: 7-38.

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>.

NEBRA (2007) A National Biosolids Regulation, Quality, End Use & Disposal Survey. North East Biosolids and Residuals Association, July 21, 2007

Noller, J. (1996) Personal Communication. John Noller, Missouri Department of Natural Resources and Heike Mainhardt, ICF Incorporated. July 30, 1996.

Nusser, S.M., J.J. Goebel (1997) The national resources inventory: a long term monitoring programme. Environmental and Ecological Statistics, 4, 181-204.

Oregon Department of Energy (1995) Report on Reducing Oregon's Greenhouse Gas Emissions: Appendix D Inventory and Technical Discussion. Oregon Department of Energy. Salem, OR.

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.

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.

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.

Ruddy B.C., D.L. Lorenz, and D.K. Mueller (2006) County-level estimates of nutrient inputs to the land surface of the conterminous United States, 1982-2001. Scientific Investigations Report 2006-5012. U.S Department of the Interior.

Scheer, C., S.J. Del Grosso, W.J. Parton, D.W. Rowlings, P.R. Grace (2013) Modeling Nitrous Oxide Emissions from Irrigated Agriculture: Testing DAYCENT with High Frequency Measurements, Ecological Applications, in press, <http://dx.doi.org/10.1890/13-0570.1>.

Soil Survey Staff (2011) State Soil Geographic (STATSGO) Database for State. Natural Resources Conservation Service, United States Department of Agriculture. Available online at <http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html>.

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 (1991 through 1992a, 1993 through 1994) Commercial Fertilizers. Tennessee Valley Authority, Muscle Shoals, AL.

USDA-ERS (2011) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Online at: <http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices.aspx>.

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-NASS (2014) Quick Stats. National Agricultural Statistics Service, United States Department of Agriculture, Washington, D.C. <http://quickstats.nass.usda.gov/>.

USDA-NRCS (2015) Summary Report: 2012 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/nrcseprd396218.pdf>.

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>

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.

Wisconsin Department of Natural Resources (1993) Wisconsin Greenhouse Gas Emissions: Estimates for 1990. Bureau of Air Management, Wisconsin Department of Natural Resources, Madison, WI.

Field Burning of Agricultural Residues

Barnard, G., and L. Kristoferson (1985) *Agricultural Residues as Fuel in the Third World*. Earthscan Energy Information Programme and the Beijer Institute of the Royal Swedish Academy of Sciences. London, England.

Cantens, G. (2004 through 2005) Personal Communication. Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company and ICF International.

Deren, C. (2002) Personal communication. Dr. Chris Deren, Everglades Research and Education Centre at the University of Florida and Caren Mintz, ICF International. August 15, 2002.

EPA (1994) *International Anthropogenic Methane Emissions: Estimates for 1990, Report to Congress.* EPA 230-R-93-010. Office of Policy Planning and Evaluation, U.S. Environmental Protection Agency, Washington, D.C.

Gonzalez, R. (2007 through 2014) Email correspondence. Rene Gonzalez, Plant Manager, Sem-Chi Rice Company and ICF International.

Huang, Y., W. Zhang, W. Sun, and X. Zheng (2007) "Net Primary Production of Chinese Croplands from 1950 to 1999." *Ecological Applications*, 17(3):692-701.

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/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency, Paris, France.

Kinoshita, C.M. (1988) "Composition and processing of burned and unburned cane in Hawaii." *Intl. Sugar Jnl.* 90:1070, 34-37.

Kirstein, A. (2003 through 2004) Personal Communication. Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, Florida and ICF International.

Lachnicht, S.L., P.F. Hendrix, R.L. Potter, D.C. Coleman, and D.A. Crossley Jr. (2004) "Winter decomposition of transgenic cotton residue in conventional-till and no-till systems." *Applied Soil Ecology*, 27:135-142.

Lee, D. (2003 through 2007) Email correspondence. Danny Lee, OK Farm Service Agency and ICF International.

McCarty, J.L. (2011) “Remote Sensing-Based Estimates of Annual and Seasonal Emissions from Crop Residue Burning in the Contiguous United States.” *Journal of the Air & Waste Management Association*, 61:1,22-34, DOI: 10.3155/1047-3289.61.1.22.

McCarty, J.L. (2010) Agricultural Residue Burning in the Contiguous United States by Crop Type and State. Geographic Information Systems (GIS) Data provided to the EPA Climate Change Division by George Pouliot, Atmospheric Modeling and Analysis Division, EPA. Dr. McCarty’s research was supported by the NRI Air Quality Program of the Cooperative State Research, Education, and Extension Service, USDA, under Agreement No. 20063511216669 and the NASA Earth System Science Fellowship.

McCarty, J.L. (2009) *Seasonal and Interannual Variability of Emissions from Crop Residue Burning in the Contiguous United States*. Dissertation. University of Maryland, College Park.

Murphy, W.J. (1993). “Tables for weights and measurement: crops”. *Extension publications. (University of Missouri Extension)* <http://extension.missouri.edu/publications/DisplayPub.aspx?P=G4020>.

Schueneman, T. (1999 through 2001) Personal Communication. Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL and ICF International. July 30, 2001.Schueneman, T.J. and C.W. Deren (2002) “An Overview of the Florida Rice Industry.” SS-AGR-77, Agronomy Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Revised November 2002.

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.

Turn, S.Q., B.M. Jenkins, J.C. Chow, L.C. Pritchett, D. Campbell, T. Cahill, and S.A. Whalen (1997) “Elemental characterization of particulate matter emitted from biomass burning: Wind tunnel derived source profiles for herbaceous and wood fuels.” *Journal of Geophysical Research* 102(D3):3683-3699.

USDA (2013) 2010 National Resources Inventory, Natural Resources Conservation Service, Washington DC and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa.

USDA (2015) Quick Stats: U.S. & All States Data; Crops; Production and Area Harvested; 1990 - 2014. National Agricultural Statistics Service, U.S. Department of Agriculture. Washington, D.C. U.S. Department of Agriculture, National Agricultural Statistics Service. Washington, D.C., Available online at <http://quickstats.nass.usda.gov/>.

Land Use, Land-Use Change, and Forestry

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.

UNFCCC (2013) *Report of the Conference of the Parties on its nineteenth session*, *held in Warsaw from 11 to 23 November 2013.* Available at <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>

Representation of the U.S. Land Base

Alaska Department of Natural Resources (2006) Alaska Infrastructure 1:63,360. Available online at <http://dnr.alaska.gov/SpatialUtility/SUC?cmd=extract&layerid=75>.

Alaska Interagency Fire Management Council (1998) Alaska Interagency Wildland Fire Management Plan. Available online at <http://agdc.usgs.gov/data/blm/fire/index.html>.

Alaska Oil and Gas Conservation Commission (2009) Oil and Gas Information System. Available online at <http://doa.alaska.gov/ogc/publicdb.html>.

EIA (2011) Coal Production and Preparation Report Shapefile. Available online at <http://www.eia.gov/state/notes-sources.cfm#maps>.

ESRI (2008) ESRI Data & Maps. Redlands, CA: Environmental Systems Research Institute. [CD-ROM]

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and J. Wickham. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, *PE&RS*, Vol. 77(9):858-864.

Homer, C., J. Dewitz, J. Fry, M. Coan, N. Hossain, C. Larson, N. Herold, A. McKerrow, J.N. VanDriel and J. Wickham. (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.

IPCC (2010) Revisiting the use of managed land as a proxy for estimating national anthropogenic emissions and removals. Eggleston HS, Srivastava N, Tanabe K, Baasansuren J, (eds.).Institute for Global Environmental Studies, Intergovernmental Panel on Climate Change, Hayama, Kanagawa, Japan.

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.

Jin, S., L. Yang, P. Danielson, C. Homer, J. Fry, and G. Xian. (2013) A comprehensive change detection method for updating the National Land Cover Database to circa 2011. Remote Sensing of Environment, 132: 159-175.

NOAA Coastal Change Analysis Program (C-CAP) Regional Land Cover Database. Data collected 1995-present. Charleston, SC: National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center. Data accessed at <www.csc.noaa.gov/landcover>.

Nusser, S.M. and J.J. Goebel (1997) "The national resources inventory: a long-term multi-resource monitoring programme." *Environmental and Ecological Statistics* 4:181-204.

Smith, W.B., P.D. Miles, C.H. Perry, and S.A. Pugh (2009) *Forest Resources of the United States, 2007*. Gen. Tech. Rep. WO-78. U.S. Department of Agriculture Forest Service, Washington, D.C.

U.S. Census Bureau (2010) Topologically Integrated Geographic Encoding and Referencing (TIGER) system shapefiles. U.S. Census Bureau, Washington, D.C. Available online at <http://www.census.gov/geo/www/tiger>.

U.S. Department of Agriculture (2014) County Data - Livestock, 1990-2014. U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, D.C.

U.S. Department of Interior (2005) *Federal Lands of the United States*. National Atlas of the United States, U.S. Department of the Interior, Washington D.C. Available online at <http://nationalatlas.gov/atlasftp.html?openChapters=chpbound#chpbound>.

United States Geological Survey (USGS), Gap Analysis Program (2012) Protected Areas Database of the United States (PADUS), version 1.3 Combined Feature Class. November 2012.

USGS (2012) Alaska Resource Data File. Available online at <http://ardf.wr.usgs.gov/>.

USGS (2005) Active Mines and Mineral Processing Plants in the United States in 2003. U.S. Geological Survey, Reston, VA.

Forest Land Remaining Forest Land: Changes in Forest Carbon Stocks

AF&PA (2006a and earlier) Statistical roundup. (Monthly). Washington, D.C. American Forest & Paper Association.

AF&PA (2006b and earlier) Statistics of paper, paperboard and wood pulp. Washington, D.C. 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, D.C., 1-26 and 261-379 (appendices 262 and 263)..

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.

Domke, G.M., J.E. Smith, and C.W. Woodall. (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., 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., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (in review). A framework for estimating litter carbon stocks in forests of the United States. Intended outlet: *Science of the Total Environment*

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., Nave, L.E., Woodall, C.W., Swanston, C.W. In Prep. Towards field-based estimates of soil organic carbon in forests of the United States.

EPA (2006) *Municipal solid waste in the United States: 2005 Facts and figures*. Office of Solid Waste, U.S. Environmental Protection Agency. Washington, D.C. (5306P) EPA530-R-06-011. Available online at <http://www.epa.gov/msw/msw99.htm>.

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. (1958) "Historical forestry statistics of the United States." Statistical Bull. 228. U.S. Department of Agriculture Forest Service, 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, D.C.

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.

Howard, J. L. (forthcoming) *U.S. timber production, trade, consumption, and price statistics 1965 to 2013*. Res. Pap. FPL-RP-XXX. 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.

Howard, J. 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>.

Ince, P.J., Kramp, A.D., Skog, K.E., Spelter, H.N. and Wear, D.N., 2011. US 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 (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 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.

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.

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.

Ogle, S.M., Woodall, C.W., Swan, A., Smith, J.E., Wirth. T. In preparation. Determining the Managed Land Base for Delineating Carbon Sources and Sinks in the United States. Environmental Science and Policy.

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: US 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. Gen. Tech. Rep. WO-91. Washington, D.C. 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 Folliott, 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).

Russell, M.B.; D’Amato, A.W.; Schulz, B.K.; Woodall, C.W.; Domke, G.M.; Bradford, J.B. 2014 Quantifying understory vegetation in the U.S. Lake States: a proposed framework to inform regional forest carbon stocks. Forestry. 87: 629-638.

Russell, M.B.; Domke, G.M.; Woodall, C.W.; D’Amato, A.W. 2015. Comparisons of allometric and climate-derived estimates of tree coarse root carbon in forests of the United States. Carbon Balance and Management. 10: 20.

Skog, K.E. (2008) Sequestration of carbon in harvested wood products for the United States. *Forest Products Journal* 58:56-72.

Smith, W. B., P. D. Miles, C. H. Perry, and S. A. Pugh (2009) *Forest Resources of the United States, 2007*. General Technical Report WO-78, U.S. Department of Agriculture Forest Service, Washington Office.

Steer, Henry B. (1948) *Lumber production in the United States*. Misc. Pub. 669, U.S. Department of Agriculture Forest Service. Washington, D.C.

Ulrich, Alice (1985) *U.S. Timber Production, Trade, Consumption, and Price Statistics 1950-1985*. Misc. Pub. 1453, U.S. Department of Agriculture Forest Service. Washington, D.C.

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, D.C, 77.

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.

USDA Forest Service (2015a) 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 17 September 2015.

USDA Forest Service. (2015b) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at <http://apps.fs.fed.us/fiadb-downloads/datamart.html>. Accessed 17 September 2015.

USDA Forest Service. (2015c) 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 17 September 2015.

USDA Forest Service (2015d) 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 17 September 2015.

U.S. Census Bureau (1976) *Historical Statistics of the United States, Colonial Times to 1970, Vol. 1*. Washington, D.C.

Wear, D.N., Coulston, J.W. 2015. From sink to source: Regional variation in U.S. forest carbon futures. Scientific Reports. 5: 16518.

Westfall, J.A., Woodall, C.W., Hatfield, M.A. (2013) A statistical power analysis of woody carbon flux from forest inventory data. Climatic Change. 118: 919-931.

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 US 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. (2012) Where did the U.S. forest biomass/carbon go? Journal of Forestry. 110: 113-114.

Woodall, C.W., Amacher, M.C., Bechtold, W.A., Coulston, J.W., Jovan, S., Perry, C.H., Randolph, K.C., Schulz, B.K., Smith, G.C., Tkacz, B., Will-Wolf, S. (2011b) "Status and future of the forest health indicators program of the United States." *Environmental Monitoring and Assessment*. 177: 419-436.

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., Domke, G.M., Riley, K, Oswalt, C.M., Crocker, S.J. Yohe, G.W. (2013) Developing a framework for assessing global change risks to forest carbon stocks. PLOS One. 8: e73222.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011a) 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., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

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., 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.

Forest Land Remaining Forest Land: Non-CO_2 Emissions from Forest Fires

deVries, R.E. (1987) A Preliminary Investigation of the Growth and Longevity of Trees in Central Park. M.S. thesis, Rutgers University, New Brunswick, NJ.

Dwyer, J.F., D.J. Nowak, M.H. Noble, and S.M. Sisinni (2000) Connecting People with Ecosystems in the 21st Century: An Assessment of Our Nation's Urban Forests. General Technical Report PNW-GTR-490, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Fleming, L.E. (1988) Growth Estimation of Street Trees in Central New Jersey. M.S. thesis, Rutgers University, New Brunswick, NJ.

Frelich, L.E. (1992) Predicting Dimensional Relationships for Twin Cities Shade Trees. University of Minnesota, Department of Forest Resources, St. Paul, MN, p. 33.

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.

Nowak, D.J. (2011) Phone conference regarding Changes in Carbon Stocks in Urban Trees estimation methodology. David Nowak, USDA, Jennifer Jenkins, EPA, and Mark Flugge and Nikhil Nadkarni, ICF International. January 4, 2011.

Nowak, D.J. (2009) E-mail correspondence regarding new data for Chicago's urban forest. David Nowak, USDA Forest Service to Nikhil Nadkarni, ICF International. October 7, 2009.

Nowak, D.J. (2007a) "New York City's Urban Forest." USDA Forest Service. Newtown Square, PA, February 2007.

Nowak, D.J. (2007b) E-mail correspondence regarding revised sequestration values and standard errors for sequestration values. David Nowak, USDA Forest Service to Susan Asam, ICF International. October 31, 2007.

Nowak, D.J. (1994) "Atmospheric Carbon Dioxide Reduction by Chicago's Urban Forest." In: Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. E.G. McPherson, D.J. Nowak, and R.A. Rowntree (eds.). General Technical Report NE-186. U.S. Department of Agriculture Forest Service, Radnor, PA. pp. 83–94.

Nowak, D.J. (1986) "Silvics of an Urban Tree Species: Norway Maple (Acer platanoides L.)." M.S. thesis, College of Environmental Science and Forestry, State University of New York, Syracuse, NY.

Nowak, D.J., Buckelew-Cumming, A., Twardus, D., Hoehn, R., and Mielke, M. (2007). National Forest Health Monitoring Program, Monitoring Urban Forests in Indiana: Pilot Study 2002, Part 2: Statewide Estimates Using the UFORE Model. Northeastern Area Report. NA-FR-01e07, p. 13.

Nowak, D.J. and D.E. Crane (2002) "Carbon Storage and Sequestration by Urban Trees in the United States." Environmental Pollution 116(3):381–389.

Nowak, D.J., D.E. Crane, J.C. Stevens, and M. Ibarra (2002) Brooklyn's Urban Forest. General Technical Report NE-290. U.S. Department of Agriculture Forest Service, Newtown Square, PA.

Nowak, D.J., and E.J. Greenfield (2012) Tree and impervious cover in the United States. *Journal of Landscape and Urban Planning* (107) pp. 21-30.

Nowak, D.J., E.J. Greenfield, R.E. Hoehn, and E. Lapoint (2013) Carbon Storage and Sequestration by Trees in Urban and Community Areas of the United States. *Environmental Pollution* 178: 229-236. March 12, 2013.

Nowak, D.J., J.T. Walton, L.G. Kaya, and J.F. Dwyer (2005) "The Increasing Influence of Urban Environments on U.S. Forest Management." Journal of Forestry 103(8):377–382.

Smith, W.B. and S.R. Shifley (1984) Diameter Growth, Survival, and Volume Estimates for Trees in Indiana and Illinois. Research Paper NC-257. North Central Forest Experiment Station, U.S. Department of Agriculture Forest Service, St. Paul, MN.

U.S. Census Bureau (2012) “A national 2010 urban area file containing a list of all urbanized areas and urban clusters (including Puerto Rico and the Island Areas) sorted by UACE code.” U.S. Census Bureau, Geography Division.

Forest Land Remaining Forest Land: N_2O Fluxes from Soils

Albaugh, T.J., Allen, H.L., Fox, T.R. (2007) Historical Patterns of Forest Fertilization in the Southeastern United States from 1969 to 2004. Southern Journal of Applied Forestry, 31, 129-137(9).

Binkley, D. (2004) Email correspondence regarding the 95% CI for area estimates of southern pine plantations receiving N fertilizer (±20%) and the rate applied for areas receiving N fertilizer (100 to 200 pounds/acre). Dan Binkley, Department of Forest, Rangeland, and Watershed Stewardship, Colorado State University and Stephen Del Grosso, Natural Resource Ecology Laboratory, Colorado State University. September 19, 2004.

Binkley, D., R. Carter, and H.L. Allen (1995) Nitrogen Fertilization Practices in Forestry. In: *Nitrogen Fertilization in the Environment*, P.E. Bacon (ed.), Marcel Decker, Inc., New York.

Briggs, D. (2007) *Management Practices on Pacific Northwest West-Side Industrial Forest Lands, 1991-2005: With Projections to 2010*. Stand Management Cooperative, SMC Working Paper Number 6, College of Forest Resources, University of Washington, Seattle.

Fox, T.R., H. L.Allen, T.J. Albaugh, R. Rubilar, and C.A. Carlson (2007) Tree Nutrition and Forest Fertilization of Pine Plantations in the Southern United States. Southern Journal of Applied Forestry. 31, 5-11.

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.

USDA Forest Service (2001) *U.S. Forest Facts and Historical Trends*. FS-696. U.S. Department of Agriculture Forest Service, Washington, D.C. Available online at <http://www.fia.fs.fed.us/library/ForestFactsMetric.pdf>.

Cropland Remaining Cropland: Mineral and Organic Soil Carbon Stock Changes

Armentano, T. V., and E.S. Menges (1986). Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. Journal of Ecology 74: 755-774.

Brady, N.C. and R.R. Weil (1999) The Nature and Properties of Soils. Prentice Hall. Upper Saddle River, NJ, 881.
Conant, R. T., K. Paustian, and E.T. Elliott (2001). "Grassland management and conversion into grassland: effects on soil carbon." Ecological Applications 11: 343-355.

CTIC (2004) National Crop Residue Management Survey: 1989-2004. Conservation Technology Information Center, Purdue University, Available at <http://www.ctic.purdue.edu/CRM/>

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.

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 Modeling Carbon and Nitrogen Dynamics for Soil Management, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

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: Understanding Greenhouse Gas Emissions from Agricultural Management, L. Guo, A. Gunasekara, L. McConnell (eds.). American Chemical Society, Washington, D.C.

Edmonds, L., R. L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaefer (2003) "Costs associated with development and implementation of Comprehensive Nutrient Management Plans." Part I—Nutrient management, land treatment, manure and wastewater handling and storage, and recordkeeping. Natural Resources Conservation Service, U.S. Department of Agriculture. Available online at <http://www.nrcs.usda.gov/technical/land/pubs/cnmp1.html>.

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.

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.

Gurung, R.B., F.J. Breidt, A. Dutin, and S.M. Ogle (2009) Predicting Enhanced Vegetation Index (EVI) for ecosystem modeling applications. Remote Sensing of Environment 113:2186-2193.

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.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K., 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, v. 81, no. 5, p. 345-354

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>.

Jones, C., R. Claassen, E. Marx and S.M. Ogle (forthcoming) GHG mitigation and the CRP: the role of post-contract land use change.

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.

Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, E. Rogers, E. H. Berbery, M. B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi (2006) North American regional reanalysis. Bulletin of the American Meteorological Society 87:343-360.

NASS (2004) Agricultural Chemical Usage: 2003 Field Crops Summary. Report AgCh1(04)a. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at <Hhttp://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdfH>.

NASS (1999) Agricultural Chemical Usage: 1998 Field Crops Summary. Report AgCH1(99). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. 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, Washington, D.C. Available online at <http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txtH>.

NRCS (1999) Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys, 2nd Edition. Agricultural Handbook Number 436, Natural Resources Conservation Service, U.S. Department of Agriculture, Washington, D.C.

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.

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 16:810-820.

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., et al. (2005) "Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions." Biogeochemistry 72: 87-121.

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. Eve, M. Sperrow, F.J. Breidt, and K. Paustian (2002) Agricultural Soil C Emissions, 1990-2001: Documentation to Accompany EPA Inventory Tables. Natural Resources Ecology Laboratory, Fort Collins, CO. Provided in an e-mail from Stephen Ogle, NREL to Barbara Braatz, ICF International. September 23, 2002

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., 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., 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.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." Biogeochemistry 5:109-131.

Paustian, K., et al. (1997a). "Agricultural soils as a sink to mitigate CO_2 emissions." Soil Use and Management 13: 230-244.

Paustian, K., et al. (1997b). Management controls on soil carbon. In Soil organic matter in temperate agroecosystems: long-term experiments in North America (Paul E.A., K. Paustian, and C.V. Cole, eds). Boca Raton, CRC Press, pp. 15-49.

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 (2015) *PRISM Climate Data*. Oregon State University. July 24, 2015. Available online at: <http://prism.oregonstate.edu>.

Soil Survey Staff (2015) State Soil Geographic (STATSGO) Database for State. Natural Resources Conservation Service, United States Department of Agriculture. Available online at <http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html>.

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.

USDA-ERS (2011) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Online at: <http://ers.usda.gov/Data/ARMS/CropOverview.htm.>.

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, D.C. Available online at <https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/Conservation/PDF/summarysept2014.pdf>.

USDA-NRCS (2000) Digital Data and Summary Report: 1997 National Resources Inventory. Revised December 2000. Resources Inventory Division, Natural Resources Conservation Service, United States Department of Agriculture, Beltsville, MD.

USDA-NRCS (2015) Summary Report: 2012 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/nrcseprd396218.pdf>.

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>.

Cropland Remaining Cropland: Liming

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.

Tepordei, V.V. (1997 through 2006) "Crushed Stone," In *Minerals Yearbook*. U.S. Department of the Interior/U.S. Geological Survey. Washington, D.C. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

Tepordei, V.V. (2003b) Personal communication. Valentin Tepordei, U.S. Geological Survey and ICF Consulting, August 18, 2003.

Tepordei, V.V. (1996) "Crushed Stone," In *Minerals Yearbook 1994*. U.S. Department of the Interior/Bureau of Mines, Washington, D.C. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2000.

Tepordei, V.V. (1995) "Crushed Stone," In *Minerals Yearbook 1993*. U.S. Department of the Interior/Bureau of Mines, Washington, D.C. pp. 1107–1147.

Tepordei, V. V. (1994) "Crushed Stone," In *Minerals Yearbook 1992*. U.S. Department of the Interior/Bureau of Mines, Washington, D.C. pp. 1279-1303.

Tepordei, V.V. (1993) "Crushed Stone," In *Minerals Yearbook 1991*. U.S. Department of the Interior/Bureau of Mines, Washington, D.C. pp. 1469-1511.

USGS (2015) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2015*, U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

USGS (2014) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2014*, U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

USGS (2013) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2013*, U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

USGS (2012) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2012*, U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

USGS (2011) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2011*, U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

USGS (2010) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2010*, U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

USGS (2009) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2009*, U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

USGS (2008) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2008*, U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

USGS (2007) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2007*. U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

West, T.O. (2008) Email correspondence. Tristram West, Environmental Sciences Division, Oak Ridge National Laboratory, U.S. Department of Energy and Nikhil Nadkarni, ICF International on suitability of liming emission factor for the entire United States. June 9, 2008.

West, T.O., and A.C. McBride (2005) “The contribution of agricultural lime to carbon dioxide emissions in the United States: dissolution, transport, and net emissions,” *Agricultural Ecosystems & Environment* 108:145-154.

Willett, J.C. (2015) "Crushed Stone," In *Minerals Yearbook 2013*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed September 2015.

Willett, J.C. (2014) "Crushed Stone," In *Minerals Yearbook 2012*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed September 2014.

Willett, J.C. (2013a) "Crushed Stone," In *Minerals Yearbook 2011*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed May 2013.

Willett, J.C. (2013b) Personal Communication. Jason Willet, U.S. Geological Survey and ICF International. September 9, 2013.

Willett, J.C. (2011a) "Crushed Stone," In *Minerals Yearbook 2009*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2011.

Willett, J.C. (2011b) "Crushed Stone," In *Minerals Yearbook 2010*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed September 2012.

Willett, J.C. (2010) "Crushed Stone," In *Minerals Yearbook 2008*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2010.

Willett, J.C. (2009) "Crushed Stone," In *Minerals Yearbook 2007*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2009.

Willett, J.C. (2007a) "Crushed Stone," In *Minerals Yearbook 2005*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2007.

Willett, J.C. (2007b) "Crushed Stone," In *Minerals Yearbook 2006*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2008.

Cropland Remaining Cropland: Urea Fertilization

AAPFCO (2008 through 2014) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

AAPFCO (1995 through 2000a, 2002 through 2007) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Kentucky. Lexington, KY.

AAPFCO (2000b) *1999-2000 Commercial Fertilizers Data, ASCII files.* Available from David Terry, Secretary, AAPFCO.

EPA (2000) Preliminary Data Summary: Airport Deicing Operations (Revised). EPA-821-R-00-016. August 2000.

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.

Itle, C. (2009) Email correspondence. Cortney Itle, ERG and Tom Wirth, U.S. Environmental Protection Agency on the amount of urea used in aircraft deicing. January 7, 2009.

Terry, D. (2007) Email correspondence. David Terry, Fertilizer Regulatory program, University of Kentucky and David Berv, ICF International. September 7, 2007.

TVA (1991 through 1994) *Commercial Fertilizers*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1992b) Fertilizer Summary Data 1992. Tennessee Valley Authority, Muscle Shoals, AL.

Land Converted to Cropland

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 Modeling Carbon and Nitrogen Dynamics for Soil Management, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

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: Understanding Greenhouse Gas Emissions from Agricultural Management (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

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

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.

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 16:810-820.

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., 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., 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.

USDA-NRCS (2015) Summary Report: 2012 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/nrcseprd396218.pdf>.

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>.

Grassland Remaining Grassland

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: Understanding Greenhouse Gas Emissions from Agricultural Management (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

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 Modeling Carbon and Nitrogen Dynamics for Soil Management, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Edmonds, L., R. L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaefer (2003) “Costs associated with development and implementation of Comprehensive Nutrient Management Plans.” Part I—Nutrient management, land treatment, manure and wastewater handling and storage, and recordkeeping. Natural Resources Conservation Service, U.S. Department of Agriculture. Available online at <http://www.nrcs.usda.gov/technical/land/pubs/cnmp1.html>.

EPA (1999) Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste, U.S. Environmental Protection Agency. Available online at <http://biosolids.policy.net/relatives/18941.PDF>.

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.

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.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K., 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, v. 81, no. 5, p. 345-354

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.

Kellogg, R.L., C.H. Lander, D.C. Moffitt, and N. Gollehon (2000) Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States. U.S. Department of Agriculture, Washington, D.C. Publication number nps00-0579.

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.

NASS (2004) Agricultural Chemical Usage: 2003 Field Crops Summary. Report AgCh1(04)a. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at <Hhttp://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdfH>.

NASS (1999) Agricultural Chemical Usage: 1998 Field Crops Summary. Report AgCH1(99). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. 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, Washington, D.C. Available online at <http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txtH>.

NEBRA (2007) A National Biosolids Regulation, Quality, End Use & Disposal Survey. North East Biosolids and Residuals Association. July 21, 2007.

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 16:810-820.

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. 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., 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.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." Biogeochemistry 5:109-131.

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.

United States Bureau of Land Management (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>.

USDA-ERS (2011) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Online at: <http://ers.usda.gov/Data/ARMS/CropOverview.htm.>.

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-NRCS (2015) Summary Report: 2012 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/nrcseprd396218.pdf>.

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>.

Land Converted to Grassland

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: Understanding Greenhouse Gas Emissions from Agricultural Management (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

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

Modeling Carbon and Nitrogen Dynamics for Soil Management (Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

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.

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.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K., 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, v. 81, no. 5, p. 345-354

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.

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.

NASS (2004) Agricultural Chemical Usage: 2003 Field Crops Summary. Report AgCh1(04)a. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at <Hhttp://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdfH>.

NASS (1999) Agricultural Chemical Usage: 1998 Field Crops Summary. Report AgCH1(99). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. 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, Washington, D.C. Available online at <http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txtH>.

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 16:810-820.

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. 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., 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.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." Biogeochemistry 5:109-131.

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.

United States Bureau of Land Management (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>.

USDA-ERS (2011) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Online at: <http://ers.usda.gov/Data/ARMS/CropOverview.htm>.

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-NRCS (2015) Summary Report: 2012 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/nrcseprd396218.pdf>.

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>.

Wetlands Remaining Wetlands: CO_2, CH_4, and N_2O Emissions from Peatlands Remaining Peatlands

Apodaca, L. (2011) Email correspondence. Lori Apodaca, Peat Commodity Specialist, USGS and Emily Rowan, ICF International. November.

Apodaca, L. (2008) E-mail correspondence. Lori Apodaca, Peat Commodity Specialist, USGS and Emily Rowan, ICF International. October and November.

Cleary, J., N. Roulet and T.R. Moore (2005) "Greenhouse gas emissions from Canadian peat extraction, 1990-2000: A life-cycle analysis." *Ambio* 34:456–461.

Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2014) *Alaska's Mineral Industry Report (1997–2013).* Alaska Department of Natural Resources, Fairbanks, AK. Available online at <http://www.dggs.dnr.state.ak.us/pubs/pubs?reqtype=minerals>.

IPCC (2013) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report (AR4) of the IPCC*. The Intergovernmental Panel on Climate Change, R.K. Pachauri, A. Resinger (eds.). Geneva, Switzerland.

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.

Szumigala, D.J. (2011) Phone conversation. Dr. David Szumigala, Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources and Emily Rowan, ICF International. January 18, 2011.

Szumigala, D.J. (2008) Phone conversation. Dr. David Szumigala, Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources and Emily Rowan, ICF International. October 17, 2008.

USGS (1991–2015a) *Minerals Yearbook: Peat (1994–2014).* United States Geological Survey, Reston, VA. Available online at < http://minerals.usgs.gov/minerals/pubs/commodity/peat/index.html#myb >.

United States Geological Survey (USGS) (2015b) *Mineral Commodity Summaries: Peat (2014).* United States Geological Survey, Reston, VA. Available online at < http://minerals.usgs.gov/minerals/pubs/mcs/2015/mcs2015.pdf >.

USGS (2015c) *Mineral Commodity Summaries: Peat (2014).* United States Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/mcs/2015/mcs2015.pdf>.

Settlements Remaining Settlements: Changes in Carbon Stocks in Urban Trees

deVries, R.E. (1987) A Preliminary Investigation of the Growth and Longevity of Trees in Central Park. M.S. thesis, Rutgers University, New Brunswick, NJ.

Dwyer, J.F., D.J. Nowak, M.H. Noble, and S.M. Sisinni (2000) Connecting People with Ecosystems in the 21st Century: An Assessment of Our Nation's Urban Forests. General Technical Report PNW-GTR-490, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Fleming, L.E. (1988) Growth Estimation of Street Trees in Central New Jersey. M.S. thesis, Rutgers University, New Brunswick, NJ.

Frelich, L.E. (1992) Predicting Dimensional Relationships for Twin Cities Shade Trees. University of Minnesota, Department of Forest Resources, St. Paul, MN, p. 33.

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.

Nowak, D.J. (2011) Phone conference regarding Changes in Carbon Stocks in Urban Trees estimation methodology. David Nowak, USDA, Jennifer Jenkins, EPA, and Mark Flugge and Nikhil Nadkarni, ICF International. January 4, 2011.

Nowak, D.J. (2009) E-mail correspondence regarding new data for Chicago's urban forest. David Nowak, USDA Forest Service to Nikhil Nadkarni, ICF International. October 7, 2009.

Nowak, D.J. (2007a) "New York City's Urban Forest." USDA Forest Service. Newtown Square, PA, February 2007.

Nowak, D.J. (2007b) E-mail correspondence regarding revised sequestration values and standard errors for sequestration values. David Nowak, USDA Forest Service to Susan Asam, ICF International. October 31, 2007.

Nowak, D.J. (1994) "Atmospheric Carbon Dioxide Reduction by Chicago's Urban Forest." In: Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. E.G. McPherson, D.J. Nowak, and R.A. Rowntree (eds.). General Technical Report NE-186. U.S. Department of Agriculture Forest Service, Radnor, PA. pp. 83–94.

Nowak, D.J. (1986) "Silvics of an Urban Tree Species: Norway Maple (Acer platanoides L.)." M.S. thesis, College of Environmental Science and Forestry, State University of New York, Syracuse, NY.

Nowak, D.J., Buckelew-Cumming, A., Twardus, D., Hoehn, R., and Mielke, M. (2007). National Forest Health Monitoring Program, Monitoring Urban Forests in Indiana: Pilot Study 2002, Part 2: Statewide Estimates Using the UFORE Model. Northeastern Area Report. NA-FR-01e07, p. 13.

Nowak, D.J. and D.E. Crane (2002) "Carbon Storage and Sequestration by Urban Trees in the United States." Environmental Pollution 116(3):381–389.

Nowak, D.J., D.E. Crane, J.C. Stevens, and M. Ibarra (2002) Brooklyn's Urban Forest. General Technical Report NE-290. U.S. Department of Agriculture Forest Service, Newtown Square, PA.

Nowak, D.J., and E.J. Greenfield (2012) Tree and impervious cover in the United States. *Journal of Landscape and Urban Planning* (107) pp. 21-30.

Nowak, D.J., E.J. Greenfield, R.E. Hoehn, and E. Lapoint (2013) Carbon Storage and Sequestration by Trees in Urban and Community Areas of the United States. *Environmental Pollution* 178: 229-236. March 12, 2013.

Nowak, D.J., J.T. Walton, L.G. Kaya, and J.F. Dwyer (2005) "The Increasing Influence of Urban Environments on U.S. Forest Management." Journal of Forestry 103(8):377–382.

Smith, W.B. and S.R. Shifley (1984) Diameter Growth, Survival, and Volume Estimates for Trees in Indiana and Illinois. Research Paper NC-257. North Central Forest Experiment Station, U.S. Department of Agriculture Forest Service, St. Paul, MN.

U.S. Census Bureau (2012) "A national 2010 urban area file containing a list of all urbanized areas and urban clusters (including Puerto Rico and the Island Areas) sorted by UACE code." U.S. Census Bureau, Geography Division.

Settlements Remaining Settlements: N_2O Fluxes from Soils

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.

Ruddy B.C., D.L. Lorenz, and D.K. Mueller (2006) *County-level estimates of nutrient inputs to the land surface of the conterminous United States, 1982-2001*. Scientific Investigations Report 2006-5012. U.S. Department of the Interior.

Other: Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills

Barlaz, M.A. (2008) “Re: Corrections to Previously Published Carbon Storage Factors.” Memorandum to Randall Freed, ICF International. February 28, 2008.

Barlaz, M.A. (2005) “Decomposition of Leaves in Simulated Landfill.” Letter report to Randall Freed, ICF Consulting. June 29, 2005.

Barlaz, M.A. (1998) “Carbon Storage during Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills.” *Global Biogeochemical Cycles* 12:373–380.

De la Cruz, F.B. and M.A. Barlaz (2010) "Estimation of Waste Component Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data” *Environmental Science & Technology* 44:4722– 4728.

Eleazer, W.E., W.S. Odle, Y. Wang, and M.A. Barlaz (1997) “Biodegradability of Municipal Solid Waste Components in Laboratory-Scale Landfills.” *Environmental Science & Technology* 31:911–917.

EPA (2015a) *Advancing Sustainable Materials Management: Facts and Figures 2013*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. Available online at <http://www.epa.gov/osw/nonhaz/municipal/msw99.htm>.

EPA (2015b) *Advancing Sustainable Materials Management: 2013 Historical (summary) Data Tables*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. Available online at <http://www.epa.gov/solidwaste/conserve/tools/recmeas/msw_improv.htm#H>.

EPA (1995) *Compilation of Air Pollutant Emission Factors*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC. AP-42 Fifth Edition. Available online at < http://www3.epa.gov/ttnchie1/ap42/>.

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.). Available online at <http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm>.

Oshins, C. and D. Block (2000) “Feedstock Composition at Composting Sites.” *Biocycle* 41(9):31–34.

Tchobanoglous, G., H. Theisen, and S.A. Vigil (1993) *Integrated Solid Waste Management, 1st edition*. McGraw-Hill, NY. Cited by Barlaz (1998) “Carbon Storage during Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills.” *Global Biogeochemical Cycles* 12:373–380.

Waste

Landfills

40 CFR Part 60, Subpart CC (2005) Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills, 60.30c--60.36c, Code of Federal Regulations, Title 40. Available online at <http://www.access.gpo.gov/nara/cfr/waisidx_05/40cfr60_05.html>.

40 CFR Part 60, Subpart WWW (2005) Standards of Performance for Municipal Solid Waste Landfills, 60.750--60.759, Code of Federal Regulations, Title 40. Available online at <http://www.access.gpo.gov/nara/cfr/waisidx_05/40cfr60_05.html>.

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>.

Bronstein, K., Coburn, J., and R. Schmeltz (2012) "Understanding the EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks and Mandatory GHG Reporting Program for Landfills: Methodologies, Uncertainties, Improvements and Deferrals." Prepared for the U.S. EPA International Emissions Inventory Conference, August 2012, Tampa, Florida. Available online at <http://www.epa.gov/ttnchie1/conference/ei20/session3/kbronstein.pdf>.

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 (2015a) *Landfill Gas-to-Energy Project Database.* Landfill Methane and Outreach Program. August 2015.

EPA (2015b) 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 (2015c) Rule and Implementation Information for Standards of Performance for Municipal Solid Waste Landfills, Docket #A-88-09. Available at < http://www3.epa.gov/ttn/atw/landfill/landflpg.html>.

EPA (2015d) Advancing Sustainable Materials Management: Facts and Figures 2013. June 2015. Available online at <http://www.epa.gov/sites/production/files/2015-09/documents/2013_advncng_smm_rpt.pdf>.

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.

ERG (2014) Draft Production Data Supplied by ERG for 1990-2013 for Pulp and Paper, Fruits and Vegetables, and Meat. August.

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.

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.

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 (2015a) Update the flare correction factor for the 1990-2014 Inventory. Memorandum prepared by K. Bronstein and M. McGrath for R. Schmeltz (EPA), November 25, 2015.

RTI (2015b) 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 (2011) Updated Research on Methane Oxidation in Landfills. Memorandum prepared by K. Weitz (RTI) for R. Schmeltz (EPA), January 14, 2011.

RTI (2011) Updated Research on Methane Oxidation in Landfills. Memorandum prepared by K. Weitz (RTI) for R. Schmeltz (EPA), January 14, 2011.

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>.

Solid Waste Association of North America (SWANA) (1998) *Comparison of Models for Predicting Landfill Methane Recovery*. Publication No. GR-LG 0075. March 1998.

U.S. Census Bureau (2015). Annual Population Estimates, Vintage 2014 April 1, 2010 to July 1, 2014. Available online at < http://www.census.gov/popest/data/national/asrh/2014/ >.

Waste Business Journal (WBJ) (2010). Directory of Waste Processing & Disposal Sites 2010.

Wastewater Treatment (TO BE UPDATED)

Ahn et al. (2010) N_2O Emissions from Activated Sludge Processes, 2008-2009: Results of a National Monitoring Survey in the United States. Environ. Sci. Technol. 44: 4505-4511.

Beecher et al. (2007) “A National Biosolids Regulation, Quality, End Use & Disposal Survey, Preliminary Report.” Northeast Biosolids and Residuals Association, April 14, 2007.

Benyahia, F., M. Abdulkarim, A. Embaby, and M. Rao. (2006) Refinery Wastewater Treatment: A true Technological Challenge. Presented at the Seventh Annual U.A.E. University Research Conference.

Climate Action Reserve (CAR) (2011) Landfill Project Protocol V4.0, June 2011. Available online at <http://www.climateactionreserve.org/how/protocols/us-landfill/>.

Chandran, K. (2012) Greenhouse Nitrogen Emissions from Wastewater Treatment Operation Phase I: Molecular Level Through Whole Reactor Level Characterization. WERF Report U4R07.

Donovan (1996) Siting an Ethanol Plant in the Northeast. C.T. Donovan Associates, Inc. Report presented to Northeast Regional Biomass Program (NRBP). (April). Available online at <http://www.nrbp.org/pdfs/pub09.pdf>. Accessed October 2006.

EIA (2014) Energy Information Administration. U.S. Refinery and Blender Net Production of Crude Oil and Petroleum Products (Thousand Barrels). Available online at: <http://tonto.eia.doe.gov/dnav/pet/hist/mttrpus1a.htm>. Accessed June 2014.

EPA (2008) US Environmental Protection Agency. Municipal Nutrient Removal Technologies Reference Document: Volume 2 – Appendices. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, D.C.

EPA (2004) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2004 – Report to Congress. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, D.C.

EPA (2002) U.S. Environmental Protection Agency. Development Document for the Proposed Effluent Limitations Guidelines and Standards for the Meat and Poultry Products Industry Point Source Category (40 CFR 432). EPA-821-B-01-007. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. January 2002.

EPA (2000) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2000 - Report to Congress. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at <http://www.epa.gov/owm/mtb/cwns/2000rtc/toc.htm>. Accessed July 2007.

EPA (1999) U.S. Environmental Protection Agency. Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. EPA530-R-99-009. September 1999.

EPA (1998) U.S. Environmental Protection Agency. “AP-42 Compilation of Air Pollutant Emission Factors.” Chapter 2.4, Table 2.4-3, page 2.4-13. Available online at <http://www.epa.gov/ttn/chief/ap42/ch02/final/c02s04.pdf>.

EPA (1997a) U.S. Environmental Protection Agency. Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment. EPA-600/R-97-091. Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency. Washington, D.C. September 1997.

EPA (1997b) U.S. Environmental Protection Agency. Supplemental Technical Development Document for Effluent Guidelines and Standards (Subparts B & E). EPA-821-R-97-011. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. October 1997.

EPA (1996) U.S. Environmental Protection Agency. 1996 Clean Water Needs Survey Report to Congress. Assessment of Needs for Publicly Owned Wastewater Treatment Facilities, Correction of Combined Sewer Overflows, and Management of Storm Water and Nonpoint Source Pollution in the United States. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at <http://www.epa.gov/owm/mtb/cwns/1996rtc/toc.htm>. Accessed July 2007.

EPA (1993) U.S. Environmental Protection Agency. Development Document for the Proposed Effluent Limitations Guidelines and Standards for the Pulp, Paper and Paperboard Point Source Category. EPA-821-R-93-019. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. October 1993.

EPA (1992) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 1992 – Report to Congress. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C.

EPA (1975) U.S. Environmental Protection Agency. Development Document for Interim Final and Proposed Effluent Limitations Guidelines and New Source Performance Standards for the Fruits, Vegetables, and Specialties Segment of the Canned and Preserved Fruits and Vegetables Point Source Category. United States Environmental Protection Agency, Office of Water. EPA-440/1-75-046. Washington D.C. October 1975.

EPA (1974) U.S. Environmental Protection Agency. Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Apple, Citrus, and Potato Processing Segment of the Canned and Preserved Fruits and Vegetables Point Source Category. Office of Water, U.S. Environmental Protection Agency, Washington, D.C. EPA-440/1-74-027-a. March 1974.

ERG (2014a) Recommended Improvements to the 1990-2013 Wastewater Greenhouse Gas Inventory. September 2014.

ERG (2014b) Recommended Improvements to the 1990-2013 Wastewater Greenhouse Gas Inventory Using the GHGRP Data. September 2014.

ERG (2013a) Revisions to Pulp and Paper Wastewater Inventory. October 2013.

ERG (2013b) Revisions to the Petroleum Wastewater Inventory. October 2013.

ERG (2011) Review of Current Research on Nitrous Oxide Emissions from Wastewater Treatment. April 2011.

ERG (2008) Planned Revisions of the Industrial Wastewater Inventory Emission Estimates for the 1990-2007 Inventory. August 10, 2008.

ERG (2006) Memorandum: Assessment of Greenhouse Gas Emissions from Wastewater Treatment of U.S. Ethanol Production Wastewaters. Prepared for Melissa Weitz, EPA. 10 October 2006.

FAO (2014) FAOSTAT-Forestry Database. Available online at <http://faostat3.fao.org/home/index.html#DOWNLOAD> Accessed July 2013.

Global Water Research Coalition (GWRC) (2011) N_2O and CH_4 Emission from Wastewater Collection and Treatment Systems - technical Report. GWRC Report 2011-30.

Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. (2004) Recommended Standards for Wastewater Facilities (Ten-State Standards).

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

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.

Leverenz, H.L., G. Tchobanoglous, and J.L. Darby (2010) "Evaluation of Greenhouse Gas Emissions from Septic Systems". Water Environment Research Foundation. Alexandria, VA.

Lockwood-Post (2002) Lockwood-Post's Directory of Pulp, Paper and Allied Trades, Miller-Freeman Publications. San Francisco, CA.

McFarland (2001) Biosolids Engineering, New York: McGraw-Hill, p. 2.12.

Merrick (1998) Wastewater Treatment Options for the Biomass-to-Ethanol Process. Report presented to National Renewable Energy Laboratory (NREL). Merrick & Company. Subcontract No. AXE-8-18020-01. October 22, 1998.

Metcalf & Eddy, Inc. (2003) Wastewater Engineering: Treatment, Disposal and Reuse, 4th ed. McGraw Hill Publishing.

Nemerow, N.L. and A. Dasgupta (1991) Industrial and Hazardous Waste Treatment. Van Nostrand Reinhold. NY. ISBN 0-442-31934-7.

NRBP (2001) Northeast Regional Biomass Program. An Ethanol Production Guidebook for Northeast States. Washington, D.C. (May 3). Available online at <http://www.nrbp.org/pdfs/pub26.pdf>. Accessed October 2006.

Rendleman, C.M. and Shapouri, H. (2007) New Technologies in Ethanol Production. USDA Agricultural Economic Report Number 842.

RFA (2014) Renewable Fuels Association. Historic U.S. Fuel Ethanol Production. Available online at <http://www.ethanolrfa.org/pages/statistics>. Accessed October 2012.

Ruocco (2006a) Email correspondence. Dr. Joe Ruocco, Phoenix Bio-Systems to Sarah Holman, ERG. “Capacity of Bio-Methanators (Dry Milling).” October 6, 2006.

Ruocco (2006b) Email correspondence. Dr. Joe Ruocco, Phoenix Bio-Systems to Sarah Holman, ERG. “Capacity of Bio-Methanators (Wet Milling).” October 16, 2006.

Scheehle, E.A., and Doorn, M.R. (2001) “Improvements to the U.S. Wastewater Methane and Nitrous Oxide Emissions Estimate.” July 2001.

Sullivan (SCS Engineers) (2010) The Importance of Landfill Gas Capture and Utilization in the U.S. Presented to SWICS, April 6, 2010. Available online at <http://www.scsengineers.com/Papers/Sullivan_Importance_of_LFG_Capture_and_Utilization_in_the_US.pdf>.

Sullivan (SCS Engineers) (2007) Current MSW Industry Position and State of the Practice on Methane Destruction Efficiency in Flares, Turbines, and Engines. Presented to Solid Waste Industry for Climate Solutions (SWICS). July 2007. Available online at <http://www.scsengineers.com/Papers/Sullivan_LFG_Destruction_Efficiency_White_Paper.pdf>.

UNFCCC (2012) CDM Methodological tool, Project emissions from flaring (Version 02.0.0). EB 68 Report. Annex 15. Available online at <http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-06-v1.pdf/history_view>.

U.S. Census Bureau (2014) International Database. Available online at <http://www.census.gov/ipc/www/idb/> and <http://www.census.gov/ipc/www/idbprint.html>. Accessed August 2014.

U.S. Census Bureau (2011) “American Housing Survey.” Table 1A-4: Selected Equipment and Plumbing--All Housing Units. From 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009 and 2011 reports. Available online at <http://www.census.gov/hhes/www/housing/ahs/nationaldata.html>. Accessed October 2012.

U.S. DOE (2013) U.S. Department of Energy Bioenergy Technologies Office. Biofuels Basics. Available online at <http://www1.eere.energy.gov/bioenergy/biofuels_basics.html#Ethanol>. Accessed September 2013.

USDA (2014a) U.S. Department of Agriculture. National Agricultural Statistics Service. Washington, D.C. Available online at <http://www.nass.usda.gov/Publications/Ag_Statistics/index.asp> and <http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/>. Accessed June 2014.

USDA (2014b) U.S. Department of Agriculture. Economic Research Service. Nutrient Availability. Washington D.C. Available online at <http://www.ers.usda.gov/datafiles/Food_Availabily_Per_Capita_Data_System/Nutrient_Availability/nutrients.xls>. Accessed August 2014.

USPoultry (2006) Email correspondence. John Starkey, USPOULTRY to D. Bartram, ERG. 30 August 2006.

White and Johnson (2003) White, P.J. and Johnson, L.A. Editors. Corn: Chemistry and Technology. 2nd ed. AACC Monograph Series. American Association of Cereal Chemists. St. Paul, MN.

Willis et al. (2013) Methane Evolution from Lagoons and Ponds. Prepared for the Water Environment Research Foundation under contract U2R08c.

World Bank (1999) Pollution Prevention and Abatement Handbook 1998, Toward Cleaner Production. The International Bank for Reconstruction and Development, The World Bank, Washington, D.C. ISBN 0-8213-3638-X.

Composting

BioCycle (2010) *The State of Garbage in America.* Prepared by Rob van Haaren, Nickolas Themelis and Nora Goldstein. Available online at <http://www.biocycle.net/images/art/1010/bc101016_s.pdf>.

EPA (2015) *Advancing Sustainable Materials Management: Facts and Figures 2013.* Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at <http://www.epa.gov/wastes/nonhaz/municipal/pubs/2013_advncng_smm_rpt.pdf>.

EPA (2014) *Municipal Solid Waste in the United States: 2012 Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at <http://epa.gov/epawaste/nonhaz/municipal/pubs/2012_msw_dat_tbls.pdf>.

EPA (2011) *Municipal Solid Waste in the United States: 2010 Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at <http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf>.

EPA (2007) *Municipal Solid Waste in the United States: 2006 Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at <http://www.epa.gov/osw/nonhaz/municipal/pubs/06data.pdf>.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Volume 5: Waste, Chapter 4: Biological Treatment of Solid Waste, Table 4.1. 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. Available online at <http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf>.

Shin, D. (2014). Generation and Disposition of Municipal Solid Waste (MSW) in the United States – A National Survey. Table 3. Master of Science thesis, Department of Earth and Environmental Engineering, Fu Foundation School of Engineering and Applied Science, Columbia University. Available online at <http://www.seas.columbia.edu/earth/wtert/sofos/Dolly_Shin_Thesis.pdf>.

U.S. Census Bureau (2015). Population Estimates: Vintage 2014 Annual Estimates Available online at <http://www.census.gov/popest/data/national/totals/2014/index.html>.

U.S. Composting Council (2010). *Yard Trimmings Bans: Impact and Support.* Prepared by Stuart Buckner, Executive Director, U.S, Composting Council. Available online at <http://recyclingorganizations.org/webinars/RONA-YT-Ban-impacts-and-support-8.19.pdf>.

Waste Sources of Indirect Greenhouse Gas Emissions

EPA (2015) "1970 - 2014 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, March 2015. Available online at <http://www.epa.gov/ttn/chief/trends/index.html>.

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.

Recalculations and Improvements

Domke, G.M., Perry, C.H., Walters, B.F., Nave, L.E., Woodall, C.W., Swanston, C.W. In Prep. Towards field-based estimates of soil organic carbon in forests of the United States.

EPA (2015) Rule and Implementation Information for Standards of Performance for Municipal Solid Waste Landfills, Docket #A-88-09. Available at < http://www3.epa.gov/ttn/atw/landfill/landflpg.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.

Ogle, S.M., Woodall, C.W., Swan, A., Smith, J.E., Wirth. T. In preparation. Determining the Managed Land Base for Delineating Carbon Sources and Sinks in the United States. Environmental Science and Policy.

RTI (2015) 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 (2011) Updated Research on Methane Oxidation in Landfills. Memorandum prepared by K. Weitz (RTI) for R. Schmeltz (EPA), January 14, 2011.

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. (2015) The US 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.