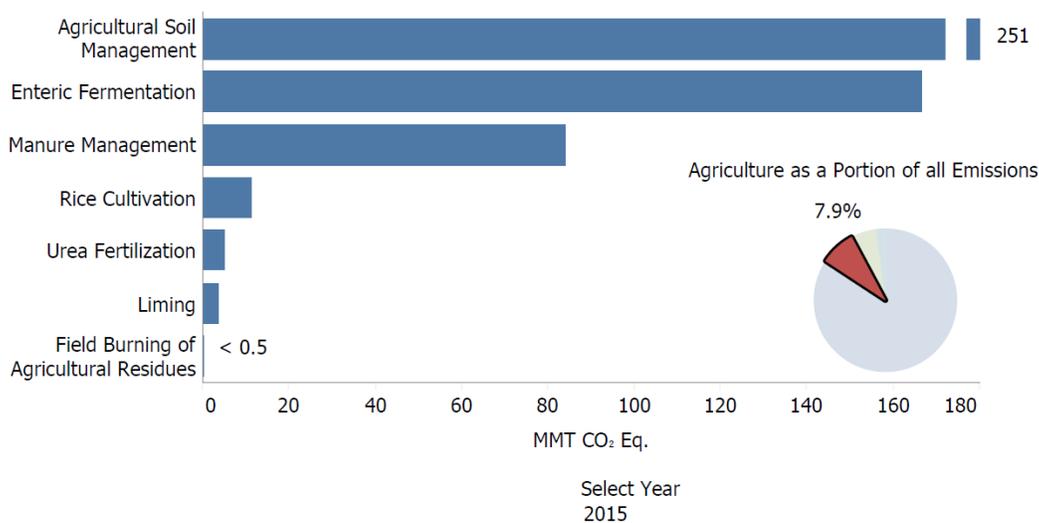


5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of methane (CH₄) and nitrous oxide (N₂O) 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, as well as CO₂ emissions from liming and urea fertilization (see Figure 5-1). Additional CO₂ emissions and removals from agriculture-related land-use and management activities, such as cultivation of cropland and conversion of grassland to cropland, are presented in the Land Use, Land-Use Change, and Forestry chapter. Carbon dioxide emissions from on-farm energy use are reported in the Energy chapter.

Figure 5-1: 2015 Agriculture Chapter Greenhouse Gas Emission Sources (MMT CO₂ Eq.)



In 2015, the Agriculture sector was responsible for emissions of 522.3 MMT CO₂ Eq.,¹ or 7.9 percent of total U.S. greenhouse gas emissions. Carbon dioxide, methane (CH₄), and nitrous oxide (N₂O) were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represent 25.4 percent and 10.1 percent of total CH₄ emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of CH₄. Rice cultivation and field burning of agricultural residues were minor sources of CH₄. Emissions of N₂O by agricultural soil management through activities such as fertilizer application and other agricultural practices that increased nitrogen availability in the soil were the largest source of U.S. N₂O emissions, accounting for 75.1 percent. Manure management and field

¹ Following the current reporting requirements under the United Nations Framework Convention on Climate Change (UNFCCC), this Inventory report presents CO₂ equivalent values based on the *IPCC Fourth Assessment Report (AR4)* GWP values. See the Introduction chapter for more information.

burning of agricultural residues were also small sources of N₂O emissions. Urea fertilization and liming each accounted for 0.1 percent of total CO₂ emissions from anthropogenic activities.

Table 5-1 and Table 5-2 present emission estimates for the Agriculture sector. Between 1990 and 2015, CO₂ and CH₄ emissions from agricultural activities increased by 24.8 percent and 12.3 percent, respectively, while N₂O emissions fluctuated from year to year, but overall decreased by 0.6 percent.

Table 5-1: Emissions from Agriculture (MMT CO₂ Eq.)

Gas/Source	1990	2005	2011	2012	2013	2014	2015
CO₂	7.1	7.9	8.0	10.2	8.4	8.4	8.8
Urea Fertilization	2.4	3.5	4.1	4.3	4.5	4.8	5.0
Liming	4.7	4.3	3.9	6.0	3.9	3.6	3.8
CH₄	217.6	242.1	246.3	244.0	240.4	238.7	244.3
Enteric Fermentation	164.2	168.9	168.9	166.7	165.5	164.2	166.5
Manure Management	37.2	56.3	63.0	65.6	63.3	62.9	66.3
Rice Cultivation	16.0	16.7	14.1	11.3	11.3	11.4	11.2
Field Burning of Agricultural Residues	0.2	0.2	0.3	0.3	0.3	0.3	0.3
N₂O	270.6	276.4	287.6	271.7	268.1	267.6	269.1
Agricultural Soil Management	256.6	259.8	270.1	254.1	250.5	250.0	251.3
Manure Management	14.0	16.5	17.4	17.5	17.5	17.5	17.7
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	495.3	526.4	541.9	525.9	516.9	514.7	522.3

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (kt)

Gas/Source	1990	2005	2011	2012	2013	2014	2015
CO₂	7,084	7,854	7,970	10,245	8,411	8,391	8,842
Urea Fertilization	2,417	3,504	4,097	4,267	4,504	4,781	5,032
Liming	4,667	4,349	3,873	5,978	3,907	3,609	3,810
CH₄	8,702	9,684	9,851	9,760	9,615	9,548	9,772
Enteric Fermentation	6,566	6,755	6,757	6,670	6,619	6,567	6,661
Manure Management	1,486	2,254	2,519	2,625	2,530	2,514	2,651
Rice Cultivation	641	667	564	453	454	456	449
Field Burning of Agricultural Residues	9	8	11	11	11	11	11
N₂O	908	928	965	912	900	898	903
Agricultural Soil Management	861	872	906	853	841	839	843
Manure Management	47	55	58	59	59	59	59
Field Burning of Agricultural Residues	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding.

Box 5-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and sinks presented in this report and the Agriculture chapter, are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National GHG Inventories*. 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. 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 are comparable to emissions and sinks reported by other countries. Emissions and sinks provided in this Inventory do not preclude alternative examinations, but rather, this Inventory 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.

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 CH₄ as a byproduct, which can be exhaled or eructated by the animal. The amount of CH₄ 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 CH₄ 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 CH₄ emissions per unit of body mass among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules and asses) also produce CH₄ emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH₄ on a per-animal-mass basis than ruminants because the capacity of the large intestine to produce CH₄ is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affect CH₄ emissions. In general, lower feed quality and/or higher feed intake leads to higher CH₄ 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 CH₄ emissions in 2015 were 166.5 MMT CO₂ Eq. (6,661 kt). Beef cattle remain the largest contributor of CH₄ emissions from enteric fermentation, accounting for 71 percent in 2015. Emissions from dairy cattle in 2015 accounted for 26 percent, and the remaining emissions were from horses, sheep, swine, goats, American bison, mules and asses.

Table 5-3: CH₄ Emissions from Enteric Fermentation (MMT CO₂ Eq.)

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

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Table 5-4: CH₄ Emissions from Enteric Fermentation (kt)

Livestock Type	1990	2005	2011	2012	2013	2014	2015
Beef Cattle	4,763	5,007	4,873	4,763	4,722	4,660	4,724

Dairy Cattle	1,574	1,503	1,645	1,670	1,664	1,679	1,706
Swine	81	92	98	100	98	96	102
Horses	40	70	67	65	64	62	61
Sheep	91	49	44	43	43	42	42
Goats	13	14	14	13	13	12	12
American Bison	4	17	14	13	13	12	13
Mules and Asses	1	2	3	3	3	3	3
Total	6,566	6,755	6,757	6,670	6,619	6,567	6,661

Note: Totals may not sum due to independent rounding.

From 1990 to 2015, emissions from enteric fermentation have increased by 1.5 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 0.8 percent from 1990 to 2015, while beef cattle populations actually declined by 7 percent and beef production increased (USDA 2016), and while dairy emissions increased 8.3 percent over the entire time series, the population has declined by 4 percent and milk production increased 40 percent (USDA 2016). 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 2015 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 to 2015 time period, while mules and asses have more than quadrupled.

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 CH₄ 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 CH₄ 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 2016).

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 CH₄ conversion rates (Y_m) (expressed as the fraction of gross energy converted to CH₄) 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). As described in ERG (2016), 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 CH₄ 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

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

in CH₄ 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 CH₄ 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 CH₄ emissions from livestock in the United States from 1990 through 2015. 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 2016). Horse, goat and mule and ass population data were available for 1987, 1992, 1997, 2002, 2007, and 2012 (USDA 1992, 1997, 2016); the remaining years between 1990 and 2015 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 2016) and from the National Bison Association (1999) for 1990 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).

See Annex 3.10 for more detailed information on the methodology and data used to calculate CH₄ 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 2015 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 CH₄ emissions in 2015 were estimated to be between 148.2 and 196.5 MMT CO₂ Eq. at a 95 percent confidence level, which indicates a range of 11 percent below to 18 percent above the 2015 emission estimate of 166.5 MMT CO₂ Eq. Among the individual cattle sub-source categories, beef cattle account for the largest amount of CH₄ 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 CH₄ Emissions from Enteric Fermentation (MMT CO₂ Eq. and Percent)

Source	Gas	2015 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	166.5	148.2	196.5	-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 2015 estimates.

^c The overall uncertainty calculated in 2003, and applied to the 2015 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 2015. 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 (EPA 2002). 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 2015 when compared against the same years in the previous Inventory—from 2008 through 2011, as well as 2014. 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:
 - Calf birth data were revised for 2008 and 2014;
 - Dairy cow milk production values were revised for several states for 2014;
 - Slaughter values were revised for 2014 for steers and heifers;
- The USDA also revised population estimates for some categories of non-cattle animals, which affected historical emissions estimated for “other” livestock. Changes included:

- Revised 2014 populations for market and breeding swine in some states; and
- Revised 2013 populations of sheep for some states.

In addition to these changes in input data, a miscount of the number of states included in the cattle on feed total for “other states” in 2011 was corrected. This resulted in revised 2011 estimates for feedlot cattle in 19 states.

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 CH₄ and N₂O emissions. Methane is produced by the anaerobic decomposition of manure. Nitrous oxide emissions are produced through both direct and indirect pathways. Direct N₂O emissions are produced as part of the nitrogen (N) cycle through the nitrification and denitrification of the organic N in livestock dung and urine.³ There are two pathways for indirect

³ Direct and indirect N₂O emissions from dung and urine spread onto fields either directly as daily spread or after it is removed from manure management systems (i.e., 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.

N₂O emissions. The first is the result of the volatilization of N in manure (as NH₃ and NO_x) and the subsequent deposition of these gases and their products (NH₄⁺ and NO₃⁻) 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 CH₄. 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 CH₄. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH₄ produced because they influence the growth of the bacteria responsible for CH₄ formation. For non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH₄ production. Manure composition, which varies by animal diet, growth rate, and type, including the animal's digestive system, also affects the amount of CH₄ produced. In general, the greater the energy content of the feed, the greater the potential for CH₄ 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 N₂O 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 N₂O emissions to occur, the manure must first be handled aerobically where ammonia (NH₃) or organic N is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to dinitrogen gas (N₂), with intermediate production of N₂O and nitric oxide (NO) (denitrification) (Groffman et al. 2000). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. A very small portion of the total N excreted is expected to convert to N₂O in the waste management system (WMS). Indirect N₂O emissions are produced when nitrogen is lost from the system through volatilization (as NH₃ or NO_x) or through runoff and leaching. The vast majority of volatilization losses from these operations are NH₃. 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 NH₃ 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 CH₄ emissions from manure management in 2015 were 66.3 MMT CO₂ Eq. (2,651 kt); in 1990, emissions were 37.2 MMT CO₂ Eq. (1,486 kt). This represents a 78 percent increase in emissions from 1990. Emissions increased on average by 1.2 MMT CO₂ Eq. (3.0 percent) annually over this period. The majority of this increase is due to swine and dairy cow manure, where emissions increased 58 and 136 percent, respectively. From 2014 to 2015, there was a 5.4 percent increase in total CH₄ emissions from manure management, mainly due to an increase in larger farms and animal populations, as well as a shifting of manure management to liquid systems with increasing farm size.

Although the majority of managed manure in the United States is handled as a solid, producing little CH₄, 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 CH₄ emissions than dry systems. This significant shift in both the dairy and swine industries was accounted for by incorporating state and WMS-specific CH₄ conversion factor (MCF) values in combination with the 1992, 1997, 2002, 2007 and 2012 farm-size distribution data reported in the *Census of Agriculture* (USDA 2016d).

In 2015, total N₂O emissions from manure management were estimated to be 17.7 MMT CO₂ Eq. (59 kt); in 1990, emissions were 14.0 MMT CO₂ Eq. (47 kt). These values include both direct and indirect N₂O emissions from manure management. Nitrous oxide emissions have remained fairly steady since 1990. Small changes in N₂O emissions from individual animal groups exhibit the same trends as the animal group populations, with the overall net effect that N₂O emissions showed a 27 percent increase from 1990 to 2015 and a 1.1 percent increase from 2014 through 2015. 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 CH₄ and N₂O emissions from manure management by animal category.

Table 5-6: CH₄ and N₂O Emissions from Manure Management (MMT CO₂ Eq.)

Gas/Animal Type	1990	2005	2011	2012	2013	2014	2015
CH₄^a	37.2	56.3	63.0	65.6	63.3	62.9	66.3
Dairy Cattle	14.7	26.4	32.4	34.3	33.4	34.0	34.8
Beef Cattle	3.1	3.3	3.3	3.2	3.0	3.0	3.1
Swine	15.6	22.9	23.7	24.5	23.2	22.2	24.6
Sheep	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Poultry	3.3	3.2	3.2	3.2	3.2	3.3	3.4
Horses	0.2	0.3	0.2	0.2	0.2	0.2	0.2
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N₂O^b	14.0	16.5	17.4	17.5	17.5	17.5	17.7
Dairy Cattle	5.3	5.6	5.8	5.9	5.9	5.9	6.1
Beef Cattle	5.9	7.2	7.7	7.7	7.7	7.8	7.7
Swine	1.2	1.7	1.9	1.9	1.9	1.8	2.0
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Goats	+	+	+	+	+	+	+
Poultry	1.4	1.6	1.5	1.6	1.6	1.6	1.6
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
American Bison	NA						
Mules and Asses	+	+	+	+	+	+	+
Total	51.1	72.9	80.4	83.2	80.8	80.4	84.0

+ Does not exceed 0.05 MMT CO₂ Eq.

NA (Not Available)

^a Accounts for CH₄ reductions due to capture and destruction of CH₄ at facilities using anaerobic digesters.

^b Includes both direct and indirect N₂O emissions.

Notes: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS; there are no American bison N₂O emissions from managed systems.

Table 5-7: CH₄ and N₂O Emissions from Manure Management (kt)

Gas/Animal Type	1990	2005	2011	2012	2013	2014	2015
CH₄^a	1,486	2,254	2,519	2,625	2,530	2,514	2,651
Dairy Cattle	590	1,057	1,297	1,373	1,338	1,361	1,391
Beef Cattle	126	133	131	128	121	120	126
Swine	622	916	949	982	930	890	985
Sheep	7	3	3	3	3	3	3
Goats	1	1	1	1	1	1	1
Poultry	131	129	127	128	128	131	135
Horses	9	12	10	10	9	9	9
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N₂O^b	47	55	58	59	59	59	59
Dairy Cattle	18	19	19	20	20	20	20
Beef Cattle	20	24	26	26	26	26	26

Swine	4	6	6	6	6	6	7
Sheep	+	1	1	1	1	1	1
Goats	+	+	+	+	+	+	+
Poultry	5	5	5	5	5	5	5
Horses	+	+	+	+	+	+	+
American Bison	NA						
Mules and Asses	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

NA (Not available)

^a Accounts for CH₄ reductions due to capture and destruction of CH₄ at facilities using anaerobic digesters.

^b Includes both direct and indirect N₂O emissions.

Notes: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS; there are no American bison N₂O emissions from managed systems.

Methodology

The methodologies presented in IPCC (2006) form the basis of the CH₄ and N₂O emission estimates for each animal type. This section presents a summary of the methodologies used to estimate CH₄ and N₂O emissions from manure management. See Annex 3.11 for more detailed information on the methodology and data used to calculate CH₄ and N₂O emissions from manure management.

Methane Calculation Methods

The following inputs were used in the calculation of CH₄ 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 (B₀) of the volatile solids (by animal type); and
- Methane conversion factors (MCF), the extent to which the CH₄ 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 2015 for all livestock types, except goats, horses, mules and asses, and American bison were obtained from the USDA 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 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; ERG 2010a). For a description of the TAM used for cattle, see Section 5.1.
- WMS usage was estimated for swine and dairy cattle for different farm size categories using state and regional data from USDA (USDA APHIS 1996; Bush 1998; Ott 2000; USDA 2016d) and EPA (ERG 2000a; EPA 2002a and 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 and 2008; 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* (IPCC 2006). American bison VS production was assumed to be the same as NOF bulls.
- The maximum CH₄-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 CH₄ 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 2016). 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 CH₄ emissions (kg CH₄ per year) from each WMS. The amount of VS (kg per year) were multiplied by the maximum CH₄ producing capacity of the VS (B_o) (m³ CH₄ per kg VS), the MCF for that WMS (percent), and the density of CH₄ (kg CH₄ per m³ CH₄). The CH₄ emissions for each WMS, state, and animal type were summed to determine the total U.S. CH₄ emissions.

Nitrous Oxide Calculation Methods

The following inputs were used in the calculation of direct and indirect N₂O 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 (N_{ex});
- Direct N₂O emission factor (EF_{WMS});
- Indirect N₂O emission factor for volatilization (EF_{volatilization});
- Indirect N₂O emission factor for runoff and leaching (EF_{runoff/leach});
- Fraction of N loss from volatilization of NH₃ and NO_x (Frac_{gas}); and
- Fraction of N loss from runoff and leaching (Frac_{runoff/leach}).

Nitrous oxide 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 and 2008; 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.⁴

- All N₂O 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 N₂O emissions from cattle (except for calves), the estimated amount of N excreted (kg per animal-year) that is 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 (N_{ex}, in kg N per 1,000 kg animal mass per day), WMS distribution (percent), and the number of days per year.

Direct N₂O emissions were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the N₂O direct emission factor for that WMS (EF_{WMS}, in kg N₂O-N per kg N) and the conversion factor of N₂O-N to N₂O. These emissions were summed over state, animal, and WMS to determine the total direct N₂O emissions (kg of N₂O per year).

Next, indirect N₂O emissions from volatilization (kg N₂O 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 N₂O per kg N), and the conversion factor of N₂O-N to N₂O. Indirect N₂O emissions from runoff and leaching (kg N₂O 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 N₂O per kg N), and the conversion factor of N₂O-N to N₂O. The indirect N₂O emissions from volatilization and runoff and leaching were summed to determine the total indirect N₂O emissions.

The direct and indirect N₂O emissions were summed to determine total N₂O emissions (kg N₂O 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 CH₄ and N₂O 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 CH₄ and N₂O 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 2015 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 CH₄ emissions in 2015 were estimated to be between 54.3 and 79.5 MMT CO₂ Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2015 emission estimate of 66.3 MMT CO₂ Eq. At the 95 percent confidence level, N₂O emissions were estimated to be between 14.9 and 22.0 MMT CO₂

⁴ The N₂O emissions from N excreted (N_{ex}) by American bison on grazing lands are accounted for and discussed in the Agricultural Soil Management source category and included under pasture, range and paddock (PRP) emissions. Because American bison are maintained entirely on unmanaged WMS and N₂O emissions from unmanaged WMS are not included in the Manure Management category, there are no N₂O emissions from American bison included in the Manure Management category.

Eq. (or approximately 16 percent below and 24 percent above the actual 2015 emission estimate of 17.7 MMT CO₂ Eq.).

Table 5-8: Approach 2 Quantitative Uncertainty Estimates for CH₄ and N₂O (Direct and Indirect) Emissions from Manure Management (MMT CO₂ Eq. and Percent)

Source	Gas	2015 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	66.3	54.3	79.5	-18%	20%
Manure Management	N ₂ O	17.7	14.9	22.0	-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 2015. 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 N₂O emissions from managed systems and CH₄ 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, B₀, 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 IPCC (2006) default values.

For additional verification, the implied CH₄ emission factors for manure management (kg of CH₄ per head per year) were compared against the default IPCC (2006) values. Table 5-9 presents the implied emission factors of kg of CH₄ per head per year used for the manure management emission estimates as well as the IPCC (2006) default emission factors. The U.S. implied emission factors fall within the range of the IPCC (2006) 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 IPCC (2006) 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 CH₄ emissions.

Table 5-9: IPCC (2006) Implied Emission Factor Default Values Compared with Calculated Values for CH₄ 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	2011	2012	2013	2014	2015
		Dairy Cattle	48-112	30.2	59.4	70.3	73.9	72.3
Beef Cattle	1-2	1.5	1.6	1.7	1.7	1.6	1.6	1.7
Swine	10-45	11.5	15.0	14.5	14.8	14.2	13.8	14.5
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	2.7	2.5	2.5	2.6
American Bison	NA	1.8	2.0	2.1	2.1	2.0	2.0	2.1
Mules and Asses	0.76-1.14	0.9	1.0	1.0	1.0	0.9	0.9	1.0
NA (Not Applicable)								

In addition, default IPCC (2006) emission factors for N₂O were compared to the U.S. Inventory implied N₂O emission factors. Default N₂O emission factors from the 2006 IPCC Guidelines were used to estimate N₂O 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 CH₄ and N₂O 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 2014;
 - Sheep in 2013;
 - Dairy heifers in 2008 through 2010, and 2014;
 - NOF cattle 2008 through 2010, and 2014;
 - OF cattle for 2008 through 2012, and 2014;
 - Both beef and dairy calves in 2008, 2009, and 2014; and
 - Swine in 2014 (USDA 2016a).
- WMS distribution data were updated with *Census of Agriculture* farm size distribution data, which resulted in WMS distribution changes for dairy cows and swine for 2008 through 2014, and poultry in 2010 (USDA 2016d).
- Temperature data were updated which resulted in MCF changes for goats, horses, mules, and sheep in 2014, as well as dairy cattle, beef cattle, swine and poultry from 2013 through 2014 (NOAA 2016).
- Anaerobic digester data were updated to reflect updated EPA AgSTAR datasets, which resulted in VS distribution changes for dairy cows, swine, and poultry from 2011 through 2014 (EPA 2016).

These changes impacted CH₄ emission estimates for 2008 through 2014, overall increasing annual estimations from 0.6 to 3.1 percent. Dairy cow CH₄ emissions increased by 1.0 percent in 2008 up to a 5.6 percent increase in 2014. Swine increased CH₄ emissions by about 0.2 percent in 2008 up to a 1.0 percent increase in 2013, but decreased CH₄ emissions in 2014 by about 0.7 percent.

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 N₂O emissions.

Potential data sources (such as the USDA Agricultural Resource Management Survey) for updated WMS distribution estimates have been reviewed and discussed with USDA. EPA is working with USDA to obtain these data sources for potential use in future Inventory reports. In addition, future Inventory reports 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)

Most of the world's rice is grown on flooded fields (Baicich 2013), and flooding creates anaerobic conditions that foster CH₄ production through a process known as methanogenesis. Approximately 60 to 90 percent of the CH₄ produced by methanogenic bacteria is oxidized in the soil and converted to CO₂ by methanotrophic bacteria. The remainder is emitted to the atmosphere (Holzapfel-Pschorn et al. 1985; Sass et al. 1990) or transported as dissolved CH₄ into groundwater and waterways (Neue et al. 1997). Methane is transported to the atmosphere primarily through the rice plants, but some CH₄ also escapes via ebullition (i.e., bubbling through the water) and to a much lesser extent by diffusion through the water (van Bodegom et al. 2001).

Water management is arguably the most important factor affecting CH₄ emissions, and improved water management has the largest potential to mitigate emissions (Yan et al. 2009). Upland rice fields are not flooded, and therefore do not produce CH₄, but large amounts of CH₄ can be emitted in continuously irrigated fields, which is the most common practices in the United States (USDA 2012). Single or multiple aeration events with drainage of a field during the growing season can significantly reduce these emissions (Wassmann et al. 2000a), but drainage may also increase N₂O emissions. Deepwater rice fields (i.e., fields with flooding depths greater than one meter, such as natural wetlands) tend to have less living stems reaching the soil, thus reducing the amount of CH₄ transport to the atmosphere through the plant compared to shallow-flooded systems (Sass 2001).

Other management practices also influence CH₄ emissions from flooded rice fields including rice residue straw management and application of organic amendments, in addition to cultivar selection due to differences in the amount of root exudates⁵ among rice varieties (Neue et al. 1997). These practices influence the amount of organic matter available for methanogenesis, and some practices, such as mulching rice straw or composting organic amendments, can reduce the amount of labile carbon and limit CH₄ emissions (Wassmann et al. 2000b). Fertilization practices also influences CH₄ emissions, particularly the use of fertilizers with sulfate (Wassmann et al. 2000b; Linqvist et al. 2012). Other environmental variables also impact the methanogenesis process such as soil temperature and soil type. Soil temperature is an important factor regulating the activity of methanogenic bacteria which in turn affects the rate of CH₄ production. Soil texture influences decomposition of soil organic matter, but is also thought to have an impact on oxidation of CH₄ in the soil (Sass et al. 1994).

Rice is currently cultivated in twelve states, including Arkansas, California, Florida, Illinois, Kentucky, Louisiana, Minnesota, Mississippi, Missouri, New York, South Carolina, Tennessee and Texas. Soil types, rice varieties, and cultivation practices vary across the United States, but most farmers apply fertilizers and do not harvest crop residues. In addition, a second, ratoon rice crop is sometimes grown in the Southeast. Ratoon crops are produced from regrowth of the stubble remaining after the harvest of the first rice crop. Methane emissions from ratoon crops are higher than those from the primary crops due to the increased amount of labile organic matter available for anaerobic decomposition in the form of relatively fresh crop residue straw. Emissions tend to be higher in rice fields if the residues have been in the field for less than 30 days before planting the next rice crop (Lindau and Bollich 1993; IPCC 2006; Wang et al. 2013).

Overall, rice cultivation is a minor source of CH₄ emissions in the United States relative to other source categories (see Table 5-10, Table 5-11, and Figure 5-2). The majority of emission occur in Arkansas, California, Louisiana and Texas. In 2015, CH₄ emissions from rice cultivation were 11.2 MMT CO₂ Eq. (449 kt). Annual emissions fluctuate between 1990 and 2015, and emissions in 2015 represented a 30 percent decrease compared to 1990. Variation in emissions is largely due to differences in the amount of rice harvested areas over time. In Arkansas rice harvested areas increased by 2 percent from 1990 to 2015, while rice harvested area declined in California, Louisiana and Texas by 2 percent, 41 percent and 78 percent respectively (see Table 5-12).

⁵ The roots of rice plants add organic material to the soil through a process called "root exudation." Root exudation is thought to enhance decomposition of the soil organic matter and release nutrients that the plant can absorb and use to stimulate more production. The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

Table 5-10: CH₄ Emissions from Rice Cultivation (MMT CO₂ Eq.)

State	1990	2005	2011	2012	2013	2014	2015
Arkansas	3.3	4.7	4.0	3.8	3.8	3.7	3.8
California	2.0	2.1	1.9	2.0	2.0	2.0	2.0
Florida	+	0.1	+	+	+	+	+
Illinois	+	+	+	+	+	+	+
Kentucky	+	+	+	+	+	+	+
Louisiana	6.1	6.5	5.6	3.9	3.9	4.0	3.8
Minnesota	+	+	+	+	+	+	+
Mississippi	0.6	0.6	0.3	0.5	0.5	0.5	0.5
Missouri	0.3	0.6	0.4	0.3	0.3	0.3	0.3
New York	+	+	+	+	+	+	+
South Carolina	+	+	+	+	+	+	+
Tennessee	+	+	+	+	+	+	+
Texas	3.7	2.1	1.8	0.9	0.9	0.9	0.9
Total	16.0	16.7	14.1	11.3	11.3	11.4	11.2

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

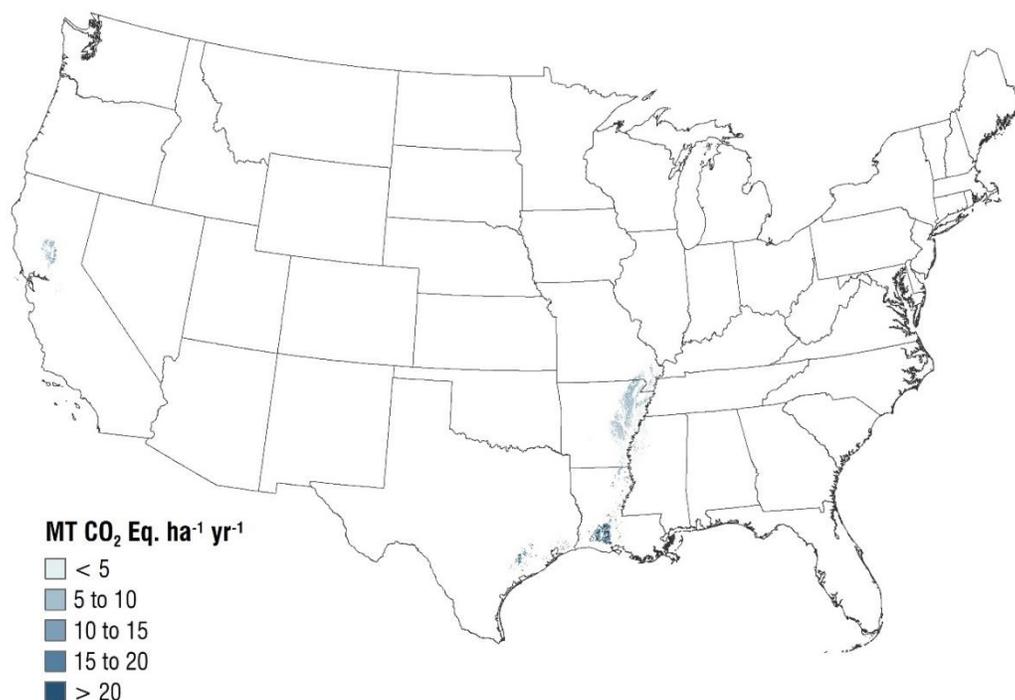
Table 5-11: CH₄ Emissions from Rice Cultivation (kt)

State	1990	2005	2011	2012	2013	2014	2015
Arkansas	132	187	162	151	151	150	150
California	81	82	75	81	81	81	81
Florida	+	3	+	+	+	+	+
Illinois	+	+	+	+	+	+	+
Kentucky	+	+	+	+	+	+	+
Louisiana	246	261	226	156	156	159	152
Minnesota	1	2	1	1	1	1	1
Mississippi	23	23	11	19	19	19	19
Missouri	12	22	15	12	12	12	12
New York	+	+	+	+	+	+	+
South Carolina	+	+	+	+	+	+	+
Tennessee	+	+	+	+	+	+	+
Texas	146	86	74	34	34	34	34
Total	641	667	564	453	454	456	449

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding.

Figure 5-2: Annual CH₄ Emissions from Rice Cultivation, 2015 (MMT CO₂ Eq./Year)



Methodology

The methodology used to estimate CH₄ emissions from rice cultivation is based on a combination of IPCC Tier 1 and 3 approaches. The Tier 3 method utilizes a process-based model (DAYCENT) to estimate CH₄ emissions from rice cultivation (Cheng et al. 2013), and has been tested in the United States (See Annex 3.12) and Asia (Cheng et al. 2013, 2014). The model simulates hydrological conditions and thermal regimes, organic matter decomposition, root exudation, rice plant growth and its influence on oxidation of CH₄, as well as CH₄ transport through the plant and via ebullition (Cheng et al. 2013). The method simulates the influence of organic amendments and rice straw management on methanogenesis in the flooded soils. In addition to CH₄ emissions, DAYCENT simulates soil C stock changes and N₂O emissions (Parton et al. 1987 and 1998; Del Grosso et al. 2010), and allows for a seamless set of simulations for crop rotations that include both rice and non-rice crops.

The Tier 1 method is applied to estimate CH₄ emissions from rice when grown in rotation with crops that are not simulated by DAYCENT, such as vegetables and perennial/horticultural crops. The Tier 1 method is also used for areas converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland, and settlements. In addition, the Tier 1 method is used to estimate CH₄ emissions from organic soils (i.e., Histosols) and from areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume). The Tier 3 method using DAYCENT has not been fully tested for estimating emissions associated with these crops and rotations, land uses, as well as organic soils or cobbly, gravelly, and shaley mineral soils.

The Tier 1 method for estimating CH₄ emissions from rice production utilizes a default base emission rate and scaling factors (IPCC 2006). The base emission factor represents emissions for continuously flooded fields with no organic amendments. Scaling factors are used to adjust for water management and organic amendments that differ from continuous flooding with no organic amendments. The method accounts for pre-season and growing season flooding; types and amounts of organic amendments; and the number of rice production seasons within a single year

(i.e., single cropping, ratooning, etc.). The Tier 1 analysis is implemented in the Agriculture and Land Use National Greenhouse Gas Inventory (ALU) software (Ogle et al. 2016).⁶

Rice cultivation areas are based on cropping and land use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2015). The NRI is a statistically-based sample of all non-federal land, and includes 380,956 survey points of which 1,588 are in locations with rice cultivation at the end of the NRI time series. The Tier 3 method is used to estimate CH₄ emissions from 1,393 of the NRI survey locations, and the remaining 195 survey locations are estimated with the Tier 1 method. Each NRI survey point is associated with an “expansion factor” that allows scaling of CH₄ emissions from NRI points 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 management information in the NRI (e.g., crop type, soil attributes, and irrigation) were collected on a 5-year cycle beginning in 1982, along with cropping rotation data in 4 out of 5 years for each 5 year time period (i.e., 1979 to 1982, 1984 to 1987, 1989 to 1992, and 1994 to 1997). The NRI program began collecting annual data in 1998, with data currently available through 2012 (USDA-NRCS 2015). This Inventory only uses NRI data through 2012 because newer data are not available, but will be incorporated when additional years of data are released by USDA-NRCS. The harvested rice areas in each state are presented in Table 5-12.

Table 5-12: Rice Area Harvested (1,000 Hectares)

State/Crop	1990	2005	2011	2012	2013	2014	2015
Arkansas	599	796	642	613	613	613	613
California	248	247	249	244	244	244	244
Florida	0	11	0	0	0	0	0
Illinois	0	0	0	0	0	0	0
Kentucky	0	0	0	0	0	0	0
Louisiana	380	402	318	226	226	226	226
Minnesota	4	10	5	6	6	6	6
Mississippi	119	115	53	92	92	92	92
Missouri	47	93	64	46	46	46	46
New York	1	0	0	0	0	0	0
South Carolina	0	0	0	0	0	0	0
Tennessee	0	1	0	0	0	0	0
Texas	300	150	120	66	66	66	66
Total	1,698	1,826	1,451	1,292	1,292	1,292	1,292

Notes: Totals may not sum due to independent rounding. States are included if NRI reports rice areas at any time between 1990 and 2012.

The Southeastern states have sufficient growing periods for a ratoon crop in some years. For example, in Arkansas, the length of growing season is occasionally sufficient for ratoon crops on an average of 1 percent of the rice fields. No data are available about ratoon crops in Missouri or Mississippi, and the average amount of ratooning in Arkansas was assigned to these states. Ratoon cropping occurs much more frequently in Louisiana (LSU 2015 for years 2000 through 2013, 2015) and Texas (TAMU 2015 for years 1993 through 2014), averaging 32 percent and 45 percent of rice acres planted, respectively. Florida also has a large fraction of area with a ratoon crop (49 percent). Ratoon rice crops are not grown in California. Ratooned crop area as a percent of primary crop area is presented in Table 5-13.

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

State	1990-2015
Arkansas ^a	1%
California	0%
Florida ^b	49%
Louisiana ^c	32%
Mississippi ^a	1%
Missouri ^a	0%

⁶ See <<http://www.nrel.colostate.edu/projects/ALUsoftware/>>.

Texas^d 45%

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

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

^c Louisiana: 1990–2013 (Linscombe 1999, 2001 through 2014).

^d 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 through 2014).

While rice crop production in the United States includes a minor amount of land with mid-season drainage or alternate wet-dry periods, the majority of rice growers use continuously flooded water management systems (Hardke 2015; UCCE 2015; Hollier 1999; Way et al. 2014). Therefore, continuous flooding was assumed in the DAYCENT simulations and the Tier 1 method. Variation in flooding can be incorporated in future Inventories if water management data are collected.

Winter flooding is another key practice associated with water management in rice fields, and the impact of winter flooding on CH₄ emissions is addressed in the Tier 3 and Tier 1 analyses. Flooding is used to prepare fields for the next growing season, and to create waterfowl habitat (Young 2013; Miller et al. 2010; Fleskes et al. 2005). Fitzgerald et al. (2000) suggests that as much as 50 percent of the annual emissions may occur during the winter flood. Winter flooding is a common practice with an average of 34 percent of fields managed with winter flooding in California (Miller et al. 2010; Fleskes et al. 2005), and approximately 21 percent of the fields managed with winter flooding in Arkansas (Wilson and Branson 2005 and 2006; Wilson and Runsick 2007 and 2008; Wilson et al. 2009 and 2010; Hardke and Wilson 2013 and 2014; Hardke 2015). No data are available on winter flooding for Texas, Louisiana, Florida, Missouri, or Mississippi. For these states, the average amount of flooding is assumed to be similar to Arkansas. In addition, the amount of flooding is assumed to be relatively constant over the Inventory time period.

Uncertainty and Time-Series Consistency

Sources of uncertainty in the Tier 3 method include management practices, uncertainties in model structure (i.e., algorithms and parameterization), and variance associated with the NRI sample. Sources of uncertainty in the IPCC (2006) Tier 1 method include the emission factors, management practices, and variance associated with the NRI sample. A Monte Carlo analysis was used to propagate uncertainties in the Tier 1 and 3 methods, and the uncertainties from each approach are combined to produce the final CH₄ emissions estimate using simple error propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.12. Rice cultivation CH₄ emissions in 2015 were estimated to be between 8.1 and 14.4 MMT CO₂ Eq. at a 95 percent confidence level, which indicates a range of 28 percent below to 28 percent above the actual 2015 emission estimate of 11.2 MMT CO₂ Eq. (see Table 5-14).

Table 5-14: Approach 2 Quantitative Uncertainty Estimates for CH₄ Emissions from Rice Cultivation (MMT CO₂ Eq. and Percent)

Source	Inventory Method	Gas	2015 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
Rice Cultivation	Tier 3	CH ₄	9.9	6.8	13.1	-32%	+32%
Rice Cultivation	Tier 1	CH ₄	1.3	0.9	1.9	-30%	+46%
Rice Cultivation	Total	CH₄	11.2	8.1	14.4	-28%	+28%

^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 2015. Details on the emission trends through time are described in more detail in the Methodology section.

QA/QC and Verification

Quality control measures include 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. No errors were found in the reporting forms and text.

Model results are compared to field measurements to verify if results adequately represent CH₄ emissions. The comparisons included over 15 long-term experiments, representing about 80 combinations of management treatments across all of the sites. A statistical relationship was developed to assess uncertainties in the model structure and adjust for model bias and assess precision in the resulting estimates (methods are described in Ogle et al. 2007). See Annex 3.12 for more information.

Recalculations Discussion

Methodological recalculations in the current Inventory are associated with the following improvements: (1) DAYCENT model development to improve the simulation of soil temperature; (2) improvements in the cropping and land use histories that are simulated in DAYCENT between 1950 and 1979, which generate initial values for the state variables in the model and (3) driving the DAYCENT simulations with updated input data for land use and management from the National Resources Inventory, which revised the time series from 1990 through 2012. These changes resulted in an increase in emissions of approximately 25 percent on average relative to the previous Inventory and an increase in uncertainty from a confidence interval with a lower bound and upper bound of 17 percent to a confidence interval with an upper and lower bound of 28 percent.

Planned Improvements

A major improvement is underway to update the time series of management data with information from the USDA-NRCS Conservation Effects Assessment Program (CEAP). This improvement will fill several gaps in the management data including more specific data on fertilizer rates, updated tillage practices, water management, organic amendments and more information on planting and harvesting dates. This improvement is expected to be completed for the 1990 through 2017 Inventory (2019 submission to the UNFCCC). However, the timeline may be extended if there are insufficient resources to fund this improvement.

5.4 Agricultural Soil Management (IPCC Source Category 3D)

Nitrous oxide is naturally produced in soils through the microbial processes of nitrification and denitrification that is driven by the availability of mineral nitrogen (N) (Firestone and Davidson 1989).⁷ 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.⁸ A number of agricultural activities increase mineral N availability in soils that lead to direct N₂O emissions from nitrification and denitrification at the site of a management activity (see Figure 5-3) (Mosier et al. 1998), including N fertilization; application of managed livestock manure and other organic materials such as

⁷ Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH₄⁺) to nitrate (NO₃⁻), and denitrification is the anaerobic microbial reduction of nitrate to N₂. 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).

⁸ Asymbiotic N fixation is the fixation of atmospheric N₂ by bacteria living in soils that do not have a direct relationship with plants.

biosolids (i.e., 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 Histosols⁹) (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 N₂O occur when N is transported from a site and is subsequently converted to N₂O; 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.¹⁰

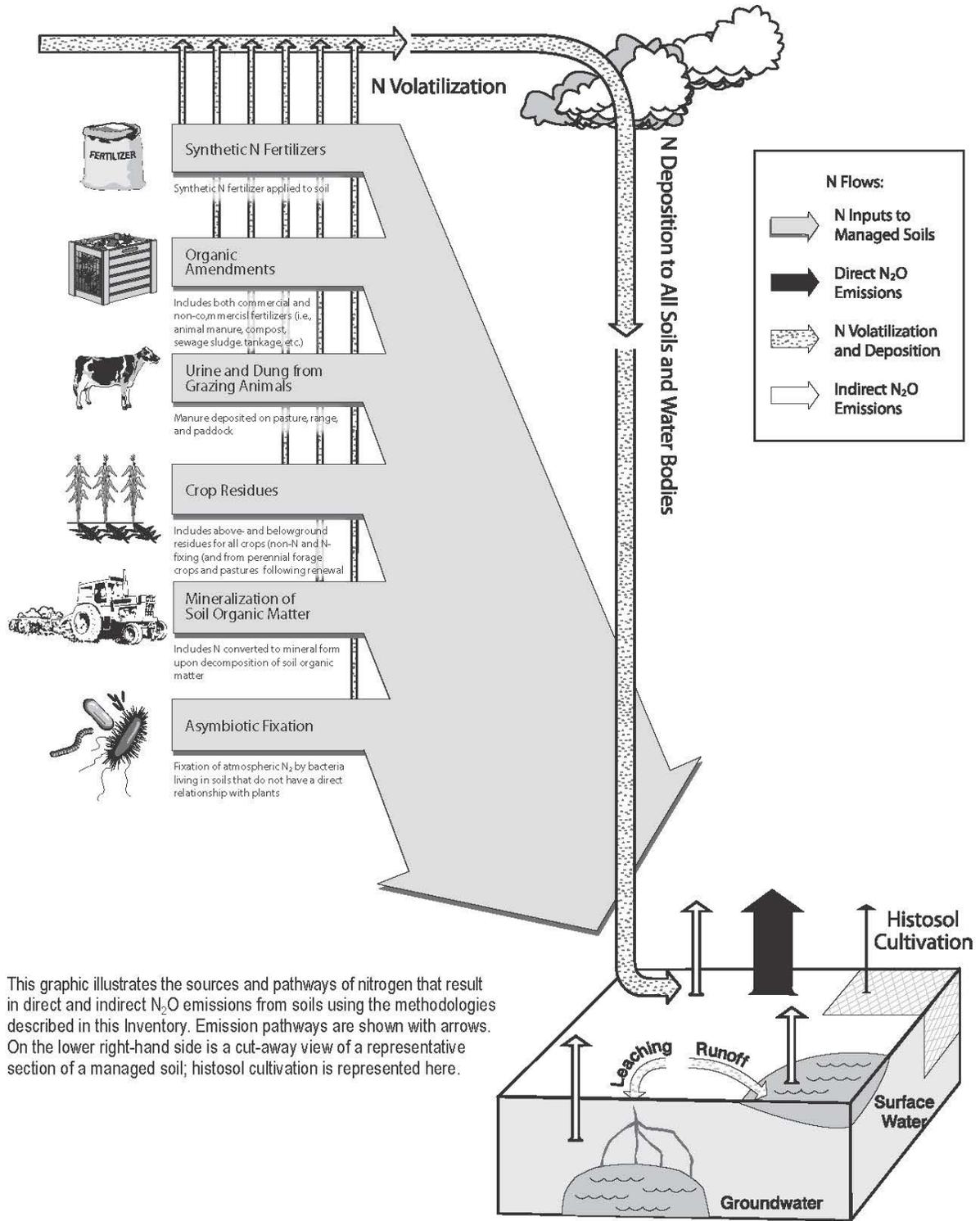
Direct and indirect emissions from agricultural lands are included in this section (i.e., cropland and grassland as defined in Section 6.1 Representation of the U.S. Land Base; N₂O emissions from Forest Land and Settlements soils are found in Sections 6.2 and 6.10, respectively). The U.S. Inventory includes 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).

⁹ Drainage of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby increasing N₂O emissions from these soils.

¹⁰ These processes entail volatilization of applied or mineralized N as NH₃ and NO_x, transformation of these gases within the atmosphere (or upon deposition), and deposition of the N primarily in the form of particulate NH₄⁺, nitric acid (HNO₃), and NO_x, in addition to leaching and runoff of NO₃⁻ that is converted to N₂O in aquatic systems.

Figure 5-3: Sources and Pathways of N that Result in N₂O Emissions from Agricultural Soil Management

Sources and Pathways of N that Result in N₂O Emissions from Agricultural Soil Management



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N₂O 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 N₂O emissions in the United States. Estimated emissions from this source in 2015 are 251.3 MMT CO₂ Eq. (843 kt) (see Table 5-15 and Table 5-16). Annual N₂O emissions from agricultural soils fluctuated between 1990 and 2015, although overall emissions are 2.0 percent lower in 2015 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 2015, 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 83 percent of indirect emissions from croplands and 17 percent for grasslands. Estimated direct and indirect N₂O emissions by sub-source category are shown in Table 5-17 and Table 5-18.

Table 5-15: N₂O Emissions from Agricultural Soils (MMT CO₂ Eq.)

Activity	1990	2005	2011	2012	2013	2014	2015
Direct	212.0	218.4	220.4	215.6	212.8	212.4	213.3
Cropland	147.5	153.9	158.3	156.7	154.2	154.3	154.6
Grassland	64.5	64.6	62.1	59.0	58.6	58.1	58.7
Indirect	44.6	41.4	49.7	38.4	37.7	37.6	38.0
Cropland	37.0	34.4	41.9	31.6	30.9	30.8	31.1
Grassland	7.6	7.0	7.8	6.9	6.8	6.7	6.9
Total	256.6	259.8	270.1	254.1	250.5	250.0	251.3

Note: Totals may not sum due to independent rounding.

Table 5-16: N₂O Emissions from Agricultural Soils (kt)

Activity	1990	2005	2011	2012	2013	2014	2015
Direct	711	733	740	724	714	713	716
Cropland	495	516	531	526	518	518	519
Grassland	217	217	208	198	197	195	197
Indirect	150	139	167	129	126	126	127
Cropland	124	115	141	106	104	103	104
Grassland	25	23	26	23	23	23	23
Total	861	872	906	853	841	839	843

Note: Totals may not sum due to independent rounding.

Table 5-17: Direct N₂O Emissions from Agricultural Soils by Land Use Type and N Input Type (MMT CO₂ Eq.)

Activity	1990	2005	2011	2012	2013	2014	2015
Cropland	147.5	153.9	158.3	156.7	154.2	154.3	154.6
Mineral Soils	144.1	150.6	155.1	153.5	151.0	151.1	151.4
Synthetic Fertilizer	53.6	54.6	58.0	60.4	58.3	58.2	58.3
Organic Amendment ^a	10.0	10.9	11.2	11.3	11.3	11.2	11.4
Residue N ^b	22.1	22.9	23.9	23.5	23.7	23.8	23.9
Mineralization and Asymbiotic Fixation	58.4	62.2	62.1	58.2	57.8	57.8	57.8
Drained Organic Soils	3.3	3.3	3.2	3.2	3.2	3.2	3.2
Grassland	64.5	64.6	62.1	59.0	58.6	58.1	58.7
Mineral Soils	61.3	61.1	58.8	55.7	55.3	54.9	55.4
Synthetic Fertilizer	0.9	0.8	0.8	0.7	0.7	0.7	0.7
PRP Manure	16.1	13.8	13.6	13.3	13.0	12.5	13.2
Managed Manure ^c	0.9	1.1	1.1	1.1	1.1	1.1	1.1
Biosolids (i.e., Sewage Sludge)	0.2	0.5	0.5	0.6	0.6	0.6	0.6
Residue N ^d	14.5	15.8	14.8	14.2	14.2	14.2	14.2
Mineralization and Asymbiotic Fixation	28.5	29.2	28.1	25.8	25.8	25.8	25.7
Drained Organic Soils	3.3	3.5	3.3	3.3	3.3	3.3	3.3
Total	212.0	218.5	220.4	215.6	212.8	212.4	213.3

^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.

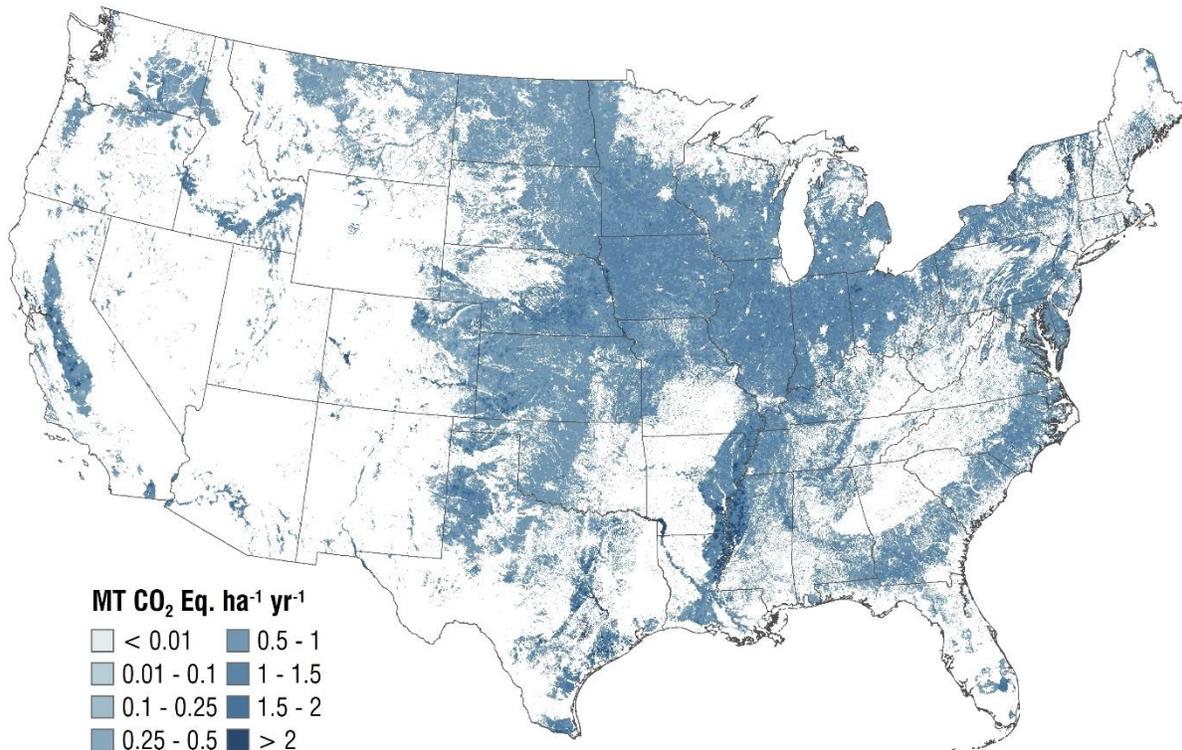
Table 5-18: Indirect N₂O Emissions from Agricultural Soils (MMT CO₂ Eq.)

Activity	1990	2005	2011	2012	2013	2014	2015
Cropland	37.0	34.4	41.9	31.6	30.9	30.8	31.1
Volatilization & Atm.							
Deposition	12.0	13.0	12.9	12.7	12.5	12.5	12.7
Surface Leaching & Run-Off	25.0	21.4	29.0	18.9	18.4	18.4	18.4
Grassland	7.6	7.0	7.8	6.9	6.8	6.7	6.9
Volatilization & Atm.							
Deposition	4.3	4.5	4.2	4.2	4.2	4.2	4.2
Surface Leaching & Run-Off	3.2	2.5	3.5	2.6	2.6	2.6	2.6
Total	44.6	41.4	49.7	38.4	37.7	37.6	38.0

Note: Totals may not sum due to independent rounding.

Figure 5-4 and Figure 5-5 show regional patterns for direct N₂O emissions, Figure 5-6 and Figure 5-7 show indirect N₂O emissions from volatilization, and Figure 5-8 and Figure 5-9 show the indirect N₂O emissions from leaching and runoff in croplands and grasslands, respectively. Annual emissions in 2015 are shown for the Tier 3 Approach only.

Figure 5-4: Crops, 2015 Annual Direct N₂O Emissions Estimated Using the Tier 3 DAYCENT Model (MMT CO₂ Eq./year)

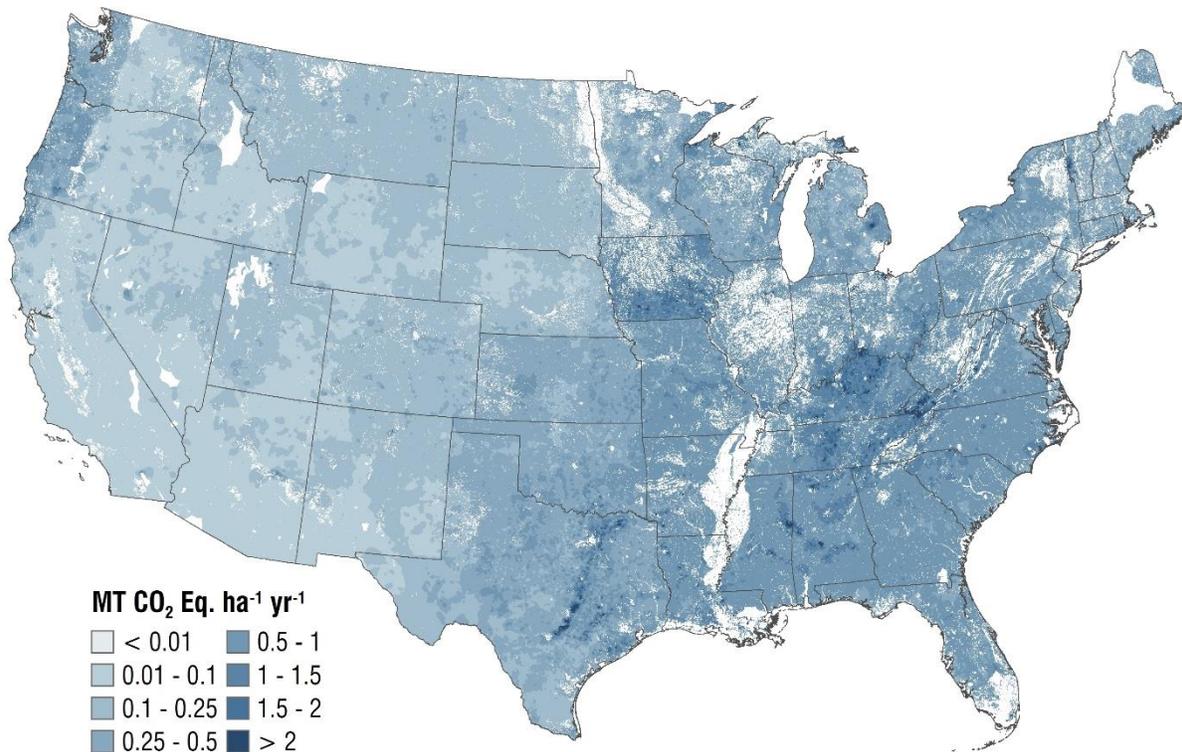


Direct N₂O emissions from croplands occur throughout all of the cropland regions but tend to be high in the Midwestern Corn Belt Region (Illinois, Iowa, Indiana, Ohio, southern Minnesota and Wisconsin, and eastern Nebraska), where a large portion of the land is used for growing highly fertilized corn and N-fixing soybean crops

(see Figure 5-4). Emissions are also high in the Lower Mississippi River Basin from Missouri to Louisiana, and highly productive irrigated areas, such as Platte River, which flows from Colorado through Nebraska, Snake River Valley in Idaho and the Central Valley in California. Direct emissions are low in many parts of the eastern United States because only a small portion of land is cultivated as well as in many western states where rainfall and access to irrigation water are limited.

Direct emissions from grasslands are highest in the southeast, particularly Kentucky and Tennessee, in addition to areas in east Texas and Iowa, where there tends to be higher rates of manure amendments on a relatively small amount of pasture, compared to other regions of the United States. However, total emissions from grasslands tend to be higher in the Great Plains and western United States (see Figure 5-5) where a high proportion of the land is dominated by grasslands and used for cattle grazing.

Figure 5-5: Grasslands, 2015 Annual Direct N₂O Emissions Estimated Using the Tier 3 DAYCENT Model (MMT CO₂ Eq./year)



Indirect N₂O emissions from volatilization in croplands have a similar pattern as the direct N₂O emissions with high emissions in the Midwestern Corn Belt and Lower Mississippi River Basin. Indirect N₂O emissions from volatilization in grasslands are higher in the Southeastern United States than in other regions. The higher emissions in this region are mainly due to highly productive pastures that support intensive grazing, which in turn, stimulates NH₃ volatilization. Indirect N₂O emissions from surface runoff and leaching of applied/mineralized N is highest in the Eastern United States for both croplands and grasslands. This region has greater precipitation and higher levels of leaching and runoff compared to the more arid region in the Western United States.

Figure 5-6: Crops, 2015 Annual Indirect N₂O Emissions from Volatilization Using the Tier 3 DAYCENT Model (MMT CO₂ Eq./year)

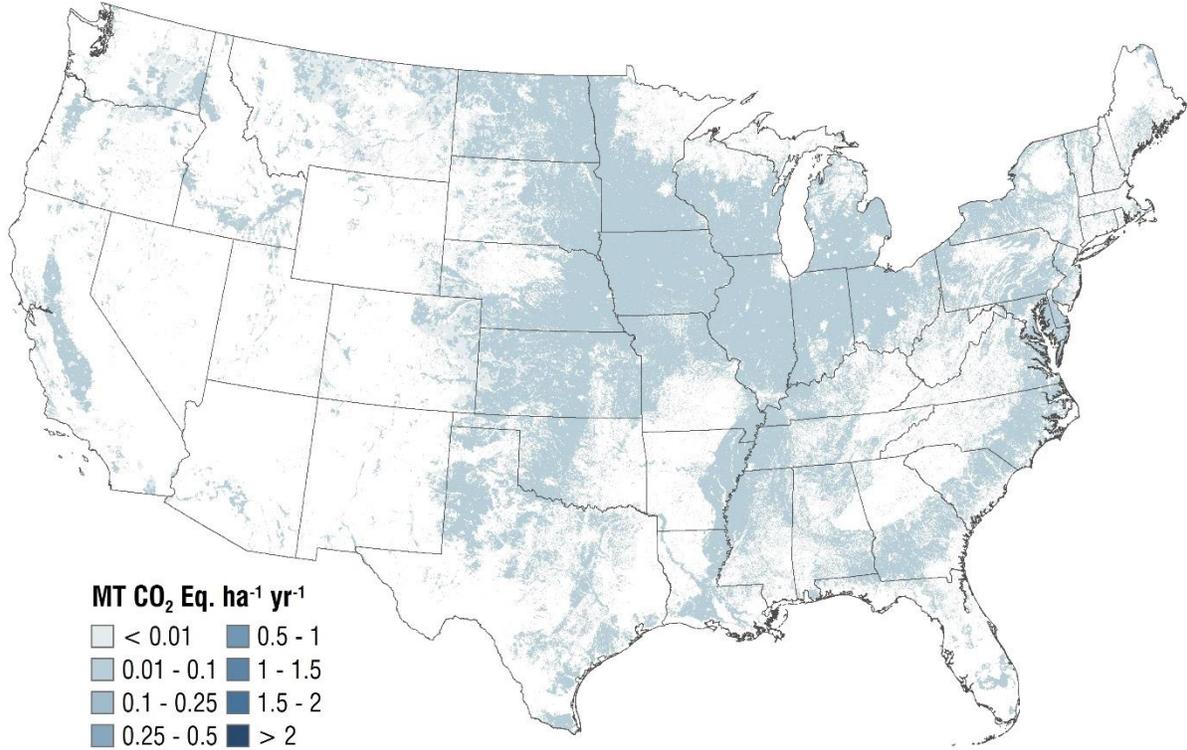


Figure 5-7: Grasslands, 2015 Annual Indirect N₂O Emissions from Volatilization Using the Tier 3 DAYCENT Model (MMT CO₂ Eq./year)

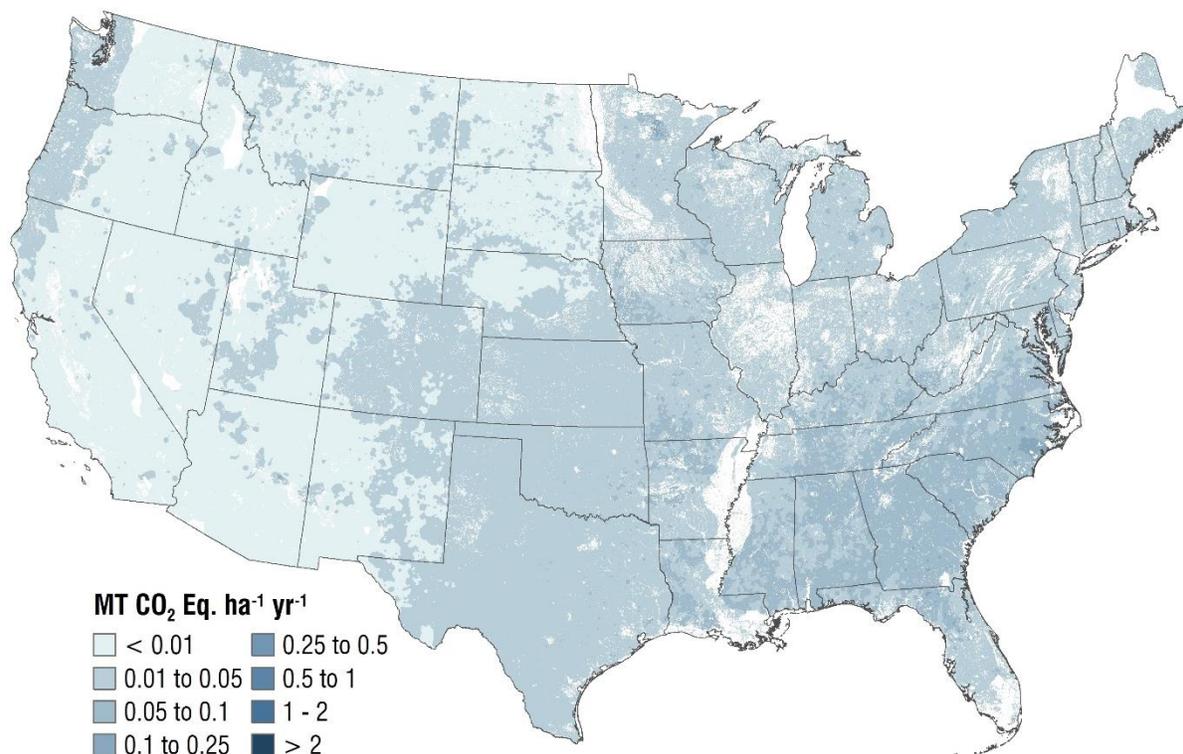


Figure 5-8: Crops, 2015 Annual Indirect N₂O Emissions from Leaching and Runoff Using the Tier 3 DAYCENT Model (MMT CO₂ Eq./year)

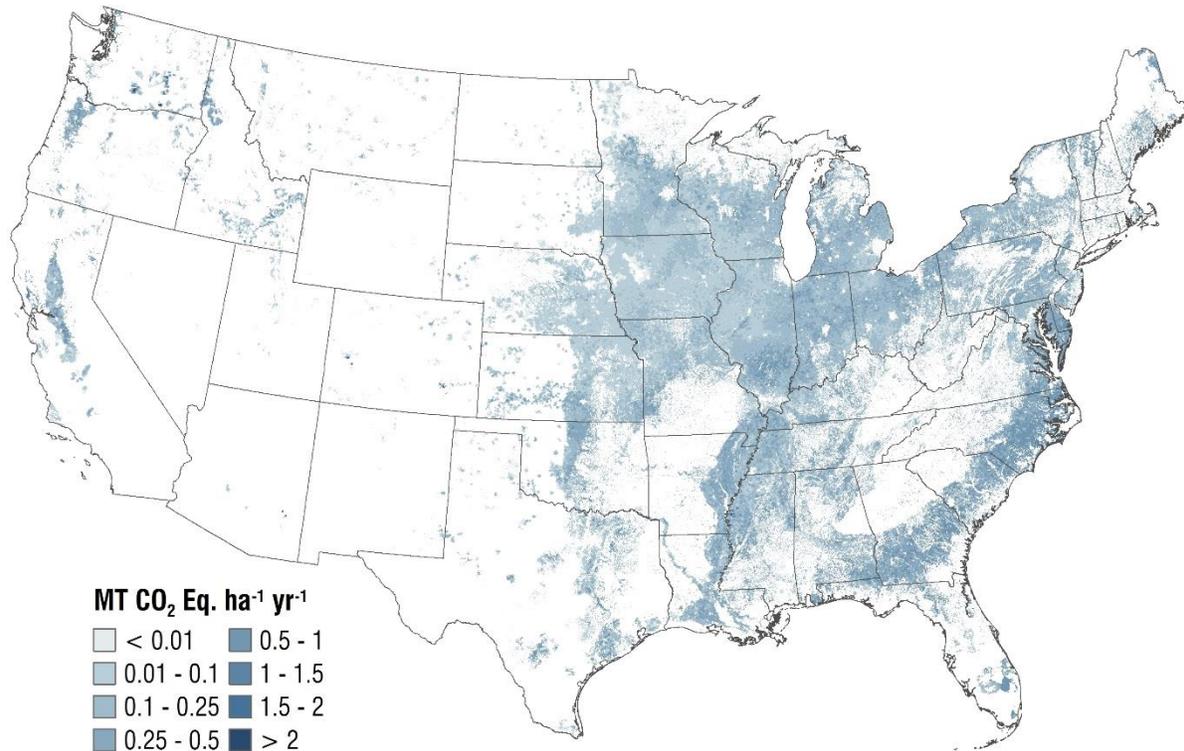
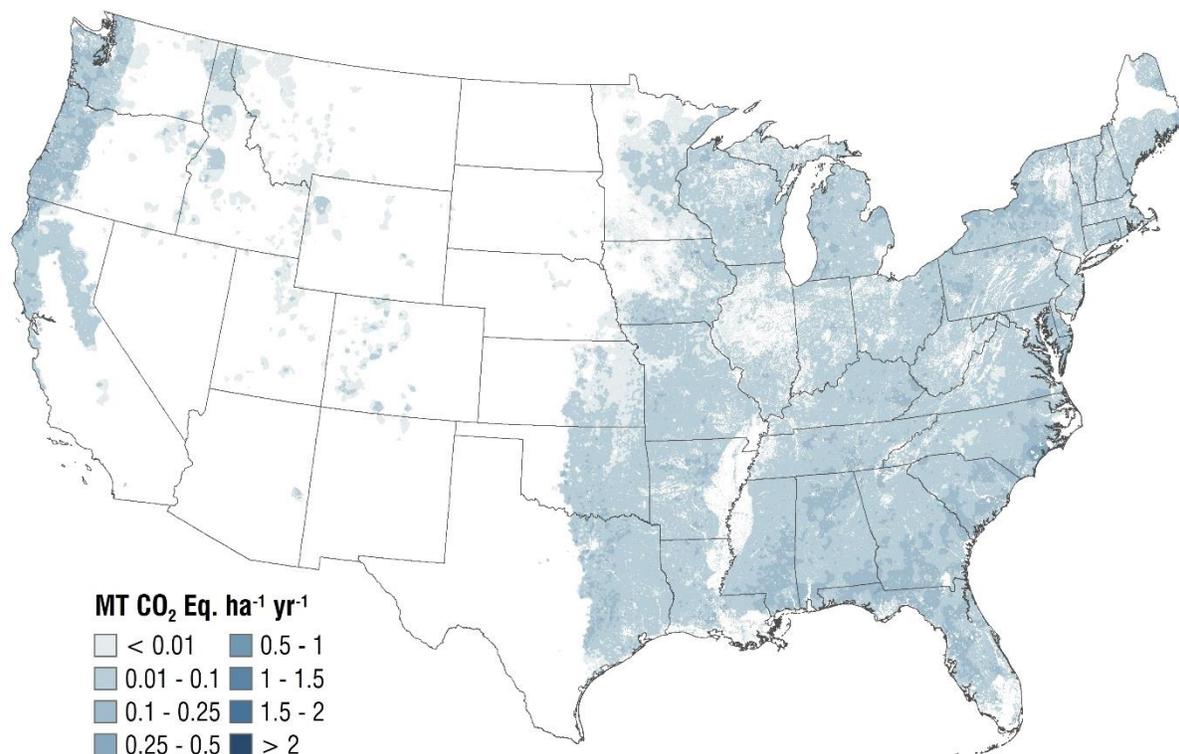


Figure 5-9: Grasslands, 2015 Annual Indirect N₂O Emissions from Leaching and Runoff Using the Tier 3 DAYCENT Model (MMT CO₂ Eq./year)



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, biosolids (i.e., 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 N₂O. The United States 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 N₂O emissions from asymbiotic fixation¹¹ 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 N₂O Emissions

The methodology used to estimate direct N₂O 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, as well as the direct emissions from non-federal grasslands with the exception of biosolids

¹¹ 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.

(i.e., sewage sludge) amendments (Del Grosso et al. 2010). The Tier 3 approach has been specifically designed and tested to estimate N₂O emissions in the United States, accounting for more of the environmental and management influences on soil N₂O 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 N₂O 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 N₂O) 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) (USDA-NRCS 2015). The NRI is a statistically-based sample of all non-federal land,¹² and includes 363,286 points on 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 205,487 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 N₂O emissions from NRI points 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). Each NRI point was sampled on a 5-year cycle from 1982 until 1997. 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, and the annual data are currently available through 2012 (USDA-NRCS 2015).

Box 5-2: Tier 1 vs. Tier 3 Approach for Estimating N₂O Emissions

The IPCC (2006) Tier 1 approach is based on multiplying activity data on different N inputs (i.e., synthetic fertilizer, manure, N fixation, etc.) by the appropriate default IPCC emission factors to estimate N₂O 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, land use and management, as well as 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 (i.e., 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 that the method is an improvement over lower tier methods 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 N₂O emissions only during that year and cannot be stored in soils and contribute to N₂O emissions in subsequent years. This is a simplifying assumption that is likely to create bias in estimated N₂O 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 N₂O during subsequent years.

DAYCENT is used to estimate N₂O emissions associated with production of alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, tomatoes, and wheat, but is not applied to estimate N₂O emissions from other crops or rotations with other crops,¹³ 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, are not simulated with DAYCENT. DAYCENT is also not used to estimate emissions from land

¹² The NRI survey does include sample points on federal lands, but the program does not collect data from those sample locations.

¹³ 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.

areas with very gravelly, cobbly, or shaley soils in the topsoil (greater than 35 percent by volume in the top 30cm of the soil profile), or to estimate emissions from drained organic soils (Histosols). The Tier 3 method has not been fully tested for estimating N₂O 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 PRP on federal grasslands; and (3) direct emissions from drained organic soils in croplands and grasslands.

Tier 3 Approach for Mineral Cropland Soils

The DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001 and 2011) is used to estimate direct N₂O emissions from mineral cropland soils that are managed for production of a wide variety of crops (see list in previous paragraph) based on the cropping histories in the 2012 NRI (USDA-NRCS 2015). 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 Moderate Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, with a pixel resolution of 250m.¹⁴

DAYCENT is used to estimate direct N₂O 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); (4) mineralization of soil organic matter; and (5) asymbiotic fixation. Note that commercial organic fertilizers (TVA 1991 through 1994; AAPFCO 1995 through 2016) 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 and are obtained primarily from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and then became the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2015). Additional data are compiled through other sources particularly 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. Nitrogen losses include direct N₂O 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 Section 5.2 Manure Management 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 N₂O emissions, but these are not model inputs. The N₂O emissions from crop residues are reduced by approximately 3 percent (the assumed average burned portion for crop residues in the United States) to avoid double-counting associated with non-CO₂ greenhouse gas emissions from agricultural residue burning. The estimate of residue

¹⁴ See <https://lpdaac.usgs.gov/products/modis_products_table>.

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 2015). The Conservation Technology Information Center (CTIC 2004) provides annual data on tillage activity with adjustments for long-term adoption of no-till agriculture (Towery 2001). Tillage has an influence on soil organic matter decomposition and subsequent soil N₂O emissions. The time series of tillage data from CTIC began in 1989 and ended in 2004, so further changes in tillage practices since 2004 are not currently captured in the Inventory and practices used in 2004 are assumed to apply for subsequent years. 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 NRI point is run 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulations for the analysis. Soil N₂O emission estimates from DAYCENT are adjusted using a structural uncertainty estimator to account for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). Soil N₂O emissions and associated 95 percent confidence intervals are estimated for each year between 1990 and 2012, but emissions from 2013 to 2015 are assumed to be similar to 2012. Annual data are currently available through 2012 (USDA-NRCS 2015), and the Inventory time series will be updated in the future as new NRI data are released.

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 N₂O production (nitrification and denitrification). It is not possible to partition N₂O emissions into each anthropogenic activity directly from model outputs due to the complexity of the interactions (e.g., N₂O 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, or made available through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere, is determined for each N source and then divided by the total amount of mineral N in the soil according to the DAYCENT model simulation. The percentages are then multiplied by the total of direct N₂O emissions in order to approximate the portion attributed to N management 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 N₂O, 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 N₂O emissions with individual sources of N.

Tier 1 Approach for Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology is used to estimate direct N₂O emissions for mineral cropland soils that are not simulated by DAYCENT (e.g., DAYCENT has not been parametrized to simulate all crop types and some soil types such as *Histosols*). For the Tier 1 Approach, estimates of direct N₂O 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) decomposition and mineralization of nitrogen from above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure commercial organic amendments are only included in the Tier 1 analysis because these data are not available at the county-level, which is necessary for the DAYCENT simulations.¹⁵ Consequently, all commercial organic fertilizer, as well as 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:

¹⁵ Commercial organic fertilizers include dried blood, tankage, compost, and other, but the dried manure and biosolids (i.e., sewage sludge) is removed from the dataset in order to avoid double counting with other datasets that are used for manure N and biosolids.

- 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 2015, state-level fertilizer for on-farm use is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 1995 through 2007, 2008 through 2016).¹⁶ After subtracting the portion of fertilizer applied to crops and grasslands simulated by DAYCENT (see Tier 3 Approach for Mineral Cropland Soils and Direct N₂O Emissions from Grassland Soils Sections 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 Mineral Cropland Soils and Direct N₂O Emissions from Grassland Soils Sections for information on data sources), and this difference is assumed to be applied to crops that are not simulated by DAYCENT.
- 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 2016). Commercial fertilizers do include some manure and biosolids (i.e., 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 biosolids (i.e., 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 2015), 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). N inputs from residue were reduced by 3 percent to account for average residue burning portions in the United States.

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 N₂O 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 N₂O 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 2012 NRI (USDA-NRCS 2015) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). Temperature data from Daly et al. (1994 and 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 2012. Emissions are assumed to be similar to 2012 from 2013 to 2015 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 N₂O Emissions from Grassland Soils

As with N₂O 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 additional management, such as irrigation, fertilization, or interseeding legumes. DAYCENT is used to simulate N₂O emissions from NRI survey locations (USDA-NRCS 2015) 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

¹⁶ Values are not available for 2014 through 2015 so a “least squares line” statistical extrapolation using the previous 5 years of data is used to arrive at an approximate value for 2014 through 2015.

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 in the Mineral Cropland Soils section. Mineral N fertilization rates are based on Carbon Sequestration Rural Appraisals (CSRA) conducted by the USDA-NRCS (USDA-NRCS, unpublished data). The CSRA was a solicitation of expert knowledge from USDA-NRCS staff throughout the United States to support the national greenhouse gas inventory. 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 (Section 5.2) 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 78 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 N₂O emissions are estimated using the IPCC (2006) Tier 1 method with IPCC default emission factors. Biosolids (i.e., 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. Biosolids application is estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007). Biosolids 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 biosolids amendments on N₂O emissions from grassland soils, and consequently, emissions from biosolids are estimated using the IPCC (2006) Tier 1 method.

Grassland area data are obtained from the U.S. Department of Agriculture NRI (Nusser and Goebel 1997; USDA-NRCS 2015) and the U.S. Geological Survey (USGS) National Land Cover Dataset (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015), 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.

N₂O emissions for the PRP manure N deposited on federal grasslands and applied biosolids N are estimated using the Tier 1 method by multiplying the N input by the default emission factor. Emissions from manure N are estimated at the state level and aggregated to the entire country, but emissions from biosolids 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 N₂O 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 N₂O emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2012, but emissions from 2013 to 2015 are assumed to be similar to 2012. The annual data are currently available through 2012 (USDA-NRCS 2015) and will be updated when additional data are released.

Total Direct N₂O Emissions from Cropland and Grassland Soils

Annual direct emissions from the Tier 1 and 3 approaches for mineral and drained organic soils occurring in both croplands and grasslands are summed to obtain the total direct N₂O emissions from agricultural soil management (see Table 5-15 and Table 5-16).

Indirect N₂O Emissions

This section describes the methods used for estimating indirect soil N₂O emissions from croplands and grasslands. Indirect N₂O 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 N₂O. There are two pathways leading to indirect emissions. The first pathway results from volatilization of N as NO_x and NH₃ following application of synthetic fertilizer, organic amendments (e.g., manure, biosolids), and deposition of PRP manure. Nitrogen 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 N₂O. The second pathway occurs via leaching and runoff of soil N (primarily in the form of NO₃⁻) 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 NO₃⁻ is subject to denitrification in water bodies, which leads to N₂O emissions. Regardless of the eventual location of the indirect N₂O emissions, the emissions are assigned to the original source of the N for reporting purposes, which here includes croplands and grasslands.

Indirect N₂O 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 N₂O. 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 N₂O emissions in the Tier 3 Approach for Mineral Cropland Soils and Direct N₂O Emissions from Grassland Soils sections. Nitrogen volatilization from 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, biosolids [i.e., 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 N₂O emissions occurring due to re-deposition of the volatilized N (see Table 5-18).

Indirect N₂O 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 N₂O. DAYCENT is used to simulate the amount of N transported from lands in the Tier 3 Approach. Nitrogen 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, biosolids 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 N₂O 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 N₂O emissions that occur in groundwater and waterways (see Table 5-18).

Uncertainty and Time-Series Consistency

Uncertainty is estimated for each of the following five components of N₂O 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 calculated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) calculated 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 N₂O 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) Tier 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Tier 1 method, and indirect N₂O emissions are estimated with a simple error propagation approach (IPCC 2006). In addition, 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. Table 5-19 shows the combined uncertainty for direct soil N₂O emissions ranged from 16 percent below to 26 percent above the 2015 emission estimate of 213.3 MMT CO₂ Eq., and the combined uncertainty for indirect soil N₂O emissions range from 46 percent below to 155 percent above the 2015 estimate of 38.0 MMT CO₂ Eq.

Table 5-19: Quantitative Uncertainty Estimates of N₂O Emissions from Agricultural Soil Management in 2015 (MMT CO₂ Eq. and Percent)

Source	Gas	2015 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate (%)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N ₂ O Emissions	N ₂ O	213.3	179.7	267.9	-16%	26%
Indirect Soil N ₂ O Emissions	N ₂ O	38.0	20.5	96.8	-46%	155%

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

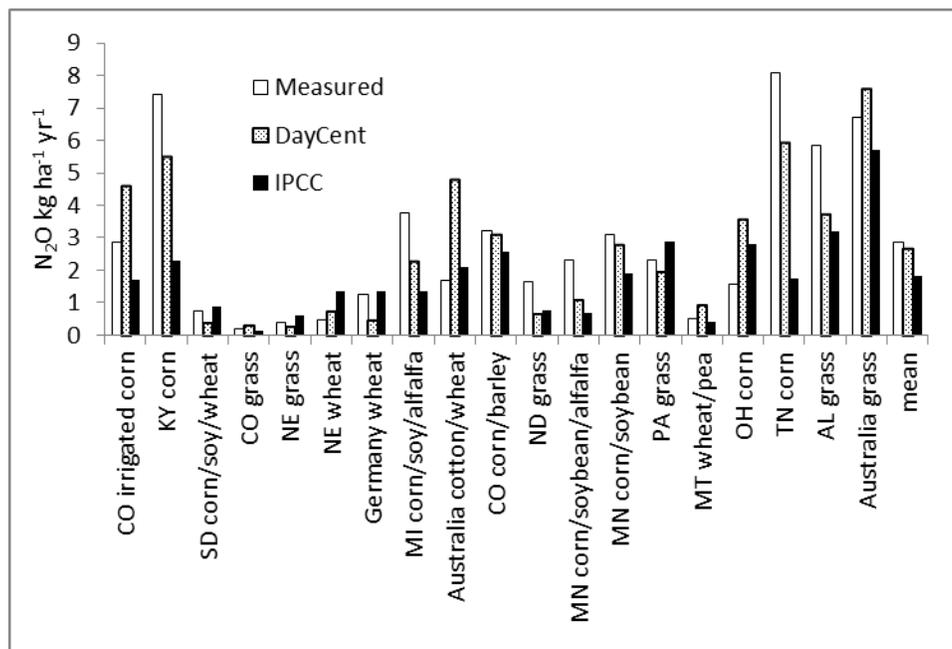
Additional uncertainty is associated with an incomplete estimation of N₂O emissions from managed croplands and grasslands in Hawaii and Alaska. The Inventory currently includes the N₂O emissions from mineral fertilizer and PRP N additions in Alaska and Hawaii, and drained organic soils in Hawaii. Land areas used for agriculture in Alaska and Hawaii are small relative to major commodity cropping states in the conterminous United States, so the emissions are likely to be small for the other sources of N (e.g., crop residue inputs), which are not currently included in the Inventory.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2015. Details on the emission trends through time are described in more detail in the Methodology section.

QA/QC and Verification

DAYCENT results for N₂O emissions and NO₃⁻ 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. Nitrous oxide measurement data are available for 41 sites, which mostly occur in the United States, with five in Europe and three in Australia, representing over 200 different combinations of fertilizer treatments and cultivation practices. Nitrate leaching data are available for four sites in the United States, representing 10 different combinations of fertilizer amendments/tillage practices. DAYCENT estimates of N₂O emissions are closer to measured values at most sites compared to the IPCC Tier 1 estimate (see Figure 5-10). In general, the 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 (i.e., 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 N₂O emissions. DAYCENT does have a tendency to under-estimate very high N₂O 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 N₂O emissions, and is an improvement over the IPCC Tier 1 method.

Figure 5-10: Comparison of Measured Emissions at Field Sites and Modeled Emissions Using the DAYCENT Simulation Model and IPCC Tier 1 Approach (kg N₂O per ha per year)



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 method have been checked and updated as needed.

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 2012; (2) modifying the number of experimental study sites used to quantify model uncertainty for direct N₂O emissions; (3) DAYCENT model development to improve the simulation of soil temperature; (4) improvements in the cropping and land use histories that are simulated in DAYCENT between 1950 and 1979 that generate initial values for the model state variables, such as initial soil organic C stock values; and (5) implementing a more robust set of model output variables that enabled a more accurate and detailed accounting of N from synthetic fertilizers, managed manure, and PRP manure applied to grasslands. These changes resulted in a decrease in emissions of approximately 14.4 percent on average relative to the previous Inventory and an increase in the upper bound of the 95 percent confidence interval for direct N₂O emissions from 24 to 31 percent. The differences in emissions and uncertainty are mainly due to modifying the number of study sites used to quantify model uncertainty.

Planned Improvements

Several planned improvements are underway. The DAYCENT biogeochemical model will be improved with a better representation of plant phenology, particularly senescence events following grain filling in crops. In addition, crop parameters associated with temperature effects on plant production will be further improved in DAYCENT with additional model calibration. Model development is underway to represent the influence of nitrification inhibitors and slow-release fertilizers (e.g., polymer-coated fertilizers) on N₂O emissions. An improved representation of drainage as well as freeze-thaw cycles are also under development. Experimental study sites will continue to be

added for quantifying model structural uncertainty, and studies that have continuous (daily) measurements of N₂O (e.g., Scheer et al. 2013) will be given priority.

The time series of management data will be updated with information from the USDA-NRCS Conservation Effects Assessment Program (CEAP). This improvement will fill several gaps in the management data including more specific data on fertilizer rates, updated tillage practices, and more information on planting and harvesting dates for crops.

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 (see Section 5.7).

Alaska and Hawaii are not included for all sources in the current Inventory for agricultural soil management, with the exception of N₂O emissions from drained organic soils in croplands and grasslands for Hawaii, synthetic fertilizer and PRP N amendments for grasslands in Alaska and Hawaii. A planned improvement over the next two years is to add the remaining sources for these states into the Inventory analysis.

There is also an improvement based on updating the Tier 1 emission factor for N₂O emissions from drained organic soils by using the revised factor in the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (IPCC 2013).

All of these improvements are expected to be completed for the 1990 through 2017 Inventory (2019 submission to the UNFCCC). However, the time line may be extended if there are insufficient resources to fund all or part of these planned improvements.

5.5 Liming (IPCC Source Category 3G)

Crushed limestone (CaCO₃) and dolomite (CaMg(CO₃)₂) are added to soils 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 25 years in the United States, ranging from 3.6 MMT CO₂ Eq. to 6.0 MMT CO₂ Eq. In 2015, liming of soils in the United States resulted in emissions of 3.8 MMT CO₂ Eq. (1.0 MMT C), representing an 18 percent decrease in emissions since 1990 (see Table 5-20 and Table 5-21). The trend is driven by the amount of limestone and dolomite applied to soils over the time period.

Table 5-20: Emissions from Liming (MMT CO₂ Eq.)

Source	1990	2005	2011	2012	2013	2014	2015
Limestone	4.1	3.9	3.4	4.5	3.6	3.3	3.5
Dolomite	0.6	0.4	0.4	1.5	0.3	0.3	0.3
Total	4.7	4.3	3.9	6.0	3.9	3.6	3.8

Note: Totals may not sum due to independent rounding.

Table 5-21: Emissions from Liming (MMT C)

Source	1990	2005	2011	2012	2013	2014	2015
Limestone	1.1	1.1	0.9	1.2	1.0	0.9	0.9
Dolomite	0.2	0.1	0.1	0.4	0.1	0.1	0.1
Total	1.3	1.2	1.1	1.6	1.1	1.0	1.0

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 5-22) were multiplied by CO₂ 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, 2015 and 2016; USGS 2008 through 2016). 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 5-3: 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 rivers and eventually the ocean where CaCO₃ 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 2015 U.S. emission estimate from liming of soils is 3.8 MMT CO₂ Eq. using the U.S.-specific factors. In contrast, emissions would be estimated at 7.8 MMT CO₂ 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 manufacturers 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 that is 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 2015 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 2015 data, 2014 fractions were applied to a 2015 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2016* (USGS 2016).

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.

Table 5-22: Applied Minerals (MMT)

Mineral	1990	2005	2011	2012	2013	2014	2015
Limestone	19.0	18.1	15.9	20.8	16.4	15.3	16.1
Dolomite	2.4	1.9	1.9	6.3	1.5	1.3	1.4

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.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty in CO₂ emissions from liming. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-23. Carbon dioxide emissions from carbonate lime application to soils in 2015 were estimated to be between -0.4 and 7.2 MMT CO₂ Eq. at the 95 percent confidence level. This confidence interval represents a range of 111 percent below to 88 percent above the 2015 emission estimate of 3.8 MMT CO₂ Eq.

Table 5-23: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Liming (MMT CO₂ Eq. and Percent)

Source	Gas	2015 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate ^a			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Liming	CO ₂	3.8	(0.4)	7.2	-111%	+88%

^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 2015. 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. No errors were found.

Recalculations Discussion

Adjustments were made in the current Inventory to improve the results. First, limestone and dolomite application data for 2014 were approximated in the previous Inventory using a ratio of total crushed stone for 2014 relative to 2015 (similar to 2015 in the current Inventory). The estimates for 2014 were updated with the recently published

data from USGS (2016). With this revision in the activity data, the emissions decreased by 12.8 percent in 2014 relative to the previous Inventory.

5.6 Urea Fertilization (IPCC Source Category 3H)

The use of urea ($\text{CO}(\text{NH}_2)_2$) 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 5.0 MMT CO_2 Eq. (1.4 MMT C) in 2015 (Table 5-24 and Table 5-25). Due to an increase in application of urea fertilizers between 1990 and 2015, CO_2 emissions have increased by 108 percent from this management activity.

Table 5-24: CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq.)

Source	1990	2005	2011	2012	2013	2014	2015
Urea Fertilization	2.4	3.5	4.1	4.3	4.5	4.8	5.0

Table 5-25: CO_2 Emissions from Urea Fertilization (MMT C)

Source	1990	2005	2011	2012	2013	2014	2015
Urea Fertilization	0.7	1.0	1.1	1.2	1.2	1.3	1.4

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 5-26) were derived from the state-level fertilizer sales data provided in *Commercial Fertilizer* reports (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2016). 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, in 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 2014 and 2015 fertilizer years (i.e., July 2013 through June 2014 and July 2014 through June 2015) were not available for this Inventory. Therefore, urea application in the 2014 and 2015 fertilizer years were estimated using a linear, least squares trend of consumption over the data from the previous five years (2009 through 2013) 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.

Table 5-26: Applied Urea (MMT)

	1990	2005	2011	2012	2013	2014	2015
Urea Fertilizer ^a	3.3	4.8	5.6	5.8	6.1	6.5	6.9

^aThese 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*, as it is not currently possible to apportion the data by land-use category.

Uncertainty and Time-Series Consistency

Uncertainty estimates are presented in Table 5-27 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(NH₂)₂ applied to soils is ultimately emitted into the environment as CO₂. 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, urea consumption data also have uncertainty that is propagated through the emission calculation using a Monte Carlo simulation approach as described by the IPCC (2006). Carbon dioxide emissions from urea fertilization of agricultural soils in 2015 were estimated to be between 2.9 and 5.2 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of 43 percent below to 3 percent above the 2015 emission estimate of 5.0 MMT CO₂ Eq.

Table 5-27: Quantitative Uncertainty Estimates for CO₂ Emissions from Urea Fertilization (MMT CO₂ Eq. and Percent)

Source	Gas	2015 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate ^a			
			Lower Bound	Upper Bound	Lower Bound (%)	Upper Bound (%)
Urea Fertilization	CO ₂	5.0	2.9	5.2	-43%	3%

^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 2015. 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 Fertilization has been developed and implemented, and no errors were found.

Recalculations Discussion

Recalculations resulted from updated urea application estimates in a new AAPFCO report (2016). Specifically, the 2012, 2013 and 2014 activity data (i.e., amount of urea applied) for the states of Alabama and Virginia were updated. This resulted in an emissions increase for the United States of 1 percent in 2012, 3.7 percent in 2013 and 5.9 percent in 2014.

5.7 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 CO₂ emissions because the C released to the atmosphere as CO₂ during burning is reabsorbed during the next growing season by the crop. However, crop residue burning is a net source of CH₄, N₂O, 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 2015, CH₄ and N₂O emissions from field burning of agricultural residues were 0.3 MMT CO₂ Eq. (11 kt) and 0.1 MMT CO₂ Eq. (0.3 kt), respectively (see Table 5-28 and Table 5-29). Annual emissions of CH₄ and N₂O have increased from 1990 to 2015 by 25 percent and 23 percent, respectively. The increase in emissions over time is due to larger amounts of residue production with higher yielding crop varieties and fuel loads.

Table 5-28: CH₄ and N₂O Emissions from Field Burning of Agricultural Residues (MMT CO₂ Eq.)

Gas/Crop Type	1990	2005	2011	2012	2013	2014	2015
CH₄	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	+
Sugarcane	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Lentil	+	+	+	+	+	+	+
N₂O	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 CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Table 5-29: CH₄, N₂O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (kt)

Gas/Crop Type	1990	2005	2011	2012	2013	2014	2015
CH₄	9	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	2	2
Corn	1	1	1	1	1	2	2
Soybeans	1	1	1	1	1	1	1
Lentil	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
N₂O	+						
Wheat	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Lentil	+	+	+	+	+	+	+
CO	191	178	234	232	239	240	239
NO_x	6	6	7	7	7	8	8

+ Does not exceed 0.5 kt.

Methodology

A U.S.-specific Tier 2 method was used to estimate greenhouse gas emissions from field burning of agricultural residues (for more details comparing the U.S.-specific approach to the IPCC (2006) default approach, see Box 5-4). In order to estimate the amounts of C and N released during burning, the following equation was used:

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

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 consumed¹⁷
- 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 (2016) for all crops (except rice in Florida and Oklahoma, as detailed below). The amount of C or N released was used in the following equation to determine the CH₄, CO, N₂O, and NO_x emissions from the Field Burning of Agricultural Residues:

$$\text{CH}_4 \text{ and CO, or N}_2\text{O and NO}_x \text{ Emissions from Field Burning of Agricultural Residues} = \text{C or N Released} \times \text{ER} \times \text{CF}$$

¹⁷ 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).

where,

Emissions Ratio (ER)	= g CH ₄ -C or CO-C/g C released, or g N ₂ O-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 ₂ O-N to N (44/28), or NO _x -N to N (30/14)

Box 5-4: 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 the 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 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 2015 Inventory report to determine the difference in overall estimates between the two approaches. To estimate greenhouse gas emissions from field burning of agricultural residues 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 × C _f)	= IPCC (2006) default fuel biomass consumption (metric tons dry matter burnt ha ⁻¹) and US-Specific Values using NASS Statistics (USDA 2016)
Emission Factor (G _{ef})	= IPCC (2006) emission factor (g kg ⁻¹ dry matter burnt)

The IPCC (2006) Tier 1 method approach that utilizes default mass of fuel values resulted in 1 percent higher emissions of CH₄ and 14 percent higher emissions of N₂O compared to this Inventory. If U.S.-specific data are used to derive the Mass of Fuel (M_b) from USDA NASS statistics (USDA 2016), i.e., Tier 2 method, then the IPCC (2006) method resulted in 28 percent higher emissions of CH₄ and 44 percent higher emissions of N₂O compared to this Inventory. This larger difference is attributable to lower combustion efficiency values in IPCC/UNEP/OECD/IEA (1997). In particular, sugarcane has a much lower combustion efficiency value in the earlier guidelines. A lower value is justified because sugarcane is burned prior to harvesting and has a higher moisture content that reduces the combustion efficiency, unlike most other crops (IPCC/UNEP/OECD/IEA 1997). IPCC (2006) does not address the unique burning regime of sugarcane. Overall, the IPCC/UNEP/OECD/IEA (1997) method is considered more appropriate for U.S. conditions because it is more flexible for incorporating country-specific data compared to IPCC (2006) approach.

Crop yield data (except rice in Florida) were based on USDA's *QuickStats* (USDA 2016), and crop area data were based on the 2012 NRI (USDA-NRCS 2015). 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 5-30. 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 state¹⁸ from McCarty (2010) for corn, cotton, lentils, rice, soybeans, sugarcane, and wheat.¹⁹ McCarty (2010) used remote sensing data from 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 5-31. 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 5-31 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 Stützel (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 Stützel (1987); the value for lentil residue was assumed to equal the value for bean residue. 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 5-32 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 5-33).

Table 5-30: Agricultural Crop Production (kt of Product)

Crop	1990	2005	2011	2012	2013	2014	2015
Corn ^a	249,806	323,724	356,783	311,751	398,817	429,405	422,436
Cotton	4,633	6,560	5,607	5,967	5,647	5,934	5,575
Lentils	+	119	59	121	147	134	117
Rice	9,428	12,253	10,408	10,080	10,381	10,347	10,202
Soybeans	56,626	88,036	87,557	85,523	93,928	102,065	102,772
Sugarcane	18,765	18,211	16,795	16,555	16,129	17,136	18,336
Wheat	79,951	69,190	61,902	71,234	69,287	64,650	66,672

+ Does not exceed 0.5 kt.

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

Table 5-31: U.S. Average Percent Crop Area Burned by Crop (Percent)

State	1990	2005	2011	2012	2013	2014	2015
Corn	+	+	+	+	+	+	+
Cotton	1%	1%	1%	1%	1%	1%	1%
Lentils	+	1%	+	+	+	+	+
Rice	8%	5%	7%	7%	7%	7%	7%
Soybeans	+	+	+	+	+	+	+
Sugarcane	13%	25%	53%	53%	52%	53%	54%
Wheat	2%	2%	3%	3%	3%	3%	2%

+ Does not exceed 0.5 percent.

¹⁸ Alaska and Hawaii were excluded.

¹⁹ 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.

Table 5-32: Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue: Crop	Dry Matter			Burning Efficiency (Fraction)	Combustion Efficiency (Fraction)
	Ratio	Fraction	C Fraction	N 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 5-33: 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 ₂ O: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 5-34. Methane emissions from field burning of agricultural residues in 2015 were estimated to be between 0.17 and 0.39 MMT CO₂ Eq. at a 95 percent confidence level. This indicates a range of 40 percent below and 41 percent above the 2015 emission estimate of 0.3 MMT CO₂ Eq. Nitrous oxide emissions were estimated to be between 0.07 and 0.13 MMT CO₂ Eq., or approximately 29 percent below and 30 percent above the 2015 emission estimate of 0.1 MMT CO₂ Eq.

Table 5-34: Approach 2 Quantitative Uncertainty Estimates for CH₄ and N₂O Emissions from Field Burning of Agricultural Residues (MMT CO₂ Eq. and Percent)

Source	Gas	2015 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	0.17
Field Burning of Agricultural Residues	N ₂ O	0.1	0.07	0.13	-29%	30%

^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, particularly 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 2015. 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 analyses, and no errors were found in this Inventory.

Recalculations Discussion

The crop area data were updated with the 2012 NRI survey (USDA-NRCS 2015). This change resulted in a relatively small change in emissions, with CH₄ and N₂O emissions decreasing by 0.8 percent and 0.5 percent, respectively.

Planned Improvements

A new method is in development that will directly link agricultural residue burning with the Tier 3 methods that are used in several other source categories, including 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.