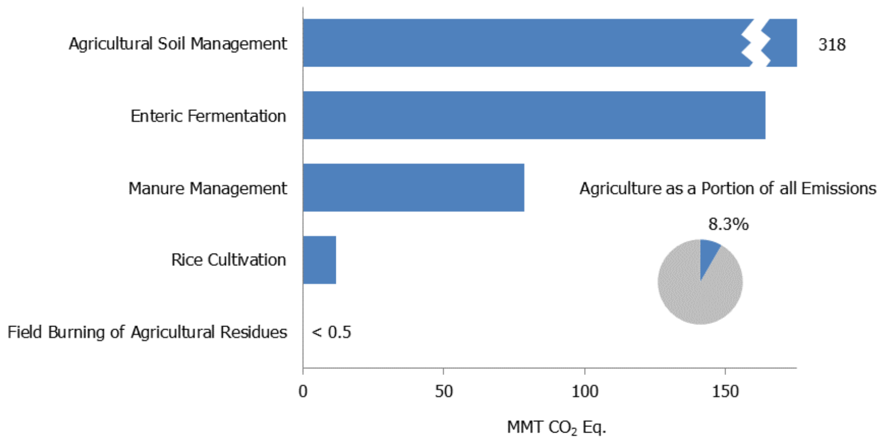
5. Agriculture

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

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



In 2014, the Agriculture sector was responsible for emissions of 573.6 MMT CO_2 Eq.,[1] or 8.3 percent of total U.S. greenhouse gas emissions. Methane (CH_4) and nitrous oxide (N_2O) were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represent 22.5 percent and 8.4 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of CH_4. Rice cultivation and field burning of agricultural residues were minor sources of CH_4. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 78.9 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions.

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

Table 5-1 and Table 5-2 present emission estimates for the Agriculture sector. Between 1990 and 2014, CH_4 emissions from agricultural activities increased by 10.7 percent, while N_2O emissions fluctuated from year to year, but overall increased by 5.9 percent.

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

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CH_4	**214.7**	**238.4**	**244.4**	**242.5**	**242.6**	**239.0**	**237.7**
Enteric Fermentation	164.2	168.9	171.3	168.9	166.7	165.5	164.3
Manure Management	37.2	56.3	60.9	61.5	63.7	61.4	61.2
Rice Cultivation	13.1	13.0	11.9	11.8	11.9	11.9	11.9
Field Burning of Agricultural Residues	0.2	0.2	0.3	0.3	0.3	0.3	0.3
N_2O	**317.4**	**313.8**	**338.0**	**340.6**	**340.7**	**336.2**	**336.0**
Agricultural Soil Management	303.3	297.2	320.7	323.1	323.1	318.6	318.4
Manure Management	14.0	16.5	17.2	17.4	17.5	17.5	17.5
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**532.0**	**552.2**	**582.3**	**583.1**	**583.3**	**575.3**	**573.6**

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (kt)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CH_4	**8,587**	**9,537**	**9,776**	**9,702**	**9,705**	**9,562**	**9,506**
Enteric Fermentation	6,566	6,755	6,853	6,757	6,670	6,619	6,572
Manure Management	1,486	2,254	2,437	2,460	2,548	2,455	2,447
Rice Cultivation	525	521	474	474	476	477	476
Field Burning of Agricultural Residues	10	8	11	11	11	11	11
N_2O	**1,065**	**1,053**	**1,134**	**1,143**	**1,143**	**1,128**	**1,127**
Agricultural Soil Management	1,018	997	1,076	1,084	1,084	1,069	1,068
Manure Management	47	55	58	58	59	59	59
Field Burning of Agricultural Residues	+	+	+	+	+	+	+

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

5.1 Enteric Fermentation (IPCC Source Category 3A)

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

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

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

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

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

From 1990 to 2014, emissions from enteric fermentation have increased by 0.1 percent. While emissions generally follow trends in cattle populations, over the long term there are exceptions as population decreases have been coupled with production increases or minor decreases. For example, beef cattle emissions decreased 2.0 percent from 1990 to 2014, while beef cattle populations actually declined by 7 percent and beef production increased (USDA 2015), and while dairy emissions increased 6.5 percent over the entire time series, the population has declined by 5 percent and milk production increased 40 percent (USDA 2015). This trend indicates that while emission factors per head are increasing, emission factors per unit of product are going down. Generally, from 1990 to 1995 emissions from beef increased and then decreased from 1996 to 2004. These trends were mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Beef cattle emissions generally increased from 2004 to 2007, as beef populations underwent increases and an extensive literature review indicated a trend toward a decrease in feed digestibility for those years. Beef cattle emissions decreased again from 2008 to 2014 as populations again decreased. Emissions from dairy cattle generally trended downward from 1990 to 2004, along with an overall dairy population decline during the same period. Similar to beef cattle, dairy cattle emissions rose from 2004 to 2007 due to population increases and a decrease in feed digestibility (based on an analysis of more than 350 dairy cow diets). Dairy cattle emissions have continued to trend upward since 2007, in line with dairy population increases. Regarding trends in other animals populations of sheep have steadily declined, with an overall decrease of 54 percent since 1990. Horse populations are 56 percent greater than they were in 1990, but their numbers have been declining by about 2 percent annually since 2007. Goat populations increased by about 20 percent through 2007 but have since dropped below 1990 numbers, while swine populations have increased 19 percent since 1990. The population of American bison more than tripled over the 1990 through 2014 time period, while mules and asses have more than quadrupled.

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

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

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

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

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

Sheep	91		49		45	44	43	43	42
Goats	13		14		14	14	13	13	12
American Bison	4		17		15	14	13	13	12
Mules and Asses	1		2		3	3	3	3	3
Total	**6,566**		**6,755**		**6,853**	**6,757**	**6,670**	**6,619**	**6,572**

Note: Totals may not sum due to independent rounding.

Methodology

Livestock enteric fermentation emission estimate methodologies fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics, account for the majority of enteric fermentation CH_4 emissions from livestock in the United States. A more detailed methodology (i.e., Intergovernmental Panel on Climate Change [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 the U.S. Environmental Protection Agency (EPA) and used to estimate cattle CH_4 emissions from enteric fermentation, incorporates this information and other analyses of livestock population, feeding practices, and production characteristics.

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

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

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

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

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

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

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

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

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

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

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

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

Uncertainty and Time-Series Consistency

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

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

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

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

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

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[b] Note that the relative uncertainty range was estimated with respect to the 2001 emission estimates from the 2003 submission and applied to the 2014 estimates.
[c] The overall uncertainty calculated in 2003, and applied to the 2014 emission estimate, did not include uncertainty estimates for calves, American bison, and mules and asses. Additionally, for bulls the emissions estimate was based on the Tier 1 methodology. Since bull emissions are now estimated using the Tier 2 method, the uncertainty surrounding their estimates is likely lower than indicated by the previous uncertainty analysis.

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

QA/QC and Verification

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

Recalculations Discussion

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

Revisions to input data include the following:

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

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

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

Planned Improvements

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

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

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

5.2 Manure Management (IPCC Source Category 3B)

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

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

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

[3] Direct and indirect N_2O emissions from dung and urine spread onto fields either directly as daily spread or after it is removed from manure management systems (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.

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

Estimates of CH_4 emissions from manure management in 2014 were 61.2 MMT CO_2 Eq. (2,447 kt); in 1990, emissions were 37.2 MMT CO_2 Eq. (1,486 kt). This represents a 65 percent increase in emissions from 1990. Emissions increased on average by 1.0 MMT CO_2 Eq. (2.6 percent) annually over this period. The majority of this increase is due to swine and dairy cow manure, where emissions increased 44 and 118 percent, respectively. From 2013 to 2014, there was a 0.3 percent decrease in total CH_4 emissions from manure management, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

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

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

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

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

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

Dairy Cattle	5.3	5.6	5.7	5.8	5.9	5.9	5.9
Beef Cattle	5.9	7.2	7.6	7.7	7.7	7.7	7.8
Swine	1.2	1.7	1.9	1.9	1.9	1.9	1.8
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Goats	+	+	+	+	+	+	+
Poultry	1.4	1.6	1.5	1.5	1.6	1.6	1.6
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
American Bison	NA	NA	NA	NA	NA	NA	NA
Mules and Asses	+	+	+	+	+	+	+
Total	**51.1**	**72.9**	**78.1**	**78.9**	**81.2**	**78.9**	**78.7**

+ Does not exceed 0.05 MMT CO_2 Eq.
NA - Not available
[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.
[b] Includes both direct and indirect N_2O emissions.
Notes: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS; there are no American bison N_2O emissions from managed systems.

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

Gas/Animal Type	1990	2005	2010	2011	2012	2013	2014
CH_4[a]	**1,486**	**2,254**	**2,437**	**2,460**	**2,548**	**2,455**	**2,447**
Dairy Cattle	590	1,057	1,217	1,245	1,306	1,271	1,289
Beef Cattle	126	133	132	131	128	121	120
Swine	622	916	945	942	972	920	896
Sheep	7	3	3	3	3	3	3
Goats	1	1	1	1	1	1	1
Poultry	131	129	129	127	128	128	130
Horses	9	12	10	10	10	9	9
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O[b]	**47**	**55**	**58**	**58**	**59**	**59**	**59**
Dairy Cattle	18	19	19	19	20	20	20
Beef Cattle	20	24	25	26	26	26	26
Swine	4	6	6	6	6	6	6
Sheep	+	1	1	1	1	1	1
Goats	+	+	+	+	+	+	+
Poultry	5	5	5	5	5	5	5
Horses	+	+	+	+	+	+	+
American Bison	NA	NA	NA	NA	NA	NA	NA
Mules and Asses	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.
NA - Not available
[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.
[b] Includes both direct and indirect N_2O emissions.
Notes: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS; there are no American bison N_2O emissions from managed systems.

Methodology

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

Methane Calculation Methods

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

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

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

- Annual animal population data for 1990 through 2014 for all livestock types, except goats, horses, mules and asses, and American bison were obtained from 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 data from USDA (USDA APHIS 1996; Bush 1998; Ott 2000; USDA 2014a) 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 CH_4-producing capacity of the VS (B_o) was determined for each animal type based on literature values (Morris 1976; Bryant et al. 1976; Hashimoto 1981; Hashimoto 1984; EPA 1992; Hill 1982; Hill 1984).
- MCFs for dry systems were set equal to default IPCC factors based on state climate for each year (IPCC 2006). MCFs for liquid/slurry, anaerobic lagoon, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted in the van't Hoff-Arrhenius equation which is consistent with IPCC (2006) Tier 2 methodology.
- Data from anaerobic digestion systems with CH_4 capture and combustion were obtained from the EPA AgSTAR Program, including information presented in the *AgSTAR Digest* (EPA 2000, 2003, 2006) and the

AgSTAR project database (EPA 2012). Anaerobic digester emissions were calculated based on estimated methane production and collection and destruction efficiency assumptions (ERG 2008).

- For all cattle except for calves, the estimated amount of VS (kg per animal-year) managed in each WMS for each animal type, state, and year were taken from the CEFM, assuming American bison VS production to be the same as NOF bulls. For animals other than cattle, the annual amount of VS (kg per year) from manure excreted in each WMS was calculated for each animal type, state, and year. This calculation multiplied the animal population (head) by the VS excretion rate (kg VS per 1,000 kg animal mass per day), the TAM (kg animal mass per head) divided by 1,000, the WMS distribution (percent), and the number of days per year (365.25).

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

Nitrous Oxide Calculation Methods

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

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

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

- Nex rates for all cattle except for calves were calculated by head for each state and animal type in the CEFM. Nex rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996 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 N_2O emission factors (direct and indirect) were taken from IPCC (2006). These data are appropriate because they were developed using U.S. data.

- Country-specific estimates for the fraction of N loss from volatilization ($Frac_{gas}$) and runoff and leaching ($Frac_{runoff/leach}$) were developed. $Frac_{gas}$ values were based on WMS-specific volatilization values as estimated from EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). $Frac_{runoff/leaching}$ values were based on regional cattle runoff data from EPA's Office of Water (EPA 2002b; see Annex 3.11).

To estimate N_2O emissions for cattle (except for calves), 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)

[4] The N_2O emissions from N excreted (Nex) 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 N_2O emissions from unmanaged WMS are not included in the Manure Management category, there are no N_2O emissions from American bison included in the Manure Management category.

divided by 1,000, the nitrogen excretion rate (Nex, in kg N per 1,000 kg animal mass per day), WMS distribution (percent), and the number of days per year.

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

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

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

Uncertainty and Time-Series Consistency

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

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

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

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

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

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

QA/QC and Verification

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

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

For additional verification, the implied CH_4 emission factors for manure management (kg of CH_4 per head per year) were compared against the default IPCC (2006) values. Table 5-9 presents the implied emission factors of kg of CH_4 per head per year used for the manure management emission estimates as well as the IPCC (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 CH_4 emissions.

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

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

NA - Not Applicable

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

Recalculations Discussion

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

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

Planned Improvements

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

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

5.3 Rice Cultivation (IPCC Source Category 3C)

Most of the world's rice is grown on flooded fields (Baicich 2013), and flooding creates anaerobic conditions that foster CH_4 production through a process known as methanogenesis. Approximately 60 to 90 percent of the CH_4 produced by methanogenic bacteria is oxidized in the soil and converted to CO_2 by methanotrophic bacteria. The remainder is emitted to the atmosphere (Holzapfel-Pschorn et al. 1985; Sass et al. 1990) or transported as dissolved CH_4 into groundwater and waterways (Neue et al. 1997). Methane is transported to the atmosphere primarily through the rice plants, but some CH_4 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 CH_4 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 CH_4, but large amounts of CH_4 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 N_2O 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 CH_4 transport to the atmosphere through the plant compared to shallow-flooded systems (Sass 2001).

Other management practices also influence CH_4 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 exudates[5] 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 CH_4 emissions (Wassmann et al. 2000b). Fertilization practices also influences CH_4 emissions, particularly the use of fertilizers with sulfate (Wassmann et al. 2000b; Linquist et al. 2012). Other environmental variables also impact the methanogenesis process such as soil

[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.

temperature and soil type. Soil temperature is an important factor regulating the activity of methanogenic bacteria which in turn affects the rate of CH_4 production. Soil texture influences decomposition of soil organic matter, but is also thought to have an impact on oxidation of CH_4 in the soil (Sass et al. 1994).

Rice is currently cultivated in twelve states, including Arkansas, California, Florida, Illinois, 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 CH_4 emissions in the United States relative to other source categories (see Table 5-10 and Table 5-11). In 2014, CH_4 emissions from rice cultivation were 11.9 MMT CO_2 Eq. (476 kt). Annual emissions fluctuate between 1990 and 2014, and emissions in 2014 represented a 9 percent decrease compared to 1990. Variation in emissions is largely due to differences in the amount of rice harvested areas over time. In Arkansas and California, rice harvested areas increased by 33 percent and 39 percent respectively from 1990 to 2014, while rice harvested area declined in Louisiana and Texas by 14 percent and 78 percent respectively (see Table 5-12).

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

State	1990		2005		2010	2011	2012	2013	2014
Arkansas	2.8		4.2		4.5	4.5	4.6	4.6	4.6
California	1.7		2.5		2.4	2.4	2.4	2.4	2.4
Florida	+		+		+	+	+	+	+
Illinois	+		+		+	+	+	+	+
Louisiana	2.4		2.7		2.6	2.6	2.7	2.7	2.7
Minnesota	+		+		+	+	+	+	+
Mississippi	0.5		0.4		0.2	0.2	0.3	0.2	0.2
Missouri	0.3		0.5		0.7	0.7	0.7	0.7	0.7
New York	+		+		+	+	+	+	+
South Carolina	+		+		+	+	+	+	+
Tennessee	+		+		+	+	+	+	+
Texas	5.5		2.5		1.3	1.4	1.4	1.4	1.3
Total	**13.1**		**13.0**		**11.9**	**11.8**	**11.9**	**11.9**	**11.9**

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

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

State	1990		2005		2010	2011	2012	2013	2014
Arkansas	113		169		182	182	182	182	182
California	70		101		94	94	94	94	94
Florida	+		2		+	+	+	+	+
Illinois	+		+		+	+	+	+	+
Louisiana	95		109		105	104	106	107	106
Minnesota	1		2		+	+	+	+	+
Mississippi	18		18		10	10	10	10	10
Missouri	10		20		29	29	29	29	29
New York	+		+		+	+	+	+	+
South Carolina	+		+		+	+	+	+	+
Tennessee	+		+		+	+	+	+	+
Texas	218		100		54	54	54	54	54
Total	**525**		**521**		**474**	**474**	**476**	**477**	**476**

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

Methodology

The methodology used to estimate CH_4 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 CH_4 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 CH_4, as well as CH_4 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 CH_4 emissions, DAYCENT simulates soil C stock changes and N_2O 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 CH_4 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 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 CH_4 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 CH_4 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 2013). The NRI is a statistically-based sample of all non-federal land, and includes 380,956 survey points of which 2,072 are in locations with rice cultivation. The Tier 3 method is used to estimate CH_4 emissions from 1,852 of the NRI survey locations, and the remaining 220 survey locations are estimated with the Tier 1 method. Each NRI survey point is associated with an "expansion factor" that allows scaling of CH_4 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 2010 because newer data were not made available in time to incorporate the additional years of data. 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		2010	2011	2012	2013	2014
Arkansas	601		839		800	800	801	801	800
California	197		270		274	274	274	274	274
Florida	0		4		0	0	0	0	0
Illinois	0		1		0	0	0	0	0
Louisiana	365		375		315	313	317	316	315
Minnesota	5		6		1	1	1	1	1
Mississippi	104		113		53	53	53	53	53
Missouri	46		82		105	105	105	105	105
New York	0		0		0	0	0	0	0
South Carolina	0		0		0	0	0	0	0

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

Tennessee	0		1		0	0	0	0	0
Texas	323		161		73	73	73	73	72
Total	**1,641**		**1,852**		**1,621**	**1,619**	**1,624**	**1,622**	**1,620**

Notes: Totals may not sum due to independent rounding. States are included if NRI reports rice areas at any time between 1990 and 2014.

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 48 percent of rice acres planted, respectively. Florida also has a large fraction of area with a ratoon crop (45 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	1990-2014
Arkansas[a]	1%
California	0%
Florida[b]	45%
Louisiana[c]	32%
Mississippi[a]	1%
Missouri[a]	1%
Texas[d]	48%

[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 the 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 CH_4 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 CH_4 emissions estimate using simple error propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.12. Rice cultivation CH_4 emissions in 2014 were estimated to be between 9.9 and 13.9 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 17 percent below to 17 percent above the actual 2014 emission estimate of 11.9 MMT CO_2 Eq. (see Table 5-14).

Table 5-14: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq. and Percent)

Source	Inventory Method	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
				Lower Bound	Upper Bound	Lower Bound	Upper Bound
Rice Cultivation	Tier 3	CH_4	10.7	8.8	12.6	-18%	18%
Rice Cultivation	Tier 1	CH_4	1.2	0.8	1.6	-33%	40%
Rice Cultivation	**Total**	**CH_4**	**11.9**	**9.9**	**13.9**	**-17%**	**17%**

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

Methodological recalculations are applied to the entire time series to ensure time-series consistency from 1990 through 2014 using the Tier 1 and 3 methods. Details on the emission trends through time are described in more detail in the Methodology section, above.

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. Some errors were found in the handling of the cropping rotations and management data for the DAYCENT simulations that were corrected. Data inputs to the ALU software for the Tier 1 method are checked to ensure proper handling of the data through the software. There was an error in the cultivation period that was corrected in the calculation of the emission factor. 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 CH_4 emissions. The comparisons included over 15 long-term experiments, representing about 800 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) using the DAYCENT model to estimate CH_4 emissions from the majority of flooded rice production, (2) estimating CH_4 emissions from the remainder of the flooded rice area using a Tier 1 method, and (3) driving the DAYCENT simulations with updated input data for land management from the National Resources Inventory extending the time series through 2010. These changes resulted in an increase in emissions of approximately 30 percent on average relative to the previous Inventory and a decrease in uncertainty from confidence interval with a lower bound of 50 percent and upper bound of 91 percent to a confidence interval with an upper and lower bound of 17 percent.

Planned Improvements

Improvements are underway to update the land use and management data from the 2012 USDA NRI so that the time series of activity data are extended through 2012. Fertilization, tillage activity data, and water management will also be updated as part of this improvement to the extent that new data are available on these practices.

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 N_2O emissions from nitrification and denitrification at the site of a management activity (see Figure 5-2) (Mosier et al. 1998), including fertilization; application of managed livestock manure and other organic materials such as sewage sludge; deposition of manure on soils by domesticated animals in pastures, rangelands, and paddocks (PRP) (i.e., by grazing animals and other animals whose manure is not managed); production of N-fixing crops and forages; retention of crop residues; and drainage of organic soils (i.e., soils with a high organic matter content, otherwise known as Histosols[9]) in croplands and grasslands (IPCC 2006). Additionally, agricultural soil management activities, including irrigation, drainage, tillage practices, and fallowing of land, can influence N mineralization by impacting moisture and temperature regimes in soils. Indirect emissions of N_2O occur when N is transported from a site and is subsequently converted to N_2O; there are two pathways for indirect emissions: (1) volatilization and subsequent atmospheric deposition of applied/mineralized N, and (2) surface runoff and leaching of applied/mineralized N into groundwater and surface water.[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; N_2O emissions from Forest Land and Settlements are found in Chapter 6). 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).

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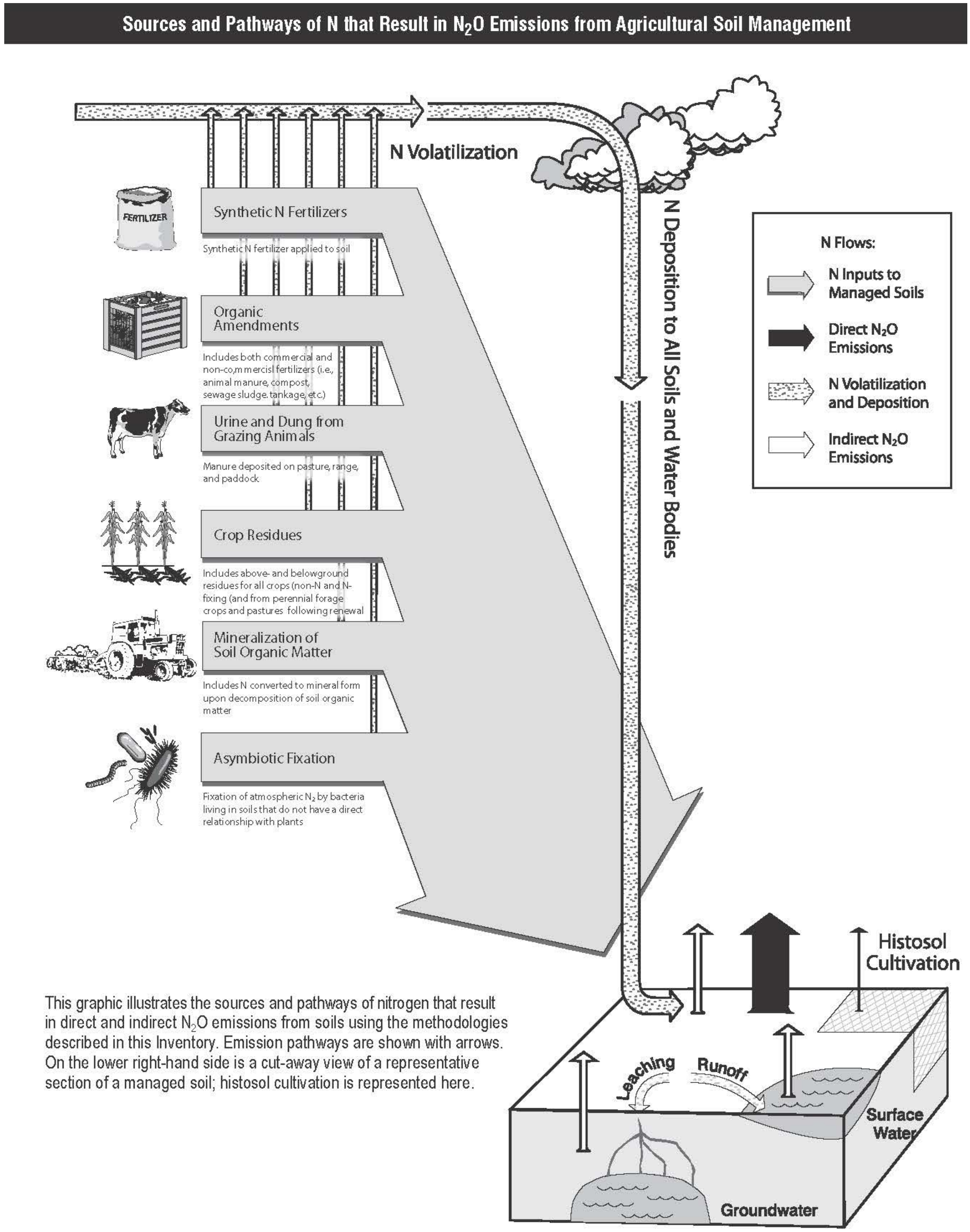
[7] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product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

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

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

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

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



Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions from this source in 2014 are 318.4 MMT CO_2 Eq. (1,068 kt) (see Table 5-15 and Table 5-16). Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2014, although overall emissions are 5 percent higher in 2014 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production. From 1990 to 2014, on average cropland accounted for approximately 70 percent of total direct emissions, while grassland accounted for approximately 30 percent. The percentages for indirect emissions on average are approximately 65 percent for croplands, 35 percent for grasslands. Estimated direct and indirect N_2O emissions by sub-source category are shown in Table 5-17 and Table 5-18.

Table 5-15: N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990		2005		2010	2011	2012	2013	2014
Direct	**245.0**		**248.3**		**263.8**	**264.5**	**264.5**	**261.2**	**261.0**
Cropland	171.9		174.4		185.7	186.9	187.9	185.2	185.0
Grassland	73.2		73.9		78.1	77.6	76.6	76.0	76.0
Indirect	**58.2**		**48.9**		**56.9**	**58.6**	**58.5**	**57.4**	**57.3**
Cropland	36.2		34.0		39.7	40.6	41.1	40.3	40.2
Grassland	22.1		14.9		17.2	17.9	17.5	17.2	17.2
Total	**303.3**		**297.2**		**320.7**	**323.1**	**323.1**	**318.6**	**318.4**

Note: Totals may not sum due to independent rounding.

Table 5-16: N_2O Emissions from Agricultural Soils (kt)

Activity	1990		2005		2010	2011	2012	2013	2014
Direct	**822**		**833**		**885**	**888**	**888**	**877**	**876**
Cropland	577		585		623	627	630	621	621
Grassland	246		248		262	260	257	255	255
Indirect	**195**		**164**		**191**	**196**	**196**	**193**	**192**
Cropland	121		114		133	136	138	135	135
Grassland	74		50		58	60	59	58	58
Total	**1,018**		**997**		**1,076**	**1,084**	**1,084**	**1,069**	**1,068**

Note: Totals may not sum due to independent rounding.

Table 5-17: Direct N_2O Emissions from Agricultural Soils by Land Use Type and N Input Type (MMT CO_2 Eq.)

Activity	1990		2005		2010	2011	2012	2013	2014
Cropland	**171.9**		**174.4**		**185.7**	**186.9**	**187.9**	**185.2**	**185.0**
Mineral Soils	**168.6**		**171.2**		**182.6**	**183.9**	**184.9**	**182.2**	**182.0**
Synthetic Fertilizer	59.2		61.4		59.3	61.0	61.8	59.5	59.3
Organic Amendment[a]	11.9		12.9		13.4	13.5	13.6	13.5	13.5
Residue N[b]	25.9		26.6		27.8	27.6	27.5	27.5	27.6
Mineralization and Asymbiotic Fixation	71.6		70.3		82.2	81.8	82.0	81.6	81.6
Drained Organic Soils	**3.2**		**3.2**		**3.0**	**3.0**	**3.0**	**3.0**	**3.0**
Grassland	**73.2**		**73.9**		**78.1**	**77.6**	**76.6**	**76.0**	**76.0**
Mineral Soils	**70.3**		**71.0**		**75.5**	**74.9**	**74.0**	**73.3**	**73.3**
Synthetic Fertilizer	1.1		1.3		1.3	1.2	1.2	1.2	1.4
PRP Manure	13.4		12.3		12.5	11.9	11.0	10.3	10.3
Managed Manure[c]	0.1		0.2		0.2	0.2	0.2	0.2	0.2
Sewage Sludge	0.2		0.5		0.5	0.5	0.6	0.6	0.6
Residue N[d]	19.7		21.0		21.8	21.7	21.7	21.7	21.6
Mineralization and Asymbiotic Fixation	35.8		35.8		39.1	39.4	39.4	39.4	39.2
Drained Organic Soils	2.9		2.9		2.7	2.7	2.7	2.7	2.7
Total	**245.0**		**248.3**		**263.8**	**264.5**	**264.5**	**261.2**	**261.0**

[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 N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990		2005		2010	2011	2012	2013	2014
Cropland	**36.2**		**34.0**		**39.7**	**40.6**	**41.1**	**40.3**	**40.2**
Volatilization & Atm. Deposition	13.0		13.8		13.9	14.3	14.5	14.2	14.2
Surface Leaching & Run-Off	23.2		20.2		25.8	26.4	26.6	26.0	26.0
Grassland	**22.1**		**14.9**		**17.2**	**17.9**	**17.5**	**17.2**	**17.2**
Volatilization & Atm. Deposition	4.4		4.7		4.8	4.7	4.6	4.5	4.5
Surface Leaching & Run-Off	17.7		10.2		12.4	13.2	12.9	12.6	12.6
Total	**58.2**		**48.9**		**56.9**	**58.6**	**58.5**	**57.4**	**57.3**

Note: Totals may not sum due to independent rounding.

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

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

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

Nitrogen losses from croplands and grasslands that lead to indirect N_2O emissions (Figure 5-5 and Figure 5-6) have similar spatial patterns as direct N_2O emissions. This is not surprising because N losses leading to indirect N_2O emissions are influenced by the same variables that drive direct N_2O emissions (N inputs, weather patterns, and soil characteristics). However, there are some exceptions to the similarity in patterns. For example, there are limited amounts of nitrate leaching from western grasslands due to lower precipitation and leaching through the soil profile, compared to grasslands in the central United States, whereas the N_2O emissions are higher in the western grasslands.

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

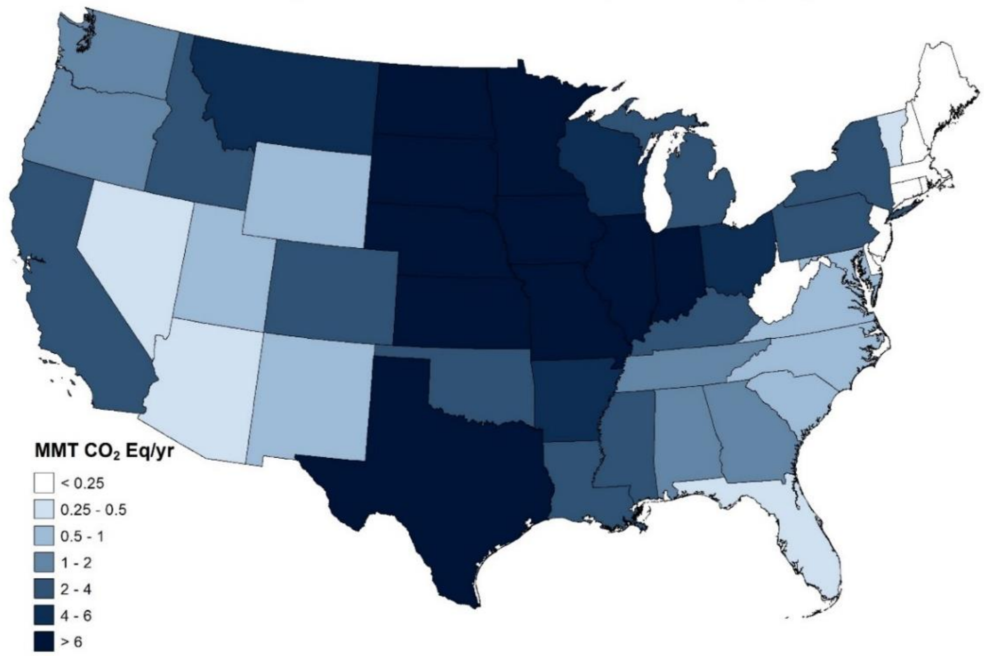


Figure 5-4: Grasslands, 2014 Annual Direct N_2O Emissions Estimated Using the Tier 3 DAYCENT Model (MMT CO_2 Eq./year)

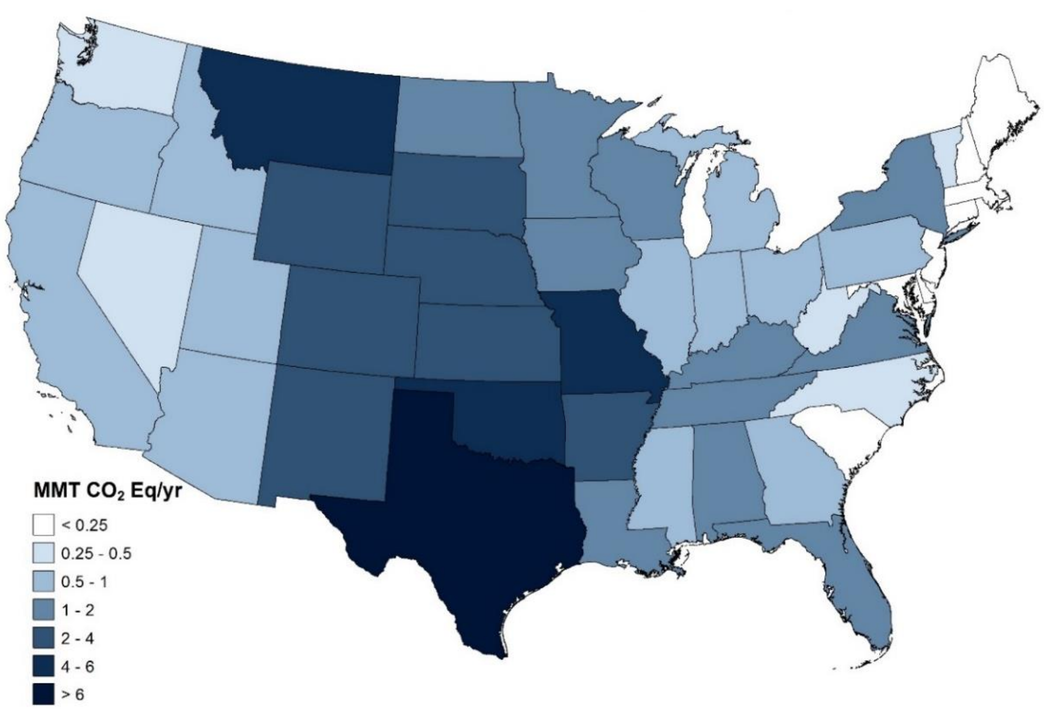


Figure 5-5: Crops, 2014 Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the Tier 3 DAYCENT Model (kt N/year)

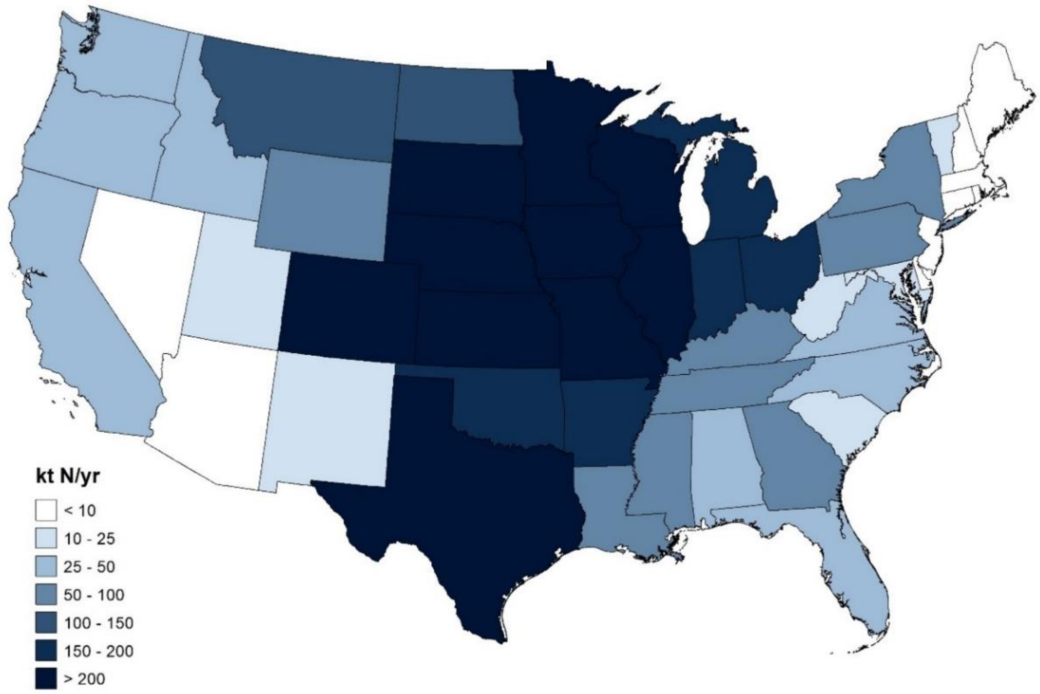
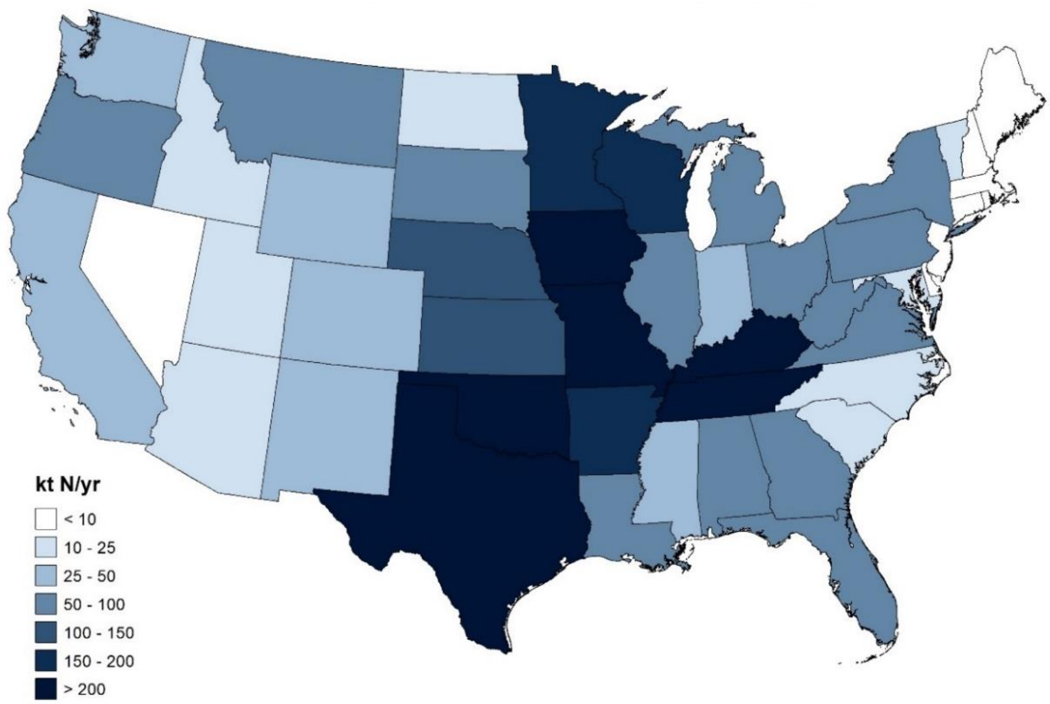


Figure 5-6: Grasslands, 2014 Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the Tier 3 DAYCENT Model (kt N/year)



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, sewage sludge applications, crop residues, organic amendments, and biological N fixation associated with planting of legumes on cropland and grassland soils; (2) direct emissions from soil organic matter mineralization due to land use and management change; (3) direct emissions from drainage of organic soils in croplands and grasslands; (4) direct emissions from soils due to manure deposited by livestock on PRP grasslands; and (5) indirect emissions from soils and water from N additions and manure deposition to soils that lead to volatilization, leaching, or runoff of N and subsequent conversion to N_2O.

The United States has adopted methods in the IPCC (2006) for the Agricultural Soil Management source category. These methods include (1) estimating the contribution of N in crop residues to indirect soil N_2O emissions; (2) adopting the revised emission factor for direct N_2O emissions for Tier 1 methods used in the Inventory (described later in this section); (3) removing double counting of emissions from N-fixing crops associated with biological N fixation and crop residue N input categories; (4) using revised crop residue statistics to compute N inputs to soils from harvest yield data; and (5) estimating emissions associated with land use and management change (which can significantly change the N mineralization rates from soil organic matter). The Inventory also reports on total emissions from all managed land, which is a proxy for anthropogenic impacts on greenhouse gas emissions (IPCC 2006), including direct and indirect N_2O emissions from asymbiotic fixation[11] and mineralization of soil organic matter and litter. One recommendation from IPCC (2006) that has not been completely adopted is the estimation of emissions from grassland pasture renewal, which involves occasional plowing to improve forage production in pastures. Currently no data are available to address pasture renewal.

Direct N_2O Emissions

The methodology used to estimate direct N_2O emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches (IPCC 2006; Del Grosso et al. 2010). A Tier 3 process-based model (DAYCENT) is used to estimate direct emissions from a variety of crops that are grown on mineral (i.e., non-organic) soils, including alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat; as well as the direct emissions from non-federal grasslands with the exception of sewage sludge amendments (Del Grosso et al. 2010). The Tier 3 approach has been specifically designed and tested to estimate N_2O emissions in the United States, accounting for more of the environmental and management influences on soil N_2O emissions than the IPCC Tier 1 method (see Box 5-1 for further elaboration). Moreover, the Tier 3 approach allows for the Inventory to address direct N_2O emissions and soil C stock changes from mineral cropland soils in a single analysis. Carbon and N dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil C and N_2O) in a single inventory analysis ensures that there is consistent activity data and treatment of the processes, and interactions are taken into account between C and N cycling in soils.

The Tier 3 approach is based on the cropping and land use histories recorded in the USDA NRI survey (USDA-NRCS 2013). The NRI is a statistically-based sample of all non-federal land, and includes 380,956 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 92,013 in the NRI survey that are designated as cropland or grassland (discussed later in this section). Each point is associated with an "expansion factor" that allows scaling of N_2O emissions from NRI points to the entire country (i.e., each expansion factor represents the amount of area with the same land-use/management history as the sample point). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. For cropland, data were collected in 4 out of 5 years in the cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, the annual

[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.

data are currently available through 2012 (USDA-NRCS 2015) although this Inventory only uses NRI data through 2010 because newer data were not made available in time to incorporate the additional years into this Inventory.

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

The IPCC (2006) Tier 1 approach is based on multiplying activity data on different N inputs (i.e., synthetic fertilizer, manure, N fixation, etc.) by the appropriate default IPCC emission factors to estimate N_2O emissions on an input-by-input basis. The Tier 1 approach requires a minimal amount of activity data, readily available in most countries (e.g., total N applied to crops); calculations are simple; and the methodology is highly transparent. In contrast, the Tier 3 approach developed for this Inventory employs a process-based model (i.e., DAYCENT) that represents the interaction of N inputs, 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 N_2O emissions only during that year and cannot be stored in soils and contribute to N_2O emissions in subsequent years. This is a simplifying assumption that is likely to create bias in estimated N_2O emissions for a specific year. In contrast, the process-based model used in the Tier 3 approach includes the legacy effect of N added to soils in previous years that is re-mineralized from soil organic matter and emitted as N_2O during subsequent years.

DAYCENT is used to estimate N_2O emissions associated with production of alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat, but is not applied to estimate N_2O emissions from other crops or rotations with other crops,[12] 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 areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume), or to estimate emissions from drained organic soils (Histosols). The Tier 3 method has not been fully tested for estimating N_2O emissions associated with these crops and rotations, land uses, as well as organic soils or cobbly, gravelly, and shaley mineral soils. In addition, federal grassland areas are not simulated with DAYCENT due to limited activity on land use histories. For areas that are not included in the DAYCENT simulations, the Tier 1 IPCC (2006) methodology is used to estimate (1) direct emissions from crops on mineral soils that are not simulated by DAYCENT; (2) direct emissions from Pasture/Range/Paddock (PRP) on federal grasslands; and (3) direct emissions from 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 N_2O emissions from mineral cropland soils that are managed for production of a wide variety of crops based on the cropping histories in the 2010 NRI (USDA-NRCS 2013). The crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat. Crops simulated by DAYCENT are grown on approximately 91 percent of total cropland area in the United States. For agricultural systems in the central region of the United States, crop production for key crops (i.e., corn, soybeans, sorghum, cotton, and wheat) is simulated in DAYCENT with a

[12] 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.

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.[13]

DAYCENT is used to estimate direct N_2O emissions due to mineral N available from the following sources: (1) the application of synthetic fertilizers; (2) the application of livestock manure; (3) the retention of crop residues and subsequent mineralization of N during microbial decomposition (i.e., leaving residues in the field after harvest instead of burning or collecting residues); (4) mineralization of soil organic matter; and (5) asymbiotic fixation. Note that commercial organic fertilizers (TVA 1991 through 1994; AAPFCO 1995 through 2014) are addressed with the Tier 1 method because county-level application data would be needed to simulate applications in DAYCENT, and currently data are only available at the national scale. The third and fourth sources are generated internally by the DAYCENT model.

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

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

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

Each 2010 NRI point is run 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulations for the analysis. Soil N_2O emission estimates from DAYCENT are adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). Soil N_2O emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2010, but emissions from 2011 to 2014 are assumed to be similar to 2010. Annual data are currently available through 2012

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

(USDA-NRCS 2015), however this Inventory only uses NRI data through 2010 because newer data were not available in time to incorporate the additional years.

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

Tier 1 Approach for Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology is used to estimate direct N_2O emissions for mineral cropland soils that are not simulated by DAYCENT. For the Tier 1 Approach, estimates of direct N_2O emissions from N applications are based on mineral soil N that is made available from the following practices: (1) the application of synthetic commercial fertilizers; (2) application of managed manure and non-manure commercial organic fertilizers; and (3) 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 not included in the DAYCENT simulations because county-level data are not available.[14] Consequently, commercial organic fertilizer, as well as additional manure that is not added to crops in the DAYCENT simulations, are included in the Tier 1 analysis. The following sources are used to derive activity data:

- A process-of-elimination approach is used to estimate synthetic N fertilizer additions for crop areas not simulated by DAYCENT. The total amount of fertilizer used on farms has been estimated at the county-level by the USGS from sales records (Ruddy et al. 2006), and these data are aggregated to obtain state-level N additions to farms. For 2002 through 2014, state-level fertilizer for on-farm use is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 1995 through 2007; AAPFCO 2008 through 2014).[15] After subtracting the portion of fertilizer applied to crops and grasslands simulated by DAYCENT (see Tier 3 Approach for Cropland Mineral Soils Section and Grasslands Section for information on data sources), the remainder of the total fertilizer used on farms is assumed to be applied to crops that are not simulated by DAYCENT.
- Similarly, a process-of-elimination approach is used to estimate manure N additions for crops that are not simulated by DAYCENT. The amount of manure N applied in the Tier 3 approach to crops and grasslands is subtracted from total manure N available for land application (see Tier 3 Approach for Cropland Mineral Soils Section and Grasslands Section for information on data sources), and this difference is assumed to be applied to crops that are not simulated by DAYCENT.
- Commercial organic fertilizer additions are based on organic fertilizer consumption statistics, which are converted to units of N using average organic fertilizer N content (TVA 1991 through 1994, AAPFCO 1995 through 2011). Commercial fertilizers do include some manure and sewage sludge, but the amounts

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

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

are removed from the commercial fertilizer data to avoid double counting with the manure N dataset described above and the sewage sludge amendment data discussed later in this section.

- Crop residue N is derived by combining amounts of above- and below-ground biomass, which are determined based on NRI crop area data (USDA-NRCS 2013), crop production yield statistics (USDA-NASS 2014), dry matter fractions (IPCC 2006), linear equations to estimate above-ground biomass given dry matter crop yields from harvest (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and N contents of the residues (IPCC 2006).

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

Drainage of Organic Soils in Croplands and Grasslands

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

Direct N_2O Emissions from Grassland Soils

As with N_2O from croplands, the Tier 3 process-based DAYCENT model and Tier 1 method described in IPCC (2006) are combined to estimate emissions from non-federal grasslands and PRP manure N additions for federal grasslands, respectively. Grassland includes pasture and rangeland that produce grass forage primarily for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding legumes. DAYCENT is used to simulate N_2O emissions from NRI survey locations (USDA-NRCS 2013) on non-federal grasslands resulting from manure deposited by livestock directly onto pastures and rangelands (i.e., PRP manure), N fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure such as Daily Spread), and synthetic fertilizer application. Other N inputs are simulated within the DAYCENT framework, including N input from mineralization due to decomposition of soil organic matter and N inputs from senesced grass litter, as well as asymbiotic fixation of N from the atmosphere. The simulations used the same weather, soil, and synthetic N fertilizer data as discussed under the Tier 3 Approach for Mineral Cropland Soils section. Managed manure N amendments to grasslands are estimated from Edmonds et al. (2003) and adjusted for annual variation using data on the availability of managed manure N for application to soils, according to methods described in the Manure Management section (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 72 percent of total PRP manure N in aggregate across the country. The remainder of the PRP manure N in each state is assumed to be excreted on federal grasslands, and the N_2O emissions are estimated using the IPCC (2006) Tier 1 method with IPCC default emission factors. Sewage sludge is assumed to be applied on grasslands because of the heavy metal content and other pollutants in human waste that limit its use as an amendment to croplands. Sewage sludge application is estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007). Sewage sludge data on soil amendments to agricultural lands are only available at the national scale, and it is not possible to associate application with specific soil conditions and weather at the county scale. Therefore, DAYCENT could not be used to simulate the influence of sewage sludge amendments on N_2O emissions from grassland soils, and consequently, emissions from sewage sludge are estimated using the IPCC (2006) Tier 1 method.

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

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

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

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from the Tier 1 and 3 approaches for mineral and drained organic soils occurring in both croplands and grasslands are summed to obtain the total direct N_2O emissions from agricultural soil management (see Table 5-15 and Table 5-16).

Indirect N_2O Emissions

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

Indirect N_2O Emissions from Atmospheric Deposition of Volatilized N

The Tier 3 DAYCENT model and IPCC (2006) Tier 1 methods are combined to estimate the amount of N that is volatilized and eventually emitted as N_2O. DAYCENT is used to estimate N volatilization for land areas whose direct emissions are simulated with DAYCENT (i.e., most commodity and some specialty crops and most grasslands). The N inputs included are the same as described for direct N_2O emissions in the Tier 3 Approach for Cropland Mineral Soils section and Grasslands section. Nitrogen volatilization for all other areas is estimated using the Tier 1 method and default IPCC fractions for N subject to volatilization (i.e., N inputs on croplands not simulated by DAYCENT, PRP manure N excreted on federal grasslands, sewage sludge application on grasslands). For the volatilization data generated from both the DAYCENT and Tier 1 approaches, the IPCC (2006) default emission factor is used to estimate indirect N_2O emissions occurring due to re-deposition of the volatilized N (see Table 5-18).

Indirect N_2O Emissions from Leaching/Runoff

As with the calculations of indirect emissions from volatilized N, the Tier 3 DAYCENT model and IPCC (2006) Tier 1 method are combined to estimate the amount of N that is subject to leaching and surface runoff into water bodies, and eventually emitted as N_2O. DAYCENT is used to simulate the amount of N transported from lands in the Tier 3 Approach. 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, sewage sludge amendments on grasslands, and PRP manure N excreted on federal grasslands. For both the DAYCENT Tier 3 and IPCC (2006) Tier 1 methods, nitrate leaching is assumed to be an insignificant source of indirect N_2O in cropland and grassland systems in arid regions, as discussed in IPCC (2006). In the United States, the threshold for significant nitrate leaching is based on the potential evapotranspiration (PET) and rainfall amount, similar to IPCC (2006), and is assumed to be negligible in regions where the amount of precipitation plus irrigation does not exceed 80 percent of PET. For leaching and runoff data estimated by the Tier 3 and Tier 1 approaches, the IPCC (2006) default emission factor is used to estimate indirect N_2O emissions that occur in groundwater and waterways (see Table 5-18).

Uncertainty and Time-Series Consistency

Uncertainty is estimated for each of the following five components of N_2O emissions from agricultural soil management: (1) direct emissions simulated by DAYCENT; (2) the components of indirect emissions (N volatilized and leached or runoff) simulated by DAYCENT; (3) direct emissions approximated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) approximated with the IPCC (2006) Tier 1 method; and (5) indirect emissions estimated with the IPCC (2006) Tier 1 method. Uncertainty in direct emissions, which account for the majority of N_2O emissions from agricultural management, as well as the components of indirect emissions calculated by DAYCENT are estimated with a Monte Carlo Analysis, addressing uncertainties in model inputs and structure (i.e., algorithms and parameterization) (Del Grosso et al. 2010). Uncertainties in direct emissions calculated with the IPCC (2006) Approach 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Approach 1 method, and indirect N_2O emissions are estimated with a simple error propagation approach (IPCC 2006). Uncertainties from the Approach 1 and Approach 3 (i.e., DAYCENT) estimates are combined using simple error propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.12. Table 5-19 shows the combined uncertainty for direct soil N_2O emissions ranged from 16 percent below to 24 percent above the 2014 emissions estimate of 261.0 MMT CO_2 Eq., and the combined uncertainty for indirect soil N_2O emissions range from 47 percent below to 139 percent above the 2014 estimate of 57.3 MMT CO_2 Eq.

Table 5-19: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2014 (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N_2O Emissions	N_2O	261.0	219.4	323.8	-16%	24%
Indirect Soil N_2O Emissions	N_2O	57.3	30.6	137.0	-47%	139%

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

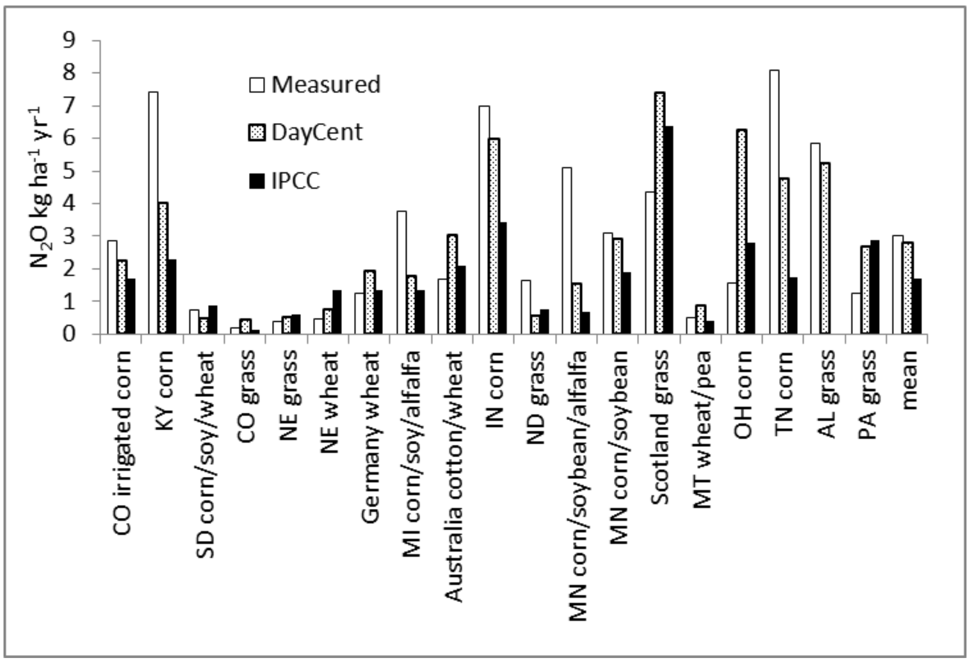
Additional uncertainty is associated with an incomplete estimation of all N_2O emissions from managed croplands and grasslands in Hawaii and Alaska. The Inventory only includes the N_2O emissions from mineral fertilizer additions in Alaska and Hawaii, and drained organic soils in Hawaii. Agriculture is not extensive in either state, so the emissions are likely to be small for the other sources of N (e.g., manure amendments), which are not currently included in the Inventory, compared to the conterminous United States.

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

QA/QC and Verification

DAYCENT results for N_2O emissions and NO_3^- leaching are compared with field data representing various cropland and grassland systems, soil types, and climate patterns (Del Grosso et al. 2005; Del Grosso et al. 2008), and further evaluated by comparing the model results to emission estimates produced using the IPCC (2006) Tier 1 method for the same sites. Nitrous oxide measurement data are available for 27 sites, which mostly occur in the United States, with four in Europe and one in Australia, representing over 75 different combinations of fertilizer treatments and cultivation practices. Nitrate leaching data are available for four sites in the United States, representing 12 different combinations of fertilizer amendments/tillage practices. DAYCENT estimates of N_2O emissions are closer to measured values at most sites compared to the IPCC Tier 1 estimate (see Figure 5-7). 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 N_2O emissions. DAYCENT does have a tendency to under-estimate very high N_2O emission rates; and estimates are adjusted using the statistical model derived from the comparison of model estimates to measurements (see Annex 3.12 for more information). Regardless, the comparison demonstrates that DAYCENT provides relatively high predictive capability for N_2O emissions, and is an improvement over the IPCC Tier 1 method.

Figure 5-7: Comparison of Measured Emissions at Field Sites and Modeled Emissions Using the DAYCENT Simulation Model and IPCC Tier 1 Approach (kg N_2O 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 approach 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 2010; (2) accounting for N inputs from residues associated with additional crops not simulated by DAYCENT including most vegetable crops; (3) modifying the number of experimental study sites used to quantify model uncertainty for direct N_2O emissions; and (4) using DAYCENT for direct N_2O emissions from most flooded rice lands, instead of using the Tier 1 approach for all rice lands. These changes resulted in an increase in emissions of approximately 24 percent on average relative to the previous Inventory and a decrease in the upper bound of the 95 percent confidence interval for direct N_2O emissions from 26 to 24 percent. The differences in emissions and uncertainty are mainly due to increasing the number of study sites used to quantify model uncertainty.

Planned Improvements

Several planned improvements are underway.

- Land use and management data will be updated with the 2012 USDA NRI so that the time series of activity data are extended through 2012. Fertilization and tillage activity data will also be updated as part of this improvement. In addition, the remote-sensing based data on the EVI will be extended through 2012 in order to use the EVI data to drive crop production in DAYCENT.
- 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 N_2O emissions. An improved representation of drainage is also under development. Experimental study sites will continue to be added for quantifying model structural uncertainty, and studies that have continuous (daily) measurements of N_2O (e.g., Scheer et al. 2013) will be given priority.
- 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 5.5). See the Planned Improvement section in the Field Burning of Agricultural Residues section for more information.
- Alaska and Hawaii are not included in the current Inventory for agricultural soil management, with the exception of N_2O emissions from drained organic soils in croplands and grasslands for Hawaii. A planned improvement over the next two years is to add these states into the Inventory analysis.
- Use the new Tier 1 emission factor for N_2O emissions from drained organic soils that is provided in the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (IPCC 2013).

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

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

In the United States, field burning of agricultural residues commonly occurs in southeastern states, the Great Plains, and the Pacific Northwest (McCarty 2011). The primary crops that are managed with residue burning include corn, cotton, lentils, rice, soybeans, sugarcane, and wheat (McCarty 2009). Rice, sugarcane, and wheat residues account for approximately 70 percent of all crop residue burning and emissions (McCarty 2011). In 2014, CH_4 and N_2O emissions from field burning of agricultural residues were 0.3 MMT CO_2 Eq. (11 kt) and 0.1 MMT. CO_2 Eq. (0.3 kt), respectively. Furthermore, annual emissions from this source from 1990 to 2014 have remained relatively constant, averaging approximately 0.3 MMT CO_2 Eq. (10 kt) of CH_4 and 0.1 MMT CO_2 Eq. (0.3 kt) of N_2O (see Table 5-20 and Table 5-21).

Table 5-20: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq.)

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

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

Table 5-21: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (kt)

Gas/Crop Type	1990		2005		2010	2011	2012	2013	2014
CH_4	**10**		**8**		**11**	**11**	**11**	**11**	**11**
Wheat	5		4		5	5	5	5	5
Rice	2		2		2	2	2	2	2
Sugarcane	1		1		1	1	1	1	2
Corn	1		1		1	1	1	1	2
Soybeans	1		1		1	1	1	1	1
Lentil	+		+		+	+	+	+	+
Cotton	+		+		+	+	+	+	+
N_2O	**+**		**+**		**+**	**+**	**+**	**+**	**+**
Wheat	+		+		+	+	+	+	+
Rice	+		+		+	+	+	+	+
Sugarcane	+		+		+	+	+	+	+
Corn	+		+		+	+	+	+	+
Cotton	+		+		+	+	+	+	+
Soybeans	+		+		+	+	+	+	+
Lentil	+		+		+	+	+	+	+
CO	**202**		**177**		**229**	**233**	**234**	**238**	**238**
NO_x	**6**		**6**		**7**	**8**	**8**	**8**	**8**

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

Methodology

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

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

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 consumed[16]
Combustion Efficiency (CE)	=	The proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively

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

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

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

where,

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

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

Emissions from field burning of agricultural residues were calculated using a Tier 2 methodology that is based on method developed by the IPCC/UNEP/OECD/IEA (1997) and incorporates crop- and country-specific emission factors and variables. The rationale for using the IPCC/UNEP/OECD/IEA (1997) approach rather than the method provided in the *2006 IPCC Guidelines* is as follows: (1) the equations from both guidelines rely on the same underlying variables (though the formats differ); (2) the IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues; and (3) the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this Inventory includes emissions from seven crops (corn, cotton, lentils, rice, soybeans, sugarcane, and wheat).

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

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

[16] 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,

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

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

Crop yield data (except rice in Florida) were based on USDA's QuickStats (USDA 2015), and crop area data were based on the 2010 NRI (USDA 2013). In order to estimate total crop production, the crop yield data from USDA Quick Stats crop yields was multiplied by the NRI crop areas. Rice yield data for Florida was estimated separately because yield data were not collected by USDA. Total rice production for Florida was determined using NRI crop areas and total yields were based on average primary and ratoon rice yields from Schueneman and Deren (2002). Relative proportions of ratoon crops were derived from information in several publications (Schueneman 1999, 2000, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007 through 2014). The production data for the crop types whose residues are burned are presented in Table 5-22. Crop weight by bushel was obtained from Murphy (1993).

The fraction of crop area burned was calculated using data on area burned by crop type and state[17] from McCarty (2010) for corn, cotton, lentils, rice, soybeans, sugarcane, and wheat.[18] 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 5-23. 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 5-23 shows the resulting percentage of crop residue burned at the national scale by crop type. State-level estimates are also available upon request.

All residue: crop product mass ratios except sugarcane and cotton were obtained from Strehler and Stützle (1987). The ratio for sugarcane is from Kinoshita (1988) and the ratio for cotton is from Huang et al. (2007). The residue: crop ratio for lentils was assumed to be equal to the average of the values for peas and beans. Residue dry matter fractions for all crops except soybeans, lentils, and cotton were obtained from Turn et al. (1997). Soybean and lentil dry matter fractions were obtained from Strehler and Stützle (1987); the value for lentil residue was assumed to equal the value for bean straw. The cotton dry matter fraction was taken from Huang et al. (2007). The residue C contents and N contents for all crops except soybeans and cotton are from Turn et al. (1997). The residue C content for soybeans is the IPCC default (IPCC/UNEP/OECD/IEA 1997), and the N content of soybeans is from Barnard and Kristoferson (1985). The C and N contents of lentils were assumed to equal those of soybeans. The C and N contents of cotton are from Lachnicht et al. (2004). The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent, for all crop types, except sugarcane (EPA 1994). For sugarcane, the burning efficiency was assumed to be 81 percent (Kinoshita 1988) and the combustion efficiency was assumed to be 68 percent (Turn et al. 1997). See Table 5-24 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 5-25).

[17] Alaska and Hawaii were excluded.

[18] 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 5-22: Agricultural Crop Production (kt of Product)

Crop	1990	2005	2010	2011	2012	2013	2014
Corn[a]	229,257	300,965	335,669	321,920	270,310	350,472	378,574
Cotton	4,446	6,811	4,814	4,369	5,156	4,841	5,104
Lentils	38	248	406	234	251	271	156
Rice	8,907	12,596	11,376	11,795	12,547	12,932	12,874
Soybeans	55,178	86,908	94,467	90,761	86,922	95,473	103,588
Sugarcane	31,827	32,496	30,333	32,469	34,925	34,186	34,160
Wheat	79,011	70,074	71,017	62,131	71,094	68,772	64,748

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

Table 5-23: U.S. Average Percent Crop Area Burned by Crop (Percent)

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

+ Does not exceed 0.5 percent.

Table 5-24: Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues

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

Table 5-25: Greenhouse Gas Emission Ratios and Conversion Factors

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

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

Uncertainty and Time-Series Consistency

The results of the Approach 2 Monte Carlo uncertainty analysis are summarized in Table 5-26. Methane emissions from field burning of agricultural residues in 2014 were estimated to be between 0.16 and 0.38 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 40 percent below and 40 percent above the 2014 emission estimate of 0.3 MMT CO_2 Eq. Also at the 95 percent confidence level, N_2O emissions were estimated to be between

0.07 and 0.12 MMT CO_2 Eq., or approximately 29 percent below and 29 percent above the 2014 emission estimate of 0.1 MMT CO_2 Eq.

Table 5-26: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH_4	0.3	0.16	0.38	-40%	40%
Field Burning of Agricultural Residues	N_2O	0.1	0.07	0.12	-29%	29%

[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, ensuring time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section above.

QA/QC and Verification

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

Recalculations Discussion

The source data for crop areas was changed from USDA NASS QuickStats to the 2010 NRI. This change ensures greater consistency in the land representation across cropland source categories, including direct and indirect soil nitrous oxide emissions in Agricultural Soil Management, and soil carbon stock changes in the *Cropland Remaining Cropland* and *Land Converted to Cropland* sections, which also rely on the NRI data as the basis for crop areas. The NRI data were used to recalculate percent crop area burned and total crop production. This change resulted in higher crop production estimates (ranging from 4 to 40 percent) and lower burned area percentages (ranging from -2 to -42 percent), compared to the previous Inventory. However, the overall impact on the recalculated emissions was relatively small, with CH_4 and N_2O emissions decreasing by 12 and 7 percent respectively. Correcting a transcription error in crop production for corn in 1990 (see Table 5-22) led to a larger recalculation in emissions for 1990 relative to the other years.

Planned Improvements

A new method is in development that will directly link agricultural residue burning with the Tier 3 methods that are used in 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.