6. 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 6-1). Carbon dioxide (CO_2) emissions and removals from agriculture-related land-use activities, such as conversion of grassland to cultivated land, are presented in the Land Use, Land-Use Change, and Forestry chapter. CO_2 emissions from on-farm energy use are accounted for in the Energy chapter.

Figure 6-1: 2006 Agriculture Chapter Greenhouse Gas Emission Sources

In 2006, the agricultural sector was responsible for emissions of 454.1 teragrams of CO_2 equivalent (Tg CO_2 Eq.), or 6 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. CH_4 emissions from enteric fermentation and manure management represent about 23 percent and 7 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 72 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions.

Table 6-1 and Table 6-2 present emission estimates for the Agriculture sector. Between 1990 and 2006, CH_4 emissions from agricultural activities increased by 5 percent, while N_2O emissions fluctuated from year to year, but overall decreased by less than 1 percent.

Table 6-1: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
CH_4	**165.7**	**175.8**	**171.7**	**172.2**	**172.6**	**173.0**	**170.9**	**174.0**	**174.4**
Enteric Fermentation	126.9	132.3	124.6	123.6	123.8	124.6	122.4	124.5	126.2
Manure Management	31.0	35.2	38.8	40.2	41.3	40.7	40.1	41.8	41.4
Rice Cultivation	7.1	7.6	7.5	7.6	6.8	6.9	7.6	6.8	5.9
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.8	0.7	0.8	0.9	0.9	0.8
N_2O	**281.8**	**278.0**	**276.3**	**291.5**	**276.4**	**261.3**	**261.2**	**279.6**	**279.8**
Agricultural Soil Management	269.4	264.8	262.1	277.0	262.0	247.3	246.9	265.2	265.0
Manure Management	12.1	12.8	13.7	14.0	14.0	13.6	13.8	13.9	14.3
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.4	0.4	0.5	0.5	0.5
Total	**447.5**	**453.8**	**447.9**	**463.7**	**449.0**	**434.3**	**432.1**	**453.6**	**454.1**

Note: Totals may not sum due to independent rounding.

Table 6-2: Emissions from Agriculture (Gg)

Gas/Source	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
CH_4	**7,890**	**8,373**	**8,174**	**8,201**	**8,219**	**8,236**	**8,138**	**8,284**	**8,304**
Enteric Fermentation	6,044	6,302	5,933	5,886	5,896	5,931	5,828	5,928	6,010
Manure Management	1,474	1,676	1,847	1,915	1,964	1,938	1,908	1,988	1,972
Rice Cultivation	339	363	357	364	325	328	360	326	282

Field Burning of Agricultural Residues	33	32	38	37	34	38	42	41	39
N_2O	**909**	**897**	**891**	**940**	**892**	**843**	**842**	**902**	**902**
Agricultural Soil Management	869	854	845	894	845	798	796	855	855
Manure Management	39	41	44	45	45	44	44	45	46
Field Burning of Agricultural Residues	1	1	1	1	1	1	2	2	2

Note: Totals may not sum due to independent rounding.

6.1. *Enteric Fermentation (IPCC Source Category 4A)*

CH_4 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 by-product, 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 among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules) 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 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 affects CH_4 emissions. In general, lower feed quality and/or higher feed intake lead to higher CH_4 emissions. Feed intake is positively correlated to animal size, growth rate, 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).

CH_4 emission estimates from enteric fermentation are provided in Table 6-3 and Table 6-4. Total livestock CH_4 emissions in 2006 were 126.2 Tg CO_2 Eq. (6,010 Gg). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71 percent in 2006. Emissions from dairy cattle in 2006 accounted for 24 percent, and the remaining emissions were from horses, sheep, swine, and goats.

From 1990 to 2006, emissions from enteric fermentation have decreased by less than 1 percent. Generally, emissions have been decreasing since 1995 to 2004, mainly due to decreasing populations of both beef and dairy cattle and improved feed quality for feedlot cattle. The last two years have shown an increase in emissions. During this timeframe, populations of sheep have decreased 45 percent since 1990 while horse populations have increased over 80 percent, mostly over the last 5 years. Goat and swine populations have increased 1 percent and 14 percent, respectively, during this timeframe.

Table 6-3: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Beef Cattle	89.9	96.9	90.4	89.4	89.3	89.5	87.2	88.2	89.2
Dairy Cattle	31.2	29.9	28.9	28.8	29.0	29.2	28.9	29.6	30.3
Horses	1.9	1.9	2.0	2.1	2.3	2.6	3.0	3.5	3.5
Sheep	1.9	1.5	1.2	1.2	1.1	1.1	1.0	1.0	1.0
Swine	1.7	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Goats	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Total	**126.9**	**132.3**	**124.6**	**123.6**	**123.8**	**124.6**	**122.4**	**124.5**	**126.2**

Note: Totals may not sum due to independent rounding.

Table 6-4: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Beef Cattle	4,281	4,616	4,304	4,257	4,251	4,260	4,155	4,198	4,249
Dairy Cattle	1,488	1,422	1,377	1,374	1,381	1,393	1,377	1,411	1,441
Horses	91	92	94	99	108	126	144	166	166
Sheep	91	72	56	55	53	51	49	49	50
Swine	81	88	88	88	90	90	91	92	93
Goats	13	12	12	12	13	13	13	13	13
Total	**6,044**	**6,302**	**5,933**	**5,886**	**5,896**	**5,931**	**5,828**	**5,928**	**6,010**

Note: Totals may not sum due to independent rounding.

Methodology

Livestock emission estimates 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 CH_4 emissions from livestock in the United States. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimate emissions for all cattle except for bulls. Emission estimates for other domesticated animals (horses, sheep, swine, goats, and bulls) 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 describes the quantity of CH_4 produced by individual ruminant animals, particularly cattle. The Cattle Enteric Fermentation Model (CEFM), developed by EPA to estimate cattle enteric CH_4 emissions, incorporates this information and other analyses of livestock population, feeding practices and production characteristics were used to estimate emissions from cattle populations.

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 Steers)
    - 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 3.9. 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 Quick Stats database (USDA 2007).

Diet characteristics were estimated by region for U.S. dairy, beef, and feedlot cattle. These estimates 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 population category. The IPCC recommends Y_m values 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, rather than using the recommended IPCC values. 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, expert opinion, and modeling of animal physiology. The diet characteristics for dairy cattle were from Donovan (1999), while those for beef cattle were derived from NRC (2000). DE and Y_m for dairy cows were calculated from diet characteristics using a model simulating ruminant digestion in growing and/or lactating cattle (Donovan and Baldwin 1999). For feedlot animals, DE and Y_m values recommended by Johnson (1999) were used. Values from EPA (1993) were used for dairy replacement heifers. For grazing beef cattle, DE values were based on diet information in NRC (2000) and Y_m values were based on Johnson (2002). Weight data were estimated from Feedstuffs (1998), Western Dairyman (1998), and expert opinion. See Annex 3.9 for more details on the method used to characterize cattle diets in the United States.

To estimate CH_4 emissions from all cattle types except bulls and calves younger than 7 months,[1] the population was divided into state, age, sub-type (e.g., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, and heifer and steer in feedlots), and production (e.g., 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, 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, and heifer feedlot animals. To estimate emissions from cattle, population data were multiplied by the emission factor for each cattle type. More details are provided in Annex 3.9.

Emission estimates for other animal types were based on average emission factors representative of entire populations of each animal type. CH_4 emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2006. Also, 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 these other livestock types, except horses and goats, as well as feedlot placement information were obtained for all years from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 2007). Horse population data were obtained from the FAOSTAT database (FAO 2007), because USDA does not estimate U.S. horse populations annually. Goat population data were obtained for 1992, 1997, and 2002 (USDA 2007); these data were interpolated and extrapolated to derive estimates for the other years. CH_4 emissions from sheep, goats, swine, and horses 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. The methodology is the same as that recommended by IPCC (2006).

See Annex 3.9 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation.

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[1] Emissions from bulls are estimated using a Tier 1 approach because it is assumed there is minimal variation in population and diets; calves younger than 7 months are assumed to emit little or no CH_4.

Uncertainty

Quantitative uncertainty of this source category was performed through the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique as described in ICF (2003). These uncertainty estimates were developed for the 1990 through 2001 inventory report. No significant changes occurred in the method of data collection, data estimation methodology, or other factors that influence the uncertainty ranges around the 2006 activity data and emission factor input variables used in the current submission. Consequently, these uncertainty estimates were directly applied to the 2006 emission estimates.

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) because we wanted to capture the fact that these variables can not be negative. 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 our 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 (Table 6-5) indicate that, on average, the emission estimate range of this source is approximately 112.3 to 148.9 Tg CO_2 Eq., calculated as 11 percent below and 18 percent above the actual 2006 emission estimate of 126.2 Tg 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 inventory emission estimates. Among non-cattle, horses account for the largest degree of uncertainty in the inventory emission estimates because there is a higher degree of uncertainty among the FAO population estimates used for horses than for the USDA population estimates used for swine, goats, and sheep.

Table 6-5: Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2006 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate**[a, b] **(Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Enteric Fermentation	CH_4	126.2	112.3	148.9	-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 submitted in 2003 and applied to 2006 estimates.

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. Particular emphasis was placed this year on reviewing and implementing the revised IPCC Guidelines (IPCC 2006). Additionally, as described below, this year the CEFM was modified to allow generation of the estimates by state, which required further QA/QC to ensure consistency of estimates generated by the updated model.

Recalculations Discussion

There were several modifications that had an effect on emission estimates, including:

- The Cfi (a coefficient used for calculating the net energy required for maintenance) used for lactating cattle was adjusted from 0.322 (previously used for all cattle) to 0.386, based on the revised IPCC equations (IPCC 2006). This change had the effect of increasing the energy requirement for maintenance of lactating cows and thus increasing emissions for dairy cows by approximately 7 percent and beef cows by approximately 16 percent.

- During the QA/QC process it was noted that the C factor (a coefficient used in calculating the net energy required for growth) of 0.8 was only being used for some feedlot heifers, and all other cows and heifers were being calculated using a C factor of 1.0. This has been updated so that all cows and heifers use a C factor of 0.8 and all steer use a C factor of 1.0, as stated in the revised IPCC Guidelines (IPCC 2006). This change resulted in an increase in emissions of between three and ten percent in animal subcategories that experience weight gain (e.g., feedlot, replacement, and stocker animals), depending on the subcategory.

- The equation used to calculate the net energy of growth (NEg), which is part of the gross energy equation, was also updated to match the simplified equation provided in the revised IPCC Guidelines (IPCC 2006). The equation now reads:

  $$NE_g = 22.02 \times \left(\frac{\text{Weight}}{\text{C} \times \text{MW}} \right)^{0.75} \times \text{WG}^{1.097}$$

  Previously the equation used was:

  $$NE_g = 4.18 \times 0.0635 \times \left[0.891 \times (\text{Weight} \times 0.96) \times \left(\frac{478}{\text{C} \times \text{MW}} \right) \right]^{0.75} \times (\text{WG} \times 0.92)^{1.097}$$

  Where,

  NEg = The net energy required for growth, MJ/day

  Weight = Average live body weight of the animals in the population, kg

  C = A coefficient that is 0.8 for females, 1.0 for steer, and 1.2 for bulls

  MW = The mature weight of an adult female in moderate condition, kg

  WG = The average weight gain for animals in the population, kg/day

  This change resulted in a decrease of less than one half of one percent in animal subcategories that experience growth (i.e., weight gain, including, feedlot, replacement, and stocker animals).

- In the current inventory, the CEFM, which was used to calculate emissions from cattle enteric fermentation, was updated to output results by individual state rather than by regional groupings, during this process two changes occurred. First, the averaging approach used to calculate the step-up DE and Y_m for feedlot animals is based on an average of the feedlot and stocker diet characteristics. Given that we changed the model to run 50 states rather than 7 regions, the final values for the step-up diet characteristics changed slightly. Second, the milk production numbers are now input at the state, rather than regional level, which allows for data input at a more detailed level. Both of these changes had a very small effect on emissions compared to the additional modifications, discussed above.

- Population estimates were revised by FAO for 2001 through 2005 for horses.

- The USDA published revised population estimates that affected historical emissions estimated for swine in

2005. In addition, some historical population estimates for certain beef and dairy populations were also updated as a result of changes in USDA inputs.

As a result of these changes, dairy cattle emissions increased an average of 99 Gg (7.6 percent) per year and beef cattle increased an average of 435 Gg (11.1 percent) per year over the entire time series. Historical emission estimates for swine in 2005 increased by less than one half of one percent as a result of the USDA revisions described above. Historical emission estimates for horses increased by an average of 35 percent from 2001 through 2005.

Planned Improvements

Continued research and regular updates are necessary to maintain a current model of cattle diet characterization, feedlot placement data, rates of weight gain and calving, among other data inputs. Research is currently underway to update the diet assumptions. There are a variety of models available to predict methane production from cattle. Four of these models (two mechanistic, and two empirical) are being evaluated to determine appropriate Y_m and DE values for each cattle type and state. In addition to the model evaluation, separate research is being conducted to update the assumptions used for cattle diet components for each animal type. At the conclusion of both of these updates, it is anticipated that a peer-reviewed article will be published and will serve as the basis for future emission estimates for enteric fermentation.

In addition to the diet characteristics discussed above several revisions will be investigated, including:

- the possible inclusion of bulls into the CEFM at a Tier 1 or 2 level;
- updating input variables that are from older data sources, such as beef births by month and beef cow lactation rates;
- the possible breakout of other animal types from national estimates to state-level estimates; and
- including bison in the estimates for other domesticated animals.

It is anticipated that these updates may result in significant changes to some of the activity data used in generating emissions. Additionally, since these revised inputs will be state-specific and peer-reviewed, uncertainty ranges around these variables will likely decrease. As a consequence, the current uncertainty analysis will become outdated, and a revision of the quantitative uncertainty surrounding emission estimates from this source category will be initiated.

6.2. Manure Management (IPCC Source Category 4B)

The management of livestock manure can produce anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. Methane is produced by the anaerobic decomposition of manure. Direct N_2O emissions are produced as part of the nitrogen cycle through the nitrification and denitrification of the organic nitrogen in livestock manure and urine.[2] Indirect N_2O emissions are produced as result of the volatilization of nitrogen as NH_3 and NO_x and runoff and leaching of nitrogen during treatment, storage and transportation.

When livestock or poultry manure are stored or treated in systems that promote anaerobic conditions (e.g., as a

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[2] Direct and indirect N_2O emissions from manure and urine spread onto fields either directly as daily spread or after it is removed from manure management systems (e.g., lagoon, pit, etc.) and from livestock manure 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.

liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of materials 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 nitrogen is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to nitrogen gas (N_2), with intermediate production of N_2O and nitric oxide (NO) (denitrification) (Groffman et al. 2000). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. A very small portion of the total nitrogen 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 NOx) 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. 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 does not include any leaching losses.

Estimates of CH_4 emissions in 2006 were 41.4 Tg CO_2 Eq. (1,972 Gg), 34 percent higher than in 1990. Emissions increased on average by 0.6 Tg CO_2 Eq. (2.0 percent) annually over this period. The majority of this increase was from swine and dairy cow manure, where emissions increased 34 and 49 percent, respectively. Although the majority of 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 limiting the application of manure nutrients have shifted manure management practices at smaller dairies from daily spread to manure managed and stored on site. Although national dairy animal populations have been generally decreasing, some states have seen increases in their dairy populations as the industry becomes more concentrated in certain areas of the country. 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 facilities is translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This shift was accounted for by incorporating state and WMS-specific CH_4 conversion factor (MCF) values in combination with the 1992, 1997, and 2002 farm-size distribution data reported in the *Census of Agriculture* (USDA 2005). Methane emissions from horses have nearly doubled since 1990 (an 82 percent increase from 1990 to 2006); however, this is due to population increases rather than changes in manure management practices. Overall, horses contribute only 2 percent of CH_4 emissions from animal manure management. From 2005 to 2006, there was a 1 percent decrease in total CH_4 emissions, due to minor shifts in the animal populations and the resultant effects on manure management system allocations and increased use of anaerobic digesters.

In 2006, total N_2O emissions were estimated to be 14.3 Tg CO_2 Eq. (46 Gg); in 1990, emissions were 12.1 Tg CO_2 Eq. (39 Gg). These values include both direct and indirect N_2O emissions from manure management. N_2O 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 an 18 percent increase from 1990 to 2006 and a 2.5 percent increase from 2005 through 2006.

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

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

Gas/Animal Type	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH_4[1]	**31.0**	**35.2**	**38.8**	**40.2**	**41.3**	**40.7**	**40.1**	**41.8**	**41.4**
Dairy Cattle	12.0	13.4	15.8	16.6	17.3	17.7	17.2	17.9	17.9
Beef Cattle	2.5	2.6	2.4	2.4	2.4	2.3	2.3	2.3	2.5
Swine	13.1	16.0	17.4	17.8	18.3	17.2	17.1	17.9	17.5
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	0.0	+	+	+	+	+
Poultry	2.8	2.7	2.6	2.7	2.7	2.7	2.6	2.6	2.7
Horses	0.5	0.4	0.5	0.5	0.5	0.6	0.7	0.8	0.8
N_2O[2]	**12.1**	**12.8**	**13.7**	**14.0**	**14.0**	**13.6**	**13.8**	**13.9**	**14.3**
Dairy Cattle	3.5	3.5	3.6	3.6	3.7	3.7	3.7	3.7	3.8
Beef Cattle	5.5	5.9	6.7	6.9	6.7	6.3	6.5	6.5	6.7
Swine	1.2	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	0.0	+	+	+	+	+
Poultry	1.5	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.8
Horses	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4
Total	**43.0**	**48.0**	**52.5**	**54.2**	**55.2**	**54.3**	**53.9**	**55.7**	**55.7**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

[1] Includes CH_4 emission reductions due to anaerobic digestion.

[2] Includes both direct and indirect N_2O emissions.

Table 6-7: CH_4 and N_2O Emissions from Manure Management (Gg)

Gas/Animal Type	1990	1995	2000	2001	2002	2003	2004	2005	2006
CH_4[1]	**1,474**	**1,676**	**1,847**	**1,915**	**1,964**	**1,938**	**1,908**	**1,988**	**1,972**
Dairy Cattle	572	638	751	792	822	844	818	854	852
Beef Cattle	120	121	114	117	113	112	111	112	117
Swine	623	762	830	849	873	821	815	853	832
Sheep	7	5	4	4	4	4	4	4	4
Goats	1	1	1	1	1	1	1	1	1
Poultry	131	128	125	129	127	127	126	126	126
Horses	22	21	22	23	25	29	34	39	39
N_2O[2]	**39**	**41**	**44**	**45**	**45**	**44**	**44**	**45**	**46**
Dairy Cattle	11	11	12	12	12	12	12	12	12
Beef Cattle	18	19	22	22	22	20	21	21	22
Swine	4	5	5	5	5	5	5	5	5
Sheep	+	+	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+	+	+
Poultry	5	5	5	5	6	6	6	6	6
Horses	1	1	1	1	1	1	1	1	1

Note: Totals may not sum due to independent rounding.

[1] Includes CH_4 emission reductions due to anaerobic digestion.

[2] Includes both direct and indirect N_2O emissions.

+ Less than 0.5 Gg.

Methodology

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal type. The calculation of emissions requires the following information:

- Animal population data (by animal type and state);
- Amount of N produced (excretion rate by animal type times animal population);
- Amount of volatile solids produced (excretion rate by animal type times animal population);
- CH_4 producing potential of the volatile solids (by animal type);

- Extent to which the CH_4 producing potential is realized for each type of manure management system (by state and manure management system, including the impacts of any biogas collection efforts);
- Portion of manure managed in each manure management system (by state and animal type); and
- Portion of manure deposited on pasture, range, or paddock or used in daily spread systems.

This section presents a summary of the methodologies used to estimate CH_4 and N_2O emissions from manure management for this inventory. See Annex 3.10 for more detailed information on the methodology and data used to calculate CH_4 and N_2O emissions from manure management.

Both CH_4 and N_2O emissions were estimated by first determining activity data, including animal population, waste characteristics, and manure management system usage. For swine and dairy cattle, manure management system usage was determined for different farm size categories using data from USDA (USDA 1996b, 1998b, 2000b) and EPA (ERG 2000a, EPA 2002a, 2002b). For beef cattle and poultry, manure management system usage data were not tied to farm size but were based on other data sources (ERG 2000a, USDA 2000c, UEP 1999). For other animal types, manure management system usage was based on previous estimates (EPA 1992).

MCFs and N_2O emission factors were determined for all manure management systems. MCFs for dry systems were set equal to default IPCC factors based on each state's 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. The MCF calculations model the average monthly ambient temperature, a minimum system temperature, the carryover of volatile solids (VS) in the system from month to month due to long storage times exhibited by anaerobic lagoon systems, and a factor to account for management and design practices that result in the loss of VS from lagoon systems. Direct N_2O emission factors for all systems were set equal to default IPCC factors (IPCC 2006). For indirect N_2O, the default indirect N_2O emission factors suggested by IPCC were used: 0.010 kg N_2O-N/kg N for volatilization and 0.0075 kg -N/kg N for runoff/leaching. The amount of nitrogen that is lost due to volatilization of NH_3 and NO_X ($Frac_{Gas}$) is based on WMS-specific volatilization values as estimated from U.S. EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). The amount of nitrogen that is lost due to runoff and leaching ($Frac_{runoff/leaching}$) is based on regional cattle runoff data from EPA's Office of Water (EPA 2002b).

CH_4 emissions were estimated using the VS production for livestock. For all cattle groups except bulls and calves, regional animal-specific VS production rates that are related to the diet of the animal for each year of the inventory were used (Pederson et al., 2007). For other animal groups, VS production was calculated using a national average VS production rate from the *Agricultural Waste Management Field Handbook* (USDA 1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. The resulting VS for each animal group were then multiplied by the maximum CH_4 producing capacity of the waste (B_o) and the state- and WMS-specific MCFs.

The maximum CH_4 producing capacity of the VS, or B_o, was determined based on data collected in a literature review (ERG 2000b). B_o data were collected for each animal type for which emissions were estimated.

Anaerobic digester reductions for 1990-2005 were estimated based on data from the EPA AgSTAR program, including information presented in the *AgSTAR Digest* (EPA 2000, 2003b, 2006). Anaerobic digestion reductions for 2006 were calculated based on data from an AgSTAR digester inventory (ERG 2008).

Nitrogen excretion rates from the USDA *Agricultural Waste Management Field Handbook* (USDA 1996a) were used for all livestock except sheep, goats, and horses. Data from the American Society of Agricultural Engineers (ASAE 1999) were used for these animal types.

Direct N_2O emissions were estimated by determining total Kjeldahl nitrogen (TKN)[3] production for all livestock

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[3] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

wastes using a national average N excretion rate for each animal group from USDA (1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. State- and WMS-specific direct N_2O emission factors were then applied to total nitrogen production to estimate direct N_2O emissions.

Indirect N_2O emissions were calculated by first estimating the amount of nitrogen loss from volatilization and runoff/leaching by multiplying the N excreted by $Frac_{Gas}$ and $Frac_{Runoff/Leaching}$. The N losses were then multiplied by the indirect N_2O emission factors to estimate indirect N_2O emissions.

Uncertainty

An analysis was conducted for the manure management emission estimates presented in EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2001* (EPA 2003a, ERG 2003) 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 Tier 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.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-8 Manure management CH_4 emissions in 2006 were estimated to be between 34.0 and 49.7 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2006 emission estimate of 41.4 Tg CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 12.0 and 17.7 Tg CO_2 Eq. (or approximately 16 percent below and 24 percent above the actual 2006 emission estimate of 14.3 Tg CO_2 Eq.).

Table 6-8: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O (Direct and Indirect) Emissions from Manure Management (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2006 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Manure Management	CH_4	41.4	34.0	49.7	-18%	+20%
Manure Management	N_2O	14.3	12.0	17.7	-16%	+24%

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

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[4] 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 nitrogen excreted and the sum of county estimates for the full time series.

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[4] N_2O emissions in the previous inventory reflect only direct emissions whereas the current N_2O emissions include both direct and indirect emissions from livestock manure management.

Recalculations Discussion

There was a major change in the N_2O and CH_4 emissions calculations for the 2006 inventory. These emissions are now calculated from the "bottom-up" such that CH_4 and N_2O are calculated for each animal group, manure management system, and state. These values are then summed to calculate the total greenhouse gas emissions from manure management in the United States. This methodology differs from previous inventories which calculated state weighted average N_2O emission factors and methane conversion factors (MCFs). Although this new methodology does not alter the overall estimates of greenhouse gases associated with this section, it now allows emissions to be viewed by animal type and manure management system at the state and national level.

In the previous N_2O inventory, dairy heifers and beef on feed each had a separate WMS distribution for managed systems and unmanaged systems. The managed WMS distribution was used to calculate a state average EF for managed systems. In the new inventory methodology, dairy heifers and beef on feed have one WMS distribution that represents managed and unmanaged systems. For all animals, emissions are calculated for each WMS using the EF for that system, and not using a state average EF. This change in calculation methodology results in a slightly different (less than one percent change) emission estimate for these animal groups.

The inventory now includes indirect N_2O emissions in the manure management sector associated with N losses from volatilization of nitrogen as ammonia (NH_3), nitrogen oxides (NO_x), and leaching and runoff, as recommended by IPCC (2006). These indirect N_2O emissions are added to the direct N_2O emissions to present a more complete picture of N_2O emissions from manure management.

The days per year used in N_2O calculations was changed from 365 to 365.25 to include leap years and to be consistent with the CH_4 inventory calculations.

Methane emission reductions from anaerobic digestion for 2006 were calculated from an AgSTAR digester inventory by summing the estimated emission reductions by animal type (ERG 2008). Anaerobic digestion reductions in previous years were based on data obtained from AgSTAR Digests (EPA 2000, 2003b, 2006).

Errors were identified in the calculation of the sheep WMS distribution; population values for other states were incorrectly distributed in the calculations. Correcting this error resulted in very small changes in N_2O emissions estimates from sheep.

Changes were made to the current calculations involving animal population data. Animal population data were updated to reflect the final estimates reports from USDA NASS (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a, 2004a-e, 2006a-c, 2007a-d). The population data may differ from previous inventories because some values changed due to USDA NASS review. For horses, state-level populations were estimated using the national FAO population data (FAO 2007) and the state distributions from the 1992, 1997, and 2002 Census of Agriculture (USDA 2005). The FAO horse population estimates for recent years increased dramatically between the 2005 and 2006 inventories, resulting in a much larger estimated horse population, and therefore greater greenhouse gas emissions from this sector.

With these recalculations, CH_4 emission estimates from manure management systems are slightly higher than reported in the previous inventory for dairy cattle and swine, as well as horses for years 2001 through 2005. On average, annual CH_4 emission estimates are more than those of the previous inventory by about one percent.

N_2O emission estimates from manure management systems have increased by approximately 30 percent for all years of the current inventory compared to the previous inventory due to the change in calculation methodology, which incorporates direct and indirect N_2O emissions. The most significant changes in N_2O emissions compared to the previous inventory occurred in the poultry and swine sectors, whose emissions were approximately 70 percent higher due to the inclusion of indirect N_2O emissions.

Changes were made to the Cattle Enteric Fermentation Model that produces the VS estimates for all cattle groups except bulls and calves. Refer to the Recalculations section in the Enteric Fermentation to see specific changes made to the model.

Planned Improvements

The manure management inventory will be updated to reflect changes in the Cattle Enteric Fermentation Model (CEFM). In addition, efforts will be made to ensure that the manure management inventory and CEFM are using the same data sources and variables where appropriate.

The American Society of Agricultural Engineers proposed new standards for manure production characteristics in 2004 and finalized them in 2005. These data were investigated and evaluated for incorporation into future estimates.

A method to better estimate anaerobic digester CH_4 emission reductions will be investigated. This method would include separating systems with anaerobic digesters from the total animal population before estimating CH_4 emissions, and then estimating emissions from the digesters using the amount of biogas/CH_4 collected and a 99 percent destruction efficiency.

The uncertainty analysis will be updated for in the future to more accurately assess uncertainty of emission calculations. This update is necessary due to the extensive changes in emission calculation methodology in the 1990 through 2006 inventory, including estimation of emissions at the WMS level and the use of new calculations and variables for indirect N_2O emissions.

The current methodology for calculating runoff for indirect N_2O emissions will be reevaluated. Currently runoff is estimated at all manure management systems based on outdoor cattle operations. A new methodology may be incorporated which takes into account more recent model runs from EPA’s Office of Water.

In order to improve the efficiency of MCF calculations, MCFs will be calculated in a database instead of spreadsheets in the next inventory. Calculating MCFs in a database will also increase the overall efficiency of CH_4 emission estimates by linking directly to the database that calculates CH_4 estimates.

6.3. Rice Cultivation (IPCC Source Category 4C)

Most of the world’s rice, and all rice in the United States, is grown on flooded fields. When fields are flooded, aerobic decomposition of organic material gradually depletes most of the oxygen present in the soil, causing anaerobic soil conditions. Once the environment becomes anaerobic, CH_4 is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. As much as 60 to 90 percent of the CH_4 produced is oxidized by aerobic methanotrophic bacteria in the soil (some oxygen remains at the interfaces of soil and water, and soil and root system) (Holzapfel-Pschorn et al. 1985, Sass et al. 1990). Some of the CH_4 is also leached away as dissolved CH_4 in floodwater that percolates from the field. The remaining un-oxidized CH_4 is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants. Minor amounts of CH_4 also escape from the soil via diffusion and bubbling through floodwaters.

The water management system under which rice is grown is one of the most important factors affecting CH_4 emissions. Upland rice fields are not flooded, and therefore are not believed to produce CH_4. In deepwater rice fields (i.e., fields with flooding depths greater than one meter), the lower stems and roots of the rice plants are dead, so the primary CH_4 transport pathway to the atmosphere is blocked. The quantities of CH_4 released from deepwater fields, therefore, are believed to be significantly less than the quantities released from areas with shallower flooding depths. Some flooded fields are drained periodically during the growing season, either intentionally or accidentally. If water is drained and soils are allowed to dry sufficiently, CH_4 emissions decrease or stop entirely. This is due to soil aeration, which not only causes existing soil CH_4 to oxidize but also inhibits further CH_4 production in soils. All rice in the United States is grown under continuously flooded conditions; none is grown under deepwater conditions. Mid-season drainage does not occur except by accident (e.g., due to levee breach).

Other factors that influence CH_4 emissions from flooded rice fields include fertilization practices (especially the use of organic fertilizers), soil temperature, soil type, rice variety, and cultivation practices (e.g., tillage, seeding, and weeding practices). The factors that determine the amount of organic material available to decompose (i.e., organic fertilizer use, soil type, rice variety,[5] and cultivation practices) are the most important variables influencing the amount of CH_4 emitted over the growing season; the total amount of CH_4 released depends primarily on the amount of organic substrate available. Soil temperature is known to be an important factor regulating the activity of methanogenic bacteria, and therefore the rate of CH_4 production. However, although temperature controls the amount of time it takes to convert a given amount of organic material to CH_4, that time is short relative to a growing season, so the dependence of total emissions over an entire growing season on soil temperature is weak. The application of synthetic fertilizers has also been found to influence CH_4 emissions; in particular, both nitrate and sulfate fertilizers (e.g., ammonium nitrate and ammonium sulfate) appear to inhibit CH_4 formation.

Rice is cultivated in eight states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, Oklahoma, and Texas.[6] Soil types, rice varieties, and cultivation practices for rice vary from state to state, and even from farm to farm. However, most rice farmers apply organic fertilizers in the form of residue from the previous rice crop, which is left standing, disked, or rolled into the fields. Most farmers also apply synthetic fertilizer to their fields, usually urea. Nitrate and sulfate fertilizers are not commonly used in rice cultivation in the United States. In addition, the climatic conditions of Arkansas, southwest Louisiana, Texas, and Florida allow for a second, or ratoon, rice crop. CH_4 emissions from ratoon crops have been found to be considerably higher than those from the primary crop. This second rice crop is produced from regrowth of the stubble after the first crop has been harvested. Because the first crop's stubble is left behind in ratooned fields, and there is no time delay between cropping seasons (which would allow the stubble to decay aerobically), the amount of organic material that is available for anaerobic decomposition is considerably higher than with the first (i.e., primary) crop.

Rice cultivation is a small source of CH_4 in the United States (Table 6-9 and Table 6-10). In 2006, CH_4 emissions from rice cultivation were 5.9 Tg CO_2 Eq. (282 Gg). Although annual emissions fluctuated unevenly between the years 1990 and 2006, ranging from an annual decrease of 14 percent to an annual increase of 17 percent, there was an overall decrease of 17 percent over the sixteen-year period, due to an overall decrease in primary crop area.[7] The factors that affect the rice acreage in any year vary from state to state, although the price of rice relative to competing crops is the primary controlling variable in most states.

Table 6-9: CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq.)

State	1990	1995	2000	2001	2002	2003	2004	2005	2006
Primary	**5.1**	**5.6**	**5.5**	**5.9**	**5.7**	**5.4**	**6.0**	**6.0**	**5.1**
Arkansas	2.1	2.4	2.5	2.9	2.7	2.6	2.8	2.9	2.5
California	0.7	0.8	1.0	0.8	0.9	0.9	1.1	0.9	0.9
Florida	+	+	+	+	+	+	+	+	+
Louisiana	1.0	1.0	0.9	1.0	1.0	0.8	1.0	0.9	0.6
Mississippi	0.4	0.5	0.4	0.5	0.5	0.4	0.4	0.5	0.3
Missouri	0.1	0.2	0.3	0.4	0.3	0.3	0.3	0.4	0.4
Oklahoma	+	+	+	+	+	+	+	+	+
Texas	0.6	0.6	0.4	0.4	0.4	0.3	0.4	0.4	0.3
Ratoon	**2.1**	**2.1**	**2.0**	**1.7**	**1.1**	**1.5**	**1.6**	**0.8**	**0.9**
Arkansas	+	+	+	+	+	+	+	+	+
Florida	+	0.1	0.1	+	+	+	+	+	+
Louisiana	1.1	1.1	1.3	1.1	0.5	1.0	1.1	0.5	0.5
Texas	0.9	0.8	0.7	0.6	0.5	0.5	0.5	0.4	0.4
Total	**7.1**	**7.6**	**7.5**	**7.6**	**6.8**	**6.9**	**7.6**	**6.8**	**5.9**

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

[6] A very small amount of rice is grown on about 20 acres in South Carolina; however, this amount was determined to be too insignificant to warrant inclusion in national emissions estimates.

[7] The 14 percent decrease occurred between 2005 and 2006; the 17 percent increase happened between 1993 and 1994.

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 6-10: CH_4 Emissions from Rice Cultivation (Gg)

State	1990	1995	2000	2001	2002	2003	2004	2005	2006
Primary	**241**	**265**	**260**	**283**	**274**	**255**	**283**	**287**	**241**
Arkansas	102	114	120	138	128	124	132	139	119
California	34	40	47	40	45	43	50	45	44
Florida	1	2	2	1	1	+	1	1	1
Louisiana	46	48	41	46	45	38	45	45	29
Mississippi	21	24	19	22	22	20	20	22	16
Missouri	7	10	14	18	15	15	17	18	18
Oklahoma	+	+	+	+	+	+	+	+	+
Texas	30	27	18	18	18	15	19	17	13
Ratoon	**98**	**98**	**97**	**81**	**52**	**73**	**77**	**39**	**41**
Arkansas	+	+	+	+	+	+	+	1	+
Florida	2	4	2	2	2	2	2	+	1
Louisiana	52	54	61	52	25	50	50	22	22
Texas	45	40	34	27	24	22	24	17	18
Total	**339**	**363**	**357**	**364**	**325**	**328**	**360**	**326**	**282**

+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

Methodology

IPCC (2006) recommends using harvested rice areas, area-based daily emission factors (i.e., amount of CH_4 emitted per day per unit harvested area), and length of growing season to estimate annual CH_4 emissions from rice cultivation. This inventory uses the recommended methodology and employs Tier 2 U.S.-specific emission factors derived from rice field measurements. State-specific and daily emission factors were not available, however, so average U.S. seasonal emission factors were used. Seasonal emissions have been found to be much higher for ratooned crops than for primary crops, so emissions from ratooned and primary areas are estimated separately using emission factors that are representative of the particular growing season. This approach is consistent with IPCC (2006).

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 6-11. Primary crop areas for 1990 through 2006 for all states except Florida and Oklahoma were taken from U.S. Department of Agriculture's *Field Crops Final Estimates 1987–1992* (USDA 1994), *Field Crops Final Estimates 1992–1997* (USDA 1998), *Field Crops Final Estimates 1997–2002* (USDA 2003), and *Crop Production Summary* (USDA 2005 through 2007). Harvested rice areas in Florida, which are not reported by USDA, were obtained from: Tom Schueneman (1999b, 1999c, 2000, 2001a) and Arthur Kirstein (2003, 2006), Florida agricultural extension agents; Dr. Chris Deren (2002) of the Everglades Research and Education Centre at the University of Florida; Gaston Cantens (2004, 2005), Vice President of Corporate Relations of the Florida Crystals Company; and Rene Gonzalez (2007a), Plant Manager of Sem-Chi Rice Company. Harvested rice areas for Oklahoma, which also are not reported by USDA, were obtained from Danny Lee of the Oklahoma Farm Services Agency (2003 through 2007). Acreages for the ratoon crops were derived from conversations with the agricultural extension agents in each state. In Arkansas, ratooning occurred only in 1998, 1999, 2005, and 2006, when the ratooned area was less than 1 percent of the primary area (Slaton 1999 through 2001a; Wilson 2002 through 2007). In Florida, the ratooned area was 50 percent of the primary area from 1990 to 1998 (Schueneman 1999a), about 65 percent of the primary area in 1999 (Schueneman 2000), around 41 percent of the primary area in 2000 (Schueneman 2001a), about 60 percent of the primary area in 2001 (Deren 2002), about 54 percent of the primary area in 2002 (Kirstein 2003), about 100 percent of the primary area in 2003 (Kirstein 2004), about 77 percent of the primary area in 2004 (Cantens 2005), 0 percent of the primary area in 2005 (there was no ratooning this year due to Hurricane Wilma), and about 28 percent of the primary area in 2006 (Gonzalez 2007a). In Louisiana, the percentage of the primary area that was ratooned was constant at 30 percent over the 1990 to 1999 period, increased to approximately 40 percent in 2000, returned to 30 percent in 2001, dropped to 15 percent in 2002, rose to 35 percent in 2003, returned to 30 percent in 2004, dropped to 13 percent in 2005 and increased to 20 percent in 2006 (Linscombe 1999, 2001a, 2002 through 2007; Bollich 2000). In Texas, the percentage of the primary area that was ratooned was constant at 40 percent over the 1990 to 1999 period, increased to 50 percent in 2000 due to an early primary crop, and then decreased to 40 percent in 2001, 37 percent in 2002, 38 percent in 2003, 35 percent in 2004, 27 percent in 2005 and increased to 39 percent in 2006 (Klosterboer 1999, 2000, 2001a, 2002, 2003; Stansel 2004, 2005; Texas Agricultural Experiment Station 2006, 2007). California, Mississippi, Missouri, and Oklahoma have not ratooned rice over the period 1990 through 2006 (Guethle 1999, 2000, 2001a, 2002 through 2007; Lee 2003 through 2007; Mutters 2002 through 2005; Street 1999 through 2003; Walker 2005, 2007).

Table 6-11: Rice Areas Harvested (Hectares)

State/Crop	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Arkansas									
Primary	485,633	542,291	570,619	656,010	608,256	588,830	629,300	661,675	566,572
Ratoon*	0	0	0	0	0	0	0	662	6
California	159,854	188,183	221,773	190,611	213,679	205,180	238,770	212,869	211,655
Florida									
Primary	4,978	9,713	7,801	4,562	5,077	2,369	3,755	4,565	4,575
Ratoon	2,489	4,856	3,193	2,752	2,734	2,369	2,899	0	1,295
Louisiana									
Primary	220,558	230,676	194,253	220,963	216,512	182,113	215,702	212,465	139,620
Ratoon	66,168	69,203	77,701	66,289	32,477	63,739	64,711	27,620	27,924
Mississippi	101,174	116,552	88,223	102,388	102,388	94,699	94,699	106,435	76,487
Missouri	32,376	45,326	68,393	83,772	73,654	69,203	78,915	86,605	86,605
Oklahoma	617	364	283	265	274	53	158	271	17
Texas									
Primary	142,857	128,693	86,605	87,414	83,367	72,845	88,223	81,344	60,704
Ratoon	57,143	51,477	43,302	34,966	30,846	27,681	30,878	21,963	23,675
Total Primary	**1,148,047**	**1,261,796**	**1,237,951**	**1,345,984**	**1,303,206**	**1,215,291**	**1,349,523**	**1,366,228**	**1,146,235**
Total Ratoon	**125,799**	**125,536**	**124,197**	**104,006**	**66,056**	**93,790**	**98,488**	**50,245**	**52,899**
Total	**1,273,847**	**1,387,333**	**1,362,148**	**1,449,991**	**1,369,262**	**1,309,081**	**1,448,011**	**1,416,473**	**1,199,135**

* Arkansas ratooning occurred only in 1998, 1999, 2005, and 2006.

Note: Totals may not sum due to independent rounding.

To determine what CH_4 emission factors should be used for the primary and ratoon crops, CH_4 flux information from rice field measurements in the United States was collected. Experiments which involved atypical or nonrepresentative management practices (e.g., the application of nitrate or sulfate fertilizers, or other substances believed to suppress CH_4 formation), as well as experiments in which measurements were not made over an entire flooding season or floodwaters were drained mid-season, were excluded from the analysis. The remaining experimental results[8] were then sorted by season (i.e., primary and ratoon) and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added). The experimental results from primary crops with added synthetic and organic fertilizer (Bossio et al. 1999; Cicerone et al. 1992; Sass et al. 1991a, 1991b) were averaged to derive an emission factor for the primary crop, and the experimental results from ratoon crops with added synthetic fertilizer (Lindau and Bollich 1993, Lindau et al. 1995) were averaged to derive an emission factor for the ratoon crop. The resultant emission factor for the primary crop is 210 kg CH_4/hectare-

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[8] In some of these remaining experiments, measurements from individual plots were excluded from the analysis because of the aforementioned reasons. In addition, one measurement from the ratooned fields (i.e., the flux of 2.041 g/m^2/day in Lindau and Bollich 1993) was excluded, because this emission rate is unusually high compared to other flux measurements in the United States, as well as IPCC (2006) default emission factors.

season, and the resultant emission factor for the ratoon crop is 780 kg CH_4/hectare-season.

Uncertainty

The largest uncertainty in the calculation of CH_4 emissions from rice cultivation is associated with the emission factors. Seasonal emissions, derived from field measurements in the United States, vary by more than one order of magnitude. This inherent variability is due to differences in cultivation practices, in particular, fertilizer type, amount, and mode of application; differences in cultivar type; and differences in soil and climatic conditions. A portion of this variability is accounted for by separating primary from ratooned areas. However, even within a cropping season or a given management regime, measured emissions may vary significantly. Of the experiments used to derive the emission factors applied here, primary emissions ranged from 22 to 479 kg CH_4/hectare-season and ratoon emissions ranged from 481 to 1,490 kg CH_4/hectare-season. The uncertainty distributions around the primary and ratoon emission factors were derived using the distributions of the relevant primary or ratoon emission factors available in the literature and described above. Variability about the rice emission factor means was not normally distributed for either primary or ratooned crops, but rather skewed, with a tail trailing to the right of the mean. A lognormal statistical distribution was, therefore, applied in the Tier 2 Monte Carlo analysis.

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

To quantify the uncertainties for emissions from rice cultivation, a Monte Carlo (Tier 2) uncertainty analysis was performed using the information provided above. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-12. Rice cultivation CH_4 emissions in 2006 were estimated to be between 2.1 and 12.8 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 65 percent below to 117 percent above the actual 2006 emission estimate of 5.9 Tg CO_2 Eq.

Table 6-12: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2006 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Rice Cultivation	CH_4	5.9	2.1	12.8	-65%	117%

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

QA/QC and Verification

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

Recalculations Discussion

When compiling the previous inventory, no data on area harvested and percent of area ratooned in Florida were available for 2005, and consequently 2004 data was held constant. This year, Gonzalez (2007a) was able to provide data for 2005 as well as 2006, resulting in an decrease of about 0.6 percent in the estimate for 2005.

6.4. Agricultural Soil Management (IPCC Source Category 4D)

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and denitrification.[9] A number of agricultural activities increase mineral nitrogen (N) availability in soils, thereby increasing the amount available for nitrification and denitrification, and ultimately the amount of N_2O emitted. These activities increase soil mineral N either directly or indirectly (see Figure 6-2). Direct increases occur through a variety of management practices that add, or lead to greater release of, mineral N to the soil, 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 and cultivation of organic cropland soils (i.e., soils with a high organic matter content, otherwise known as histosols).[10] Other agricultural soil management activities, including irrigation, drainage, tillage practices, and fallowing of land, can influence N mineralization in soils and thereby affect direct emissions. Mineral N is also made available in soils through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere.[11] Indirect emissions of N_2O occur through two pathways: (1) volatilization and subsequent atmospheric deposition of applied N,[12] and (2) surface runoff and leaching of applied N into groundwater and surface water. Direct emissions from agricultural lands (i.e., croplands and grasslands) are included in this section, while direct emissions from forest lands and settlements are presented in the Land Use, Land-Use Change, and Forestry chapter. However, indirect N_2O emissions from all sources (cropland, grassland, forest lands, settlements, and managed manure) are reported in this chapter.

Figure 6-2: Agricultural Sources and Pathways of N that Result in N_2O Emissions

Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions from this source in 2006 were 265.0 Tg CO_2 Eq. (855 Gg N_2O) (see Table 6-13 and Table 6-14). Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2006, although overall emissions were 1.6 percent lower in 2006 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production. On average, cropland accounted for approximately 64 percent of total direct emissions, while grassland accounted for approximately 36 percent. Estimated direct and indirect N_2O emissions by sub-source category are provided in Table 6-15 and Table 6-16.

Table 6-13: N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Direct	**218.3**	**210.3**	**216.0**	**222.3**	**217.7**	**202.2**	**208.6**	**217.9**	**214.7**
Cropland	130.9	133.1	142.0	147.6	137.1	130.2	136.1	140.0	138.9
Grassland	87.4	77.2	74.0	74.8	80.6	72.0	72.5	77.9	75.8

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[9] 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 nitrogen gas (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).

[10] Drainage and cultivation of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby enhancing N_2O emissions from these soils.

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

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

Indirect (All Land-Use Types)	**51.1**	**54.5**	**46.0**	**54.7**	**44.3**	**45.0**	**38.3**	**47.3**	**50.3**
Cropland	30.1	30.5	28.4	28.9	24.8	27.8	21.6	28.4	30.2
Grassland	20.6	23.6	17.1	25.2	18.9	16.7	16.1	18.3	19.5
Forest Land	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5
Total	**269.4**	**264.8**	**262.1**	**277.0**	**262.0**	**247.3**	**246.9**	**265.2**	**265.0**

+ Less than 0.05 Tg CO_2 Eq.

Table 6-14: N_2O Emissions from Agricultural Soils (Gg N_2O)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Direct	**704**	**678**	**697**	**717**	**702**	**652**	**673**	**703**	**693**
Cropland	422	429	458	476	442	420	439	452	448
Grassland	282	249	239	241	260	232	234	251	244
Indirect (All Land-Use Types)	**165**	**176**	**149**	**176**	**143**	**145**	**124**	**153**	**162**
Cropland	97	98	92	93	80	90	70	92	97
Grassland	67	76	55	81	61	54	52	59	63
Forest Land	+	+	+	+	+	+	+	+	+
Settlements	1	1	1	2	2	2	2	2	2
Total	**869**	**854**	**845**	**894**	**845**	**798**	**796**	**855**	**855**

+ Less than 0.5 Gg N_2O

Table 6-15: Direct N_2O Emissions from Agricultural Soils by Land-Use and N Input (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Cropland	**130.9**	**133.1**	**142.0**	**147.6**	**137.1**	**130.2**	**136.1**	**140.0**	**138.9**
Mineral Soils	**128.1**	**130.3**	**139.1**	**144.7**	**134.3**	**127.4**	**133.2**	**137.1**	**136.1**
Synthetic Fertilizer	51.3	55.3	55.8	57.2	54.2	50.4	55.3	53.6	53.6
Organic Amendments[a]	9.4	10.1	10.2	11.1	10.7	10.0	10.7	10.4	10.7
Residue N[b]	9.0	9.6	10.2	9.7	8.9	10.4	9.2	9.6	10.1
Other[c]	58.4	55.2	62.8	66.8	60.4	56.5	58.1	63.6	61.7
Organic Soils	**2.8**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**
Grassland	**87.4**	**77.2**	**74.0**	**74.8**	**80.6**	**72.0**	**72.5**	**77.9**	**75.8**
Synthetic Fertilizer	3.0	2.6	2.5	2.6	2.7	2.5	2.5	2.5	2.6
PRP Manure	19.8	18.4	19.6	18.5	23.3	19.2	20.9	18.9	19.6
Managed Manure[d]	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Sewage Sludge	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5
Residue N[b]	12.5	11.4	10.4	10.9	10.8	10.3	10.5	11.2	10.4
Other[c]	51.3	44.0	40.7	41.8	42.8	39.2	37.6	44.2	42.2
Total	**218.3**	**210.3**	**216.0**	**222.3**	**217.7**	**202.2**	**208.6**	**217.9**	**214.7**

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

[b] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

[c] Other N inputs include mineralization from decomposition of soil organic matter as well as asymbiotic fixation of N from the atmosphere.

[d] Accounts for managed manure that is applied to grassland soils.

Table 6-16: Indirect N_2O Emissions from all Land Use Types (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Cropland	**30.1**	**30.5**	**28.4**	**28.9**	**24.8**	**27.8**	**21.6**	**28.4**	**30.2**
Volatilization and Atm. Deposition	5.8	6.1	6.7	6.1	6.0	6.4	6.1	6.6	6.5
Surface Leaching & Run-Off	24.3	24.4	21.7	22.8	18.8	21.4	15.5	21.8	23.7
Grassland	**20.6**	**23.6**	**17.1**	**25.2**	**18.9**	**16.7**	**16.1**	**18.3**	**19.5**

Volatilization and Atm. Deposition	10.7	10.2	9.3	9.4	9.3	9.4	9.2	10.1	9.4
Surface Leaching & Run-Off	9.9	13.4	7.8	15.8	9.6	7.2	6.9	8.2	10.1
Forest Land	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Volatilization and Atm. Deposition	+	+	+	+	+	+	+	+	+
Surface Leaching & Run-Off	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements	**0.3**	**0.4**	**0.4**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Volatilization and Atm. Deposition	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Surface Leaching & Run-Off	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Total	**51.1**	**54.5**	**46.0**	**54.7**	**44.3**	**45.0**	**38.3**	**47.3**	**50.3**

+ Less than 0.05 Tg CO_2 Eq.

Figure 6-3 through Figure 6-6 show regional patterns in N_2O emissions for direct sources and regional patterns of N losses leading to indirect N_2O emissions, respectively, for major crops and grasslands across the United States. Direct N_2O emissions tend to be high in the Corn Belt (Illinois, Iowa, Indiana, Ohio, southern Minnesota, and eastern Nebraska). A large portion of the land in many of these states is covered with highly fertilized corn and with N-fixing soybean cropping. Emissions are also high in North Dakota, Kansas, and Texas, primarily from irrigated cropping and dryland wheat cropping. Emissions are low in many parts of the eastern United States because a small portion of land is cultivated, and also low in many western states where rainfall and access to irrigation water are limited.

Direct emissions (Tg CO_2 Eq./state/year) from grasslands are highest in the central and western United States (Figure 6-4) where a high proportion of the land in many states is used for cattle grazing. Some areas in the Great Lake states, the Northeast, and Southeast have moderate emissions even though emissions from these areas tend to be high on a per unit area basis, because the total amount of grazed land is much lower than states in the central and western United States.

Indirect emissions for croplands and grasslands (Figure 6-5 and Figure 6-6) show patterns similar to direct emissions, because the factors that control direct emissions (N inputs, weather, soil type) also influence indirect emissions. However, there are some exceptions, because the processes that contribute to indirect emissions (NO_3 leaching, N volatilization) do not respond in exactly the same manner as the processes that control direct emissions (nitrification and denitrification). For example, coarse-textured soils facilitate nitrification and moderate direct emissions in grasslands in some southeastern states, but indirect emissions are relatively high in Florida and Georgia grasslands due to high rates of N volatilization and NO_3 leaching in coarse-textured soils.

Figure 6-3: Major Crops, Average Annual Direct N_2O Emissions Estimated Using the DAYCENT Model, 1990–2006 (Tg CO_2 Eq./state/year)

Figure 6-4: Grasslands, Average Annual Direct N_2O Emissions Estimated Using the DAYCENT Model, 1990–2006 (Tg CO_2 Eq./state/year)

Figure 6-5: Major Crops, Average Annual N Losses Leading to Indirect N_2O Emissions Using the DAYCENT Model, 1990–2006 (Gg N/state/year)

Figure 6-6: Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions Using the DAYCENT Model, 1990–2006 (Gg N/state/year)

Methodology

The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) divide the Agricultural Soil Management source category into three components: (1) direct emissions from agricultural soils due to N additions to cropland and grassland mineral soils, planting of legumes on cropland and grassland soils, and drainage and cultivation of organic cropland soils; (2) direct emissions from soils due to the deposition of manure by livestock on PRP grasslands; and (3) indirect emissions from soils and water due to N additions and manure deposition to soils that leads to volatilization, leaching, or runoff of N and subsequent conversion to N_2O. Moreover, the *2006 IPCC Guidelines* (IPCC 2006) recommend reporting total emissions from managed lands, and, therefore, this chapter includes estimates for direct emissions due to asymbiotic fixation of N from the atmosphere[13] and decomposition of soil organic matter and litter.

The methodology used to estimate emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches. A Tier 3, process-based model (DAYCENT) was used to estimate direct emissions from major crops on mineral (i.e., non-organic) soils; as well as most of the direct emissions from grasslands. The Tier 3 approach is more refined for estimating 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 6-1 for further elaboration). The Tier 1 IPCC methodology was used to estimate (1) direct emissions from non-major crops on mineral soils, (2) the portion of the grassland direct emissions that were not estimated with the Tier 3 DAYCENT model, and (3) direct emissions from drainage and cultivation of organic cropland soils. The Tier 1 approach was based on the *2006 IPCC Guidelines* (IPCC 2006). Indirect emissions were also estimated with a combination of DAYCENT and the IPCC Tier 1 method.

Several recommendations from IPCC (2006) have been adopted that are considered improvements over previous IPCC methods, including: (1) estimating the contribution of N from crop residues to indirect soil N_2O emissions, (2) adopting a revised emission factor for direct N_2O emissions, (3) removing double counting of emissions from N-fixing crops associated with the symbiotic and crop residue N input categories, (4) using revised crop residue statistics to compute N inputs to soils based on harvest yield data, and (5) accounting for indirect as well as direct emissions from N made available via mineralization of soil organic matter and litter, in addition to asymbiotic fixation (i.e., computing total emissions from managed land). IPCC (2006) recommends reporting all emissions from managed lands, largely because management affects all processes leading to soil N_2O emissions. Agronomic practices, particularly tillage, have a pervasive impact on soil processes. In past Inventory reports, attempts were made to subtract “background” emissions that would presumably occur if the lands were not managed. However, this approach is likely to be inaccurate for estimating the anthropogenic influence on soil N_2O emissions. Moreover, if background emissions could be measured or modeled based on processes unaffected by anthropogenic activity, they would be a very small portion of the total emissions due to the high inputs of N to agricultural soils from fertilization. Given the recommendation from IPCC (2006) and the influence of management on all processes leading to N_2O emissions from soils in agricultural systems, the decision was made to report total emissions from managed lands for this source category. Annex 3.11 provides more detailed information on the methodologies and data used to calculate N_2O emissions from each component.

[BEGIN BOX]

Box 6-1. Tier 1 vs. Tier 3 Approach for Estimating N_2O Emissions

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[13] 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 Inventory.

The Tier 1 approach (IPCC 2006) is based on multiplying activity data on different N sources (e.g., synthetic fertilizer, manure, N fixation, etc.) by the appropriate default IPCC emission factors to estimate N_2O emissions on a source-by-source basis. The Tier 3 approach developed for this Inventory employs a process-based model (i.e., DAYCENT) that represents the interaction of N inputs and the environmental conditions at specific locations. Consequently, it is necessary to know the amount of N inputs and also the conditions under which the anthropogenic activity is increasing mineral N in a soil profile. 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. The Tier 3 approach is thought to produce more accurate estimates; it accounts for land-use and management impacts and their interaction with environmental factors (i.e., weather patterns and soil characteristics), which may enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more refined activity data (e.g., crop-specific N amendment rates, 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 with measured data in order to demonstrate the adequacy of the method for estimating emissions (IPCC 2006). Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding N cycling. Tier 1 assumes that N added to a system is subject to N_2O emissions only during that year and cannot be stored in soils and contribute to N_2O emission 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 such legacy effects when N is mineralized from soil organic matter and emitted as N_2O during subsequent years.

[END BOX]

Direct N_2O Emissions from Cropland Soils

Major Crop Types on Mineral Cropland Soils

The DAYCENT ecosystem model (Del Grosso et al. 2001, Parton et al. 1998) was used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of major crops—specifically corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton—representing approximately 90 percent of total croplands in the United States. DAYCENT simulated crop growth, soil organic matter decomposition, greenhouse gas fluxes, and key biogeochemical processes affecting N_2O emissions, and the simulations were driven by model input data generated from daily weather records (Thornton et al. 1997, 2000; Thornton and Running 1999), land management surveys (see citations below), and soil physical properties determined from national soil surveys (Soil Survey Staff 2005).

DAYCENT simulations were conducted for each major crop at the county scale in the United States. Simulating N_2O emissions at the county scale was facilitated by soil and weather data that were available for every county with more than 100 acres of agricultural land. However, land management data (e.g., timing of planting, harvesting, intensity of cultivation) were only available at the agricultural region level as defined by the Agricultural Sector Model (McCarl et al. 1993). There are 63 agricultural regions in the contiguous United States, and most states correspond to one region, except for those states with greater heterogeneity in agricultural practices, where there are further subdivisions. While several cropping systems were simulated for each county in an agricultural region with county-level weather and soils data, the model parameters that determined the influence of management activities on soil N_2O emissions (e.g., when crops were planted/harvested) did not differ among the counties in an agricultural region. Consequently, the results will best represent emissions at the regional (i.e., state) and national levels due to the scale of management data.

Nitrous oxide emission estimates from DAYCENT are influenced by N additions, crop type, irrigation, and other factors in aggregate, and, therefore, it is not possible to partition N_2O emissions by anthropogenic activity directly from model outputs (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). 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). To approximate emissions by activity, the amount of mineral N added to the soil for each of these sources was determined and then divided by the total amount of mineral N that was made available in the soil according to the DAYCENT model. The percentages were then multiplied by the total 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. However, this approach allows for further disaggregation by source of N, which is valuable for reporting purposes and is similar to the IPCC (2006) Tier 1 method (which assumes the rate of direct N_2O emissions does not vary by source).

DAYCENT was used to estimate direct N_2O emissions due to mineral N available from: (1) the application of synthetic fertilizers, (2) the application of livestock manure, (3) the retention of crop residues (i.e., leaving residues in the field after harvest instead of burning or collecting residues), and (4) mineralization of soil organic matter and litter, in addition to asymbiotic fixation. This last source is generated internally by the DAYCENT model. For the first three practices, annual increases in soil mineral N due to anthropogenic activity were obtained or derived from the following sources:

- Crop-specific N-fertilization rates: Data sources for fertilization rates include Alexander and Smith (1990), Anonymous (1924), Battaglin and Goolsby (1994), Engle and Makela (1947), ERS (1994, 2003), Fraps and Asbury (1931), Ibach and Adams (1967), Ibach et al. (1964), NFA (1946), NRIAI (2003), Ross and Mehring (1938), Skinner (1931), Smalley et al. (1939), Taylor (1994), USDA (1966, 1957, 1954, 1946). Information on fertilizer use and rates by crop type for different regions of the United States were obtained primarily from the USDA Economic Research Service Cropping Practices Survey (ERS 1997) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004).
- Managed manure production and application to croplands and grasslands: Manure N amendments applied to croplands and grasslands (not including PRP manure) were determined using USDA Manure N Management Databases for 1997 (Kellogg et al. 2000; Edmonds et al. 2003). Amendment data for 1997 were scaled to estimate values for other years based on the availability of managed manure N for application to soils in 1997 relative to other years. The amount of available nitrogen from managed manure for each livestock type was calculated by first determining the population of animals that were on feedlots or otherwise housed in order to collect and manage the manure. Annual animal population data for all livestock types, except horses and goats, were obtained for all years from the U.S. Department of Agriculture-National Agricultural Statistics Service. Population data used for cattle, swine, and sheep were downloaded from the USDA NASS Population Estimates Database (USDA 2007a). Poultry population data were obtained from USDA NASS reports (USDA 1995a, 1995b, 1998a, 1999, 2004a, 2004b, 2006a, 2006b, 2007b, 2007c). Horse population data were obtained from the FAOSTAT database (FAO 2007). Goat population data for 1992, 1997, and 2002 were obtained from the *Census of Agriculture* (USDA 2005); these data were interpolated and extrapolated to derive estimates for the other years. Information regarding the poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service personnel (Lange 2000). Additional population data for different farm size categories for dairy and swine were obtained from the 1992, 1997, and 2002 *Census of Agriculture* (USDA 2005). Once the animal populations for each livestock type and management system were estimated, these populations were multiplied by a typical animal mass constant (USDA 1996, ASAE 1999; NRC 2000, ERG 2003, EPA 1992, Safley 2000) to derive total animal mass for each animal type in each management system. Total Kjeldahl N[14] excreted per year for each livestock type and management system was then calculated using daily rates of N excretion per unit of animal mass (USDA 1996, ASAE 1999). The annual amounts of Kjeldahl N were then summed over all livestock types and management systems to derive estimates of the annual managed manure N produced. Nitrogen available for application was estimated for managed systems based on the total amount of N produced in manure minus N losses and including the addition of N from bedding

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[14] Total Kjeldahl N is a measure of organically bound N and ammonia N in both solid and liquid wastes.

materials. Nitrogen losses include direct nitrous oxide emissions, volatilization of ammonia and NO_x, and runoff and leaching; more information on these losses is available in Annex 3.10, Manure Management. Animal-specific bedding factors were set equal to IPCC default factors (IPCC 2006). The estimated amount of manure available for application was adjusted for the small percent of poultry manure used for cattle feed between 1990 and 2002 (Carpenter 1992, Carpenter and Starkey 2007). The remaining manure N that was not applied to major crops and grassland was assumed to be applied to non-major crop types. Frequency and rates of manure application to cropland during the inventory period were estimated from data compiled by the USDA Natural Resources Conservation Service for 1997 (Edmonds et al. 2003), with adjustments based on managed manure N excretion in other years of the inventory.

- Retention of crop residue, N mineralization from soil organic matter, and asymbiotic N fixation from the atmosphere: The IPCC approach considers this information as separate activity data. However, they are not treated as separate activity data in DAYCENT simulations because residue production, N fixation, mineralization of N from soil organic matter, and asymbiotic fixation are internally generated by the model. In other words, DAYCENT accounts for the influence of N fixation, mineralization of N from soil organic matter, and retention of crop residue on N_2O emissions, but these are not model inputs. The total input of N from these sources is determined during the model simulations.
- Historical and modern crop rotation and management information (e.g., timing and type of cultivation, timing of planting/harvest, etc.): These activity data were derived from Hurd (1930, 1929), Latta (1938), Iowa State College Staff Members (1946), Bogue (1963), Hurt (1994), USDA (2004f), USDA (2000b) as extracted by Eve (2001) and revised by Ogle (2002), CTIC (1998), Piper et al. (1924), Hardies and Hume (1927), Holmes (1902, 1929), Spillman (1902, 1905, 1907, 1908), Chilcott (1910), Smith (1911), Kezer (ca. 1917), Hargreaves (1993), ERS (2002), Warren (1911), Langston et al. (1922), Russell et al. (1922), Elliott and Tapp (1928), Elliott (1933), Ellsworth (1929), Garey (1929), Hodges et al. (1930), Bonnen and Elliott (1931), Brenner et al. (2002, 2001), and Smith et al. (2002).

DAYCENT simulations produced per-area estimates of N_2O emissions ($g\ N_2O\text{-}N\ m^{-2}$) for major crops, which were multiplied by the cropland area data to obtain county-scale emission estimates. Cropland area data were from NASS (USDA 2006g). The emission estimates by reported crop areas in the county were scaled to the regions, and the national estimate was calculated by summing results across all regions. DAYCENT is sensitive to actual interannual variability in weather patterns and other controlling variables, so emissions associated with individual activities vary through time even if the management practices remain the same (e.g., if N fertilization remains the same for two years). In contrast, Tier 1 methods do not capture this variability and rather have a linear, monotonic response that depends solely on management practices. DAYCENT's ability to capture these interactions between management and environmental conditions produces more accurate estimates of N_2O emissions than the Tier 1 method.

Non-Major Crop Types on Mineral Cropland Soils

The Tier 1 methodology (IPCC 2006) was used to estimate direct N_2O emissions for mineral cropland soils that are managed for production of non-major crop types, including barley, oats, tobacco, sugarcane, sugar beets, sunflowers, millet, rice, peanuts, and other crops which were not included in the DAYCENT simulations. Estimates of direct N_2O emissions from N applications to non-major crop types were based on mineral soil N that was made available from the following practices: (1) the application of synthetic commercial fertilizers, (2) application of other commercial organic fertilizers;[15] and (3) the retention of above- and below-ground crop residues. Non-manure organic amendments were not included in the DAYCENT simulations because county-level data were not available and this source of fertilizer is a very small portion of total organic amendments. Consequently, non-manure organic amendments, as well as manure amendments not included in the DAYCENT simulations, were

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[15] Other commercial organic fertilizers include manure applied to non-major crops, dried blood, dried manure, tankage, compost, other, but excludes sewage sludge that is used as commercial fertilizer.

included in the Tier 1 analysis. The following sources were used to derive activity data.

- A process-of-elimination approach was used to estimate N fertilizer additions for non-major crops, because little information exists on their fertilizer application rates. The total amount of fertilizer used on farms has been estimated by the USGS from sales records (Ruddy et al. 2006), and these data were aggregated to obtain state-level N additions to farms. After subtracting the portion of fertilizer applied to major crops and grasslands (see sections on Major Crops and Grasslands for information on data sources), the remainder of the total fertilizer used on farms was assumed to be applied on non-major crops.

- A process-of-elimination approach was used to estimate manure N additions for non-major crops, because little information exists on application rates for these crops. The amount of manure N applied to major crops and grasslands was subtracted from total manure N available for land application (see sections on Major Crops and Grasslands for information on data sources), and this difference was assumed to be applied to non-major crops.

- Non-manure organic fertilizer additions were based on organic fertilizer consumption statistics, which were converted to units of N using average organic fertilizer N content (TVA 1991, 1992a, 1993, 1994; AAPFCO 1995 through 2000a, 2000b, 2002 through 2007).

- Crop residue N was derived by combining amounts of above- and below-ground biomass, which were determined based on crop production yield statistics (USDA 1994a, 1998b, 2003, 2005i, 2006b, 2007), dry matter fractions (IPCC 2006), linear equations to estimate above-ground biomass given dry matter crop yields (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 was multiplied by the IPCC (2006) default emission factor (IPCC 2006) to derive an estimate of direct N_2O emissions from non-major crop types.

Drainage and Cultivation of Organic Cropland Soils

Tier 1 methods were used to estimate direct N_2O emissions due to drainage and cultivation of organic soils at a state scale. State-scale estimates of the total area of drained and cultivated organic soils were obtained from the Natural Resources Inventory (NRI) (USDA 2000b, as extracted by Eve 2001 and amended by Ogle 2002), using temperature and precipitation data from Daly et al. (1994, 1998) to subdivide areas into temperate and tropical climates. Data were available for 1982, 1992 and 1997, which were linearly interpolated and extrapolated to estimate areas for the other years in the inventory time series. To estimate annual emissions, the total temperate area was multiplied by the IPCC default emission factor for temperate regions, and the total sub-tropical area was multiplied by the average of the IPCC default emission factors for temperate and 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 the IPCC (2006) guidelines were combined to estimate emissions from grasslands. Grasslands include pastures and rangelands used for grass forage production, where the primary use is livestock grazing. Rangelands are typically extensive areas of native grasslands that are not intensively managed, while pastures are often seeded grasslands, possibly following tree removal, which may or may not be improved with practices such as irrigation and interseeding legumes.

DAYCENT was used to simulate county-scale N_2O emissions from grasslands resulting from manure deposited by livestock directly onto the pasture (i.e., PRP manure, which is simulated internally within the model), N fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure), and synthetic fertilizer application. The simulations used the same weather, soil, and synthetic N fertilizer data as discussed under the section for Major Crop Types on Mineral Cropland Soils. Managed manure N amendments to grasslands were 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 Annex 3.11. Other N inputs were simulated within the DAYCENT framework, including N input from mineralization due to decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere and atmospheric N deposition.

DAYCENT simulations produced per-area estimates of N_2O emissions (g N_2O-N m^{-2}) for pasture and rangelands, which were multiplied by the reported pasture and rangeland areas in the county. Grassland area data were obtained from the NRI (USDA 2000b). The 1997 NRI area data for pastures and rangeland were aggregated to the county level to estimate the grassland areas for 1995 to 2006, and the 1992 NRI pasture and rangeland data were aggregated to the county level to estimate areas from 1990 to 1994. The county estimates were scaled to the 63 agricultural regions, and the national estimate was calculated by summing results across all regions.

Manure N deposition from grazing animals is modeled internally within DAYCENT. Comparisons with estimates of total manure deposited on PRP (see Annex 3.11) showed that DAYCENT accounted for approximately 73 percent of total PRP manure. The remainder of the PRP manure N excretions were assumed to be excreted on federal grasslands (i.e., DAYCENT simulations were only conducted for privately-owned grasslands), and the N_2O emissions were estimated using the Tier 1 method with IPCC default emission factors (IPCC 2006).

Sewage sludge was 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 was estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007). Sewage sludge data on soil amendments in agricultural lands were only available at the national scale, and it was not possible to associate application with specific soil conditions and weather at the county scale. Consequently, emissions from sewage sludge were also estimated using the Tier 1 method with IPCC default emission factors (IPCC 2006).

Total Direct N_2O Emissions from Cropland and Grassland Soils

Emission estimates from DAYCENT and the IPCC method were summed to provide total national emissions for grasslands in the United States. Annual direct emissions from major and non-major crops on mineral cropland soils, from drainage and cultivation of organic cropland soils, and from grassland soils were summed to obtain total direct N_2O emissions from agricultural soil management (see Table 6-13 and Table 6-14).

Indirect N_2O Emissions from Managed Soils of all Land-Use Types

This section describes the methods used for estimating indirect soil N_2O emissions from all land-use types (i.e., croplands, grasslands, forest lands, and settlements). 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 or organic amendments (e.g., manure, sewage sludge) and deposition of PRP manure N made available from mineralization of soil organic matter and asymbiotic fixation also contributes to volatilized N emissions. Through atmospheric deposition, volatilized N can be returned to soils, and a portion is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil N (primarily in the form of nitrate [NO_3^-]) that was made available through anthropogenic activity on managed lands, mineralization of soil organic matter, asymbiotic fixation, and atmospheric deposition. The nitrate is subject to denitrification in water bodies, which leads to additional 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, grasslands, forest lands, and settlements.

Indirect N_2O Emissions from Atmospheric Deposition of Volatilized N from Managed Soils

Similarly to the direct emissions calculation, several approaches were combined to estimate the amount of applied N that was transported from croplands, grasslands, forest lands, and settlements, through volatilization. DAYCENT was used to simulate the amount of N transported from land areas whose direct emissions were simulated with DAYCENT (i.e., major croplands and most grasslands), while the Tier 1 method was used for areas that were not simulated with DAYCENT (i.e., non-major croplands, sewage sludge application on grasslands, PRP manure N excretion on federal grasslands) (IPCC 2006). The IPCC (2006) default emission factor was used to estimate indirect N_2O emissions associated with the amount of volatilized N (Table 6-16).

Indirect N_2O from Leaching/Runoff

As in the calculations of indirect emissions from volatilized N, several approaches were combined to estimate the amount of applied N that was transported from croplands, grasslands, forest lands, and settlements through leaching and surface runoff into water bodies. DAYCENT was used to simulate the amount of N transported from major cropland types and most grasslands. N transport from all other areas (i.e., non-major croplands, sewage sludge amendments on grasslands, PRP manure N excreted on federal grasslands, in addition to N inputs on settlements and forest lands) was estimated using the IPCC (2006) default factors for the amount of N subject to leaching and runoff from mineral fertilizer, manure, above- and below-ground crop residues, soil organic matter decomposition and asymbiotic fixation. The IPCC (2006) default emission factor was used to estimate indirect N_2O emissions associated with N losses through leaching and runoff (Table 6-16).

Uncertainty

Uncertainty was estimated differently for each of the following four components of N_2O emissions from agricultural soil management: (1) direct emissions calculated by DAYCENT, (2) the components of indirect emissions (N volatilized and leached or runoff) calculated by DAYCENT (3) direct emissions not calculated by DAYCENT, and (4) indirect emissions not calculated by DAYCENT.

Uncertainties from the Tier 1 and Tier 3 estimates were combined using simple error propagation (IPCC 2006), and the results are summarized in Table 6-17. Agricultural direct soil N_2O emissions in 2006 were estimated to be between 191.7 and 238.9 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 11 percent below and 11 percent above the 2006 emission estimate of 214.7 Tg CO_2 Eq. The indirect soil N_2O emissions in 2006 were estimated to range from 28.0 to 113.2 Tg CO_2 Eq. at a 95 percent confidence level, indicating an uncertainty of 44 percent below and 125 percent above the 2006 emission estimate of 50.3 Tg CO_2 Eq.

Table 6-17: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2006 (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2006 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct Soil N_2O Emissions	N_2O	214.7	191.7	238.9	-11%	11%
Indirect Soil N_2O Emissions	N_2O	50.3	28.0	113.2	-44%	125%

Note: Due to lack of data, uncertainties in areas for major crops, managed manure N production and PRP manure N production are currently treated as certain.

QA/QC and Verification

For quality control, DAYCENT results for N_2O emissions and NO_3 leaching were compared with field data representing various cropped/grazed systems, soils types, and climate patterns (Del Grosso et al. 2005). N_2O measurement data were available for seven sites in the United States and one in Canada, representing 25 different combinations of fertilizer treatments and cultivation practices. DAYCENT estimates of N_2O emissions were closer to measured values at all sites except for Colorado irrigated corn (Figure 6-7). In general, IPCC Tier 1 methodology tends to over-estimate when observed values are low and under-estimate when observed values are high, while DAYCENT estimates are less biased. This is not surprising because DAYCENT accounts for site-level factors (weather, soil type) that influence N_2O emissions. NO_3 leaching data were available for three sites in the United States representing nine different combinations of fertilizer amendments. Linear regressions of simulated vs. observed emission and leaching data yielded correlation coefficients of 0.73 and 0.96 for annual N_2O emissions and NO_3 leaching, respectively. This comparison demonstrates that DAYCENT provides relatively high predictive capability for N_2O emissions and NO_3 leaching, and is also an improvement over the IPCC Tier 1 method (see additional information in Annex 3.11).

Figure 6-7: Comparison of measured emissions at field sites with modeled emissions using the DAYCENT simulation model

Spreadsheets containing input data and PDFs required for DAYCENT simulations of major croplands and grasslands and unit conversion factors were checked, as well as the program scripts that were used to run the Monte Carlo Analysis. An error was identified in direct N_2O estimates from major crops. The units were not converted correctly with the transfer of data between the DAYCENT model and the structural uncertainty estimator, leading to an over-estimation of direct N_2O emissions from major crops. The error has been resolved and corrected. Spreadsheets containing input data and emission factors required for the Tier 1 approach used for non-major crops and grasslands not simulated by DAYCENT were checked and no errors were found.

Recalculations Discussion

Revisions in the calculations for the Agricultural Soil N_2O Inventory included (1) using state-level N data for on-farm use to estimate synthetic N fertilizer application on non-major crops, (2) including uncertainty in DAYCENT outputs of N volatilization and N leaching/runoff in the calculation of uncertainty for indirect emissions, (3) using a default uncertainty of ±50 percent for Tier 1 uncertainties that were addressed in previous inventory, including crop yields and organic fertilizers, (4) assuming that manure N available for land application not accounted for by the DAYCENT simulations was applied to non-major crop types, (5) revising DAYCENT parameterization for sorghum, and (6) correcting an error in the empirically-based uncertainty estimator.

In the past Inventory, N fertilizer application to minor crops was based on total N available for application after subtracting the amount applied to major crops, settlements, and forest lands. In the latest Inventory, a USGS study (Ruddy et al. 2006) provides data from sales records about the on-farm use of fertilizers, which were used to estimate the amount of N applied to non-major crops after subtracting the amount estimated for major crops from the DAYCENT simulations. Previously it was assumed that 90 percent of the synthetic N fertilizer used in the United States was applied to agricultural soils whereas the on-farm-use data raise the amount to 97 percent. In addition, after accounting for the amount applied to major crops and grasslands in the DAYCENT simulations, the latest Inventory assumes that all manure N available for agricultural land application is applied to non-major crops. Due to these changes, direct N_2O emissions from non-major crops are approximately 83 percent higher, on average, compared to the previous Inventory. However, direct soil N_2O emissions from major crops reported in the 1990-2005 Inventory were over-estimated by approximately a factor of 2 as a result of a unit conversion error in the empirically-based uncertainty estimator. Because major crops are the greatest source, total emission estimates are approximately 27.5 percent lower, on average, than reported in the 1990-2005 Inventory. The revised parameterization for sorghum had a minor influence on the emission estimates.

Planned Improvements

Three major improvements are planned for the Agricultural Soil Management sector. The first improvement is to incorporate more land-use survey data from the NRI (USDA 2000b) into the DAYCENT simulation analysis, beyond the area estimates for rangeland and pasture that are currently used to estimate emissions from grasslands. NRI has a record of land-use activities since 1982 for all U.S. agricultural land, which is estimated at about 386 Mha. NASS is used as the basis for land-use records in the current Inventory, and there are three major disadvantages to this cropping survey. First, most crops are grown in rotation with other crops (e.g., corn-soybean), but NASS data provide no information regarding rotation histories. In contrast, NRI is designed to track rotation histories, which is important because emissions from any particular year can be influenced by the crop that was grown the previous year. Second, NASS does not conduct a complete survey of cropland area each year, leading to gaps in the land base. NRI does provide a complete history of cropland areas for four out of every five years from 1979 to 1997, and then every year after 1998. Third, the current inventory based on NASS does not quantify the influence of land-use change on emissions, which can be addressed using the NRI survey records. NRI also provides additional information on pasture land management that can be incorporated into the analysis (particularly the use of irrigation). Using NRI data will also make the Agricultural Soil N_2O methods more consistent with the methods used to estimate C stock changes for agricultural soils. However, the structure of model input files that contain land management data will need to be extensively revised to facilitate use of NRI data.

The second planned improvement is to further refine the uncertainty analysis. New studies are being completed and published evaluating agricultural management impacts on soil N_2O emissions, and these studies can be incorporated into the empirical analysis, leading to a more robust assessment of structural uncertainty in DAYCENT. Moreover, structural uncertainty is currently only evaluated for emission estimates in croplands, but structural uncertainty is likely to be significant for grasslands as well, and it is anticipated that the analysis of structural uncertainty could be expanded in the near future to include grasslands. In addition, the Monte Carlo analysis will be expanded to address uncertainties in activity data related to crop- and grassland areas, as well as irrigation and tillage histories. Currently, the land-area statistics are treated as certain because the NASS data do not include a measure of uncertainty. Incorporating land-use survey data from the NRI will facilitate the assessment of uncertainties in agricultural activity data.

The third planned improvement is to further evaluate the application of manure to major and minor crops, as well as N recovery and losses from manure management systems and field application. Manure amendments are a key source of N leading to N_2O emissions so any further improvements in this estimation will reduce uncertainties in the emission estimates. We will also evaluate potential for change in application rates over time due to regulation of confined animal feeding operations; this will improve the emission estimates and reduce uncertainty. Additional improvements are minor but will lead to more accurate estimates, including updating DAYMET weather for more recent years.

6.5. Field Burning of Agricultural Residues (IPCC Source Category 4F)

Farming activities produce large quantities of agricultural crop residues, and farmers use or dispose of these residues in a variety of ways. For example, agricultural residues can be left on or plowed into the field; composted and then applied to soils; landfilled; or burned in the field. Alternatively, they can be collected and used as fuel, animal bedding material, supplemental animal feed, or construction material. Field burning of crop residues is not considered a net source of CO_2, because the carbon released to the atmosphere as CO_2 during burning is assumed to be reabsorbed during the next growing season. Crop residue burning is, however, a net source of CH_4, N_2O, CO, and NO_x, which are released during combustion.

Field burning is not a common method of agricultural residue disposal in the United States. The primary crop types whose residues are typically burned in the United States are wheat, rice, sugarcane, corn, barley, soybeans, and peanuts. Less than 5 percent of the residue for each of these crops is burned each year, except for rice.[16] Annual emissions from this source over the period 1990 to 2006 have remained relatively constant, averaging approximately 0.8 Tg CO_2 Eq. (36 Gg) of CH_4 and 0.4 Tg CO_2 Eq. (1 Gg) of N_2O (see Table 6-18 and Table 6-19).

Table 6-18: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq.)

Gas/Crop Type	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
CH_4	**0.7**	**0.7**	**0.8**	**0.8**	**0.7**	**0.8**	**0.9**	**0.9**	**0.8**
Wheat	0.1	0.1	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	0.1	0.1	0.1
Sugarcane	+	+	+	+	+	+	+	+	+
Corn	0.3	0.3	0.4	0.3	0.3	0.4	0.4	0.4	0.4
Barley	+	+	+	+	+	+	+	+	+
Soybeans	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Peanuts	+	+	+	+	+	+	+	+	+
N_2O	**0.4**	**0.4**	**0.5**	**0.5**	**0.4**	**0.4**	**0.5**	**0.5**	**0.5**
Wheat	+	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+	+

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[16] The fraction of rice straw burned each year is significantly higher than that for other crops (see "Methodology" discussion below).

Sugarcane	+	+	+	+	+	+	+	+	+
Corn	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Barley	+	+	+	+	+	+	+	+	+
Soybeans	0.2	0.2	0.3	0.3	0.3	0.2	0.3	0.3	0.3
Peanuts	+	+	+	+	+	+	+	+	+
Total	**1.1**	**1.0**	**1.3**	**1.2**	**1.1**	**1.2**	**1.4**	**1.4**	**1.3**

+ Less than 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-19: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (Gg)

Gas/Crop Type	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
CH_4	**33**	**32**	**38**	**37**	**34**	**38**	**42**	**41**	**39**
Wheat	7	5	5	5	4	6	5	5	4
Rice	4	4	4	4	3	5	4	5	4
Sugarcane	1	1	1	1	1	1	1	1	1
Corn	13	13	17	16	15	17	20	19	18
Barley	1	1	1	+	+	+	+	+	+
Soybeans	7	8	10	11	10	9	11	11	12
Peanuts	+	+	+	+	+	+	+	+	+
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**2**	**2**
Wheat	+	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+	+	+
Soybeans	1	1	1	1	1	1	1	1	1
Peanuts	+	+	+	+	+	+	+	+	+
CO	**691**	**663**	**792**	**774**	**709**	**800**	**879**	**860**	**825**
NOx	**28**	**29**	**35**	**35**	**33**	**34**	**39**	**39**	**38**

+ Less than 0.5 Gg

Note: Totals may not sum due to independent rounding.

Methodology

The Tier 2 methodology used for estimating greenhouse gas emissions from field burning of agricultural residues in the United States is consistent with IPCC (2006) (for more details, see Box 6-2). In order to estimate the amounts of carbon (C) and nitrogen (N) released during burning, the following equation was used:[17]

$$CH_4 \text{ and } N_2O \text{ Emissions from Field Burning of Agricultural Residues} = (\text{Fraction of Residues Burned In Situ}) \times (\text{Mass of Fuel Available for Combustion}) \times (\text{Burning Efficiency}) \times (\text{Emission Factor}) \times 10^{-3}$$

Where:

Burning Efficiency = The proportion of prefire fuel biomass consumed

To calculate the mass of fuel available for combustion, the following equation was used:

$$\text{Mass of Fuel Available for Combustion} = (\text{Annual Crop Production}) \times (\text{Residue/Crop Product Ratio}) \times (\text{Dry Matter Content of the Residue})$$

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[17] As is explained later in this section, the fraction of rice residues burned varies among states, so these equations were applied at the state level for rice. These equations were applied at the national level for all other crop types.

To calculate the emission factor, the following equation was used:

$$\text{Emission Factor} = (\text{Combustion Efficiency}) \times (\text{C or N Content of the Residue}) \times (\text{Emissions Ratio}) \times (\text{Conversion Factor}) \times 1{,}000$$

Where:

Combustion Efficiency = The proportion of CH_4 or N_2O released with respect to the total amount of C or N available in the burned material, respectively

Emissions Ratio = g CH_4-C/g C released or g N_2O-N/g N released

Conversion Factor = Molecular weight ratio of CH_4:C or N_2O:N

The types of crop residues burned in the United States were determined from various state-level greenhouse gas emission inventories (ILENR 1993, Oregon Department of Energy 1995, Wisconsin Department of Natural Resources 1993) and publications on agricultural burning in the United States (Jenkins et al. 1992, Turn et al. 1997, EPA 1992).

[BEGIN BOX]

Box 6-2: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

This Inventory calculates emissions from Burning of Agricultural Residues using a Tier 2 methodology that is based on IPCC/UNEP/OECD/IEA (1997) and incorporates crop- and country-specific emission factors and variables. The equation used in this Inventory varies slightly in form from the one presented in the IPCC (2006) guidelines, but both equations rely on the same underlying variables. The IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues. IPCC (2006) default factors are provided only for four crops (wheat, corn, rice, and sugarcane), while this Inventory analyzes emissions from seven crops. A comparison of the methods and factors used in (1) this year's Inventory and (2) the default IPCC (2006) approach was undertaken to determine the magnitude of the difference in overall estimates resulting from the two approaches. Since the default IPCC (2006) approach calls for area burned data that are currently unavailable for the United States, estimates of area burned were developed using USDA data on area harvested for each crop multiplied by the estimated fraction of residue burned for that crop (see Table 6-22).

The IPCC (2006) default run resulted in 20 percent higher emissions of CH_4 and 36 percent higher emissions of N_2O than the current estimates in this inventory. It was determined that it is reasonable to maintain the current methodology, since the IPCC (2006) defaults are only available for four crops and are worldwide average estimates, while current Inventory estimates are based on U.S.-specific, crop-specific, published data.

[END BOX]

Crop production data for all crops except rice in Florida and Oklahoma were taken from the USDA's *Field Crops, Final Estimates 1987–1992, 1992–1997, 1997–2002* (USDA 1994, 1998, 2003), and *Crop Production Summary* (USDA 2005, 2006, 2007). Rice production data for Florida and Oklahoma, which are not collected by USDA, were estimated separately. Average primary and ratoon crop yields for Florida (Schueneman and Deren 2002) were applied to Florida acreages (Schueneman 1999b, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007a), and crop yields for Arkansas (USDA 1994, 1998, 2003, 2005, 2006) were applied to Oklahoma acreages[18] (Lee 2003 through 2006). The production data for the crop types whose residues are burned are

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[18] Rice production yield data are not available for Oklahoma, so the Arkansas values are used as a proxy.

presented in Table 6-20.

The percentage of crop residue burned was assumed to be 3 percent for all crops in all years, except rice, based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996). Estimates of the percentage of rice residue burned were derived from state-level estimates of the percentage of rice area burned each year, which were multiplied by state-level annual rice production statistics. The annual percentages of rice area burned in each state were obtained from agricultural extension agents in each state and reports of the California Air Resources Board (Anonymous 2006; Bollich 2000; California Air Resources Board 1999, 2001; Cantens 2005; Deren 2002; Fife 1999; Guethle 2007; Klosterboer 1999a, 1999b, 2000 through 2003; Lancero 2006, 2007; Lee 2005 through 2007; Lindberg 2002 through 2005; Linscombe 1999a, 1999b, 2001 through 2007; Najita 2000, 2001; Sacramento Valley Basinwide Air Pollution Control Council 2005, 2007; Schueneman 1999a, 1999b, 2001; Stansel 2004, 2005; Street 2001 through 2003; Texas Agricultural Experiment Station 2006, 2007; Walker 2004 through 2007; Wilson 2003 through 2007) (see Table 6-21). The estimates provided for Florida remained constant over the entire 1990 through 2006 period, while the estimates for all other states varied over the time series, except for Missouri, which remained constant through 2005 and dropped in 2006. For California, the annual percentages of rice area burned in the Sacramento Valley are assumed to be representative of burning in the entire state, because the Sacramento Valley accounts for over 95 percent of the rice acreage in California (Fife 1999). These values generally declined between 1990 and 2006 because of a legislated reduction in rice straw burning (Lindberg 2002), although there was a slight increase from 2004 to 2005 (see Table 6-21).

All residue/crop product mass ratios except sugarcane were obtained from Strehler and Stützle (1987). The datum for sugarcane is from University of California (1977). Residue dry matter contents for all crops except soybeans and peanuts were obtained from Turn et al. (1997). Soybean dry matter content was obtained from Strehler and Stützle (1987). Peanut dry matter content was obtained through personal communications with Jen Ketzis (1999), who accessed Cornell University's Department of Animal Science's computer model, Cornell Net Carbohydrate and Protein System. The residue carbon contents and nitrogen contents for all crops except soybeans and peanuts are from Turn et al. (1997). The residue C content for soybeans and peanuts is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The N content of soybeans is from Barnard and Kristoferson (1985). The N content of peanuts is from Ketzis (1999). These data are listed in Table 6-22. The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent, for all crop types (EPA 1994). Emission ratios for all gases (see Table 6-23) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 6-20: Agricultural Crop Production (Gg of Product)

Crop	1990	1995	2000	2001	2002	2003	2004	2005	2006
Wheat	74,292	59,404	60,641	53,001	43,705	63,814	58,738	57,280	49,316
Rice	7,114	7,947	8,705	9,794	9,601	9,084	10,565	10,150	8,813
Sugarcane	25,525	27,922	32,762	31,377	32,253	30,715	26,320	24,137	26,752
Corn*	201,534	187,970	251,854	241,377	227,767	256,278	299,914	282,311	267,598
Barley	9,192	7,824	6,919	5,407	4,940	6,059	6,091	4,613	3,920
Soybeans	52,416	59,174	75,055	78,671	75,010	66,778	85,013	83,368	86,770
Peanuts	1,635	1,570	1,481	1,940	1,506	1,880	1,945	2,209	1,576

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

Table 6-21: Percent of Rice Area Burned by State

State	1990	1995	2000	2001	2002	2003	2004	2005	2006
Arkansas	13%	13%	13%	13%	16%	22%	17%	22%	27%
California	75%	59%	27%	23%	13%	14%	11%	16%	10%
Florida[a]	0%	0%	0%	0%	0%	0%	0%	0%	0%
Louisiana	6%	6%	5%	4%	3%	3%	3%	3%	5%
Mississippi	10%	10%	40%	40%	8%	65%	23%	23%	25%
Missouri	18%	18%	18%	18%	18%	18%	18%	18%	3%
Oklahoma	90%	90%	90%	90%	90%	100%	88%	94%	0%

Texas	1%	1%	0%	0%	0%	0%	0%	0%	0%

[a]Although rice is cultivated in Florida, crop residue burning is illegal.

Table 6-22: Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue/Crop Ratio	Fraction of Residue Burned	Dry Matter Fraction	C Fraction	N Fraction	Burning Efficiency	Combustion Efficiency
Wheat	1.3	0.03	0.93	0.4428	0.0062	0.93	0.88
Rice	1.4	Variable	0.91	0.3806	0.0072	0.93	0.88
Sugarcane	0.8	0.03	0.62	0.4235	0.0040	0.93	0.88
Corn	1.0	0.03	0.91	0.4478	0.0058	0.93	0.88
Barley	1.2	0.03	0.93	0.4485	0.0077	0.93	0.88
Soybeans	2.1	0.03	0.87	0.4500	0.0230	0.93	0.88
Peanuts	1.0	0.03	0.86	0.4500	0.0106	0.93	0.88

Table 6-23: Greenhouse Gas Emission Ratios

Gas	Emission Ratio
CH_4[a]	0.005
CO[a]	0.060
N_2O[b]	0.007
NO_x[b]	0.121

[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

A significant source of uncertainty in the calculation of non-CO_2 emissions from field burning of agricultural residues is in the estimates of the fraction of residue of each crop type burned each year. Data on the fraction burned, as well as the gross amount of residue burned each year, are not collected at either the national or state level. In addition, burning practices are highly variable among crops and among states. The fractions of residue burned used in these calculations were based upon information collected by state agencies and in published literature. Based on expert judgment, uncertainty in the fraction of crop residue burned ranged from zero to 100 percent, depending on the state and crop type.

The results of the Tier 2 Monte Carlo uncertainty analysis are summarized in Table 6-24. CH_4 emissions from field burning of agricultural residues in 2006 were estimated to be between 0.3 and 1.5 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 65 percent below and 79 percent above the 2006 emission estimate of 0.8 Tg CO_2 Eq. Also at the 95 percent confidence level, N_2O emissions were estimated to be between 0.2 and 0.9 Tg CO_2 Eq. (or approximately 64 percent below and 73 percent above the 2006 emission estimate of 0.5 Tg CO_2 Eq.).

Table 6-24: Tier 2 Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH_4	0.8	0.3	1.5	-65%	79%
Field Burning of Agricultural Residues	N_2O	0.5	0.2	0.9	-64%	73%

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

QA/QC and Verification

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

Recalculations Discussion

The crop production data for 2005 and 2006 were updated using data from USDA (2007). This change resulted in an increase in the CH_4 emission estimate for 2005 of 0.2 percent, and a decrease in the N_2O emission estimate for 2005 of 0.1 percent. In addition, a more robust uncertainty analysis was run this year, taking into account shared variables between the Field Burning of Agricultural Residues and Rice Cultivation sources and correcting errors that were identified in the uncertainty analysis undertaken for the previous inventory. These changes resulted in a greater uncertainty range surrounding the 2006 estimates than those presented in the previous inventory for the 2005 emission estimates.

Planned Improvements

The estimated 3 percent of crop residue burned for all crops, except rice, is based on data gathered from several state greenhouse gas inventories. This fraction is the most statistically significant input to the emissions equation, and an important area for future improvement. More crop- and state-specific information on the fraction burned will be investigated by literature review and/or by contacting state departments of agriculture.

Preliminary research on agricultural burning in the United States indicates that residues from several additional crop types (e.g., grass for seed, blueberries, and fruit and nut trees) are burned. Whether sufficient information exists for inclusion of these additional crop types in future inventories is being investigated. The extent of recent state crop-burning regulations is also being investigated.

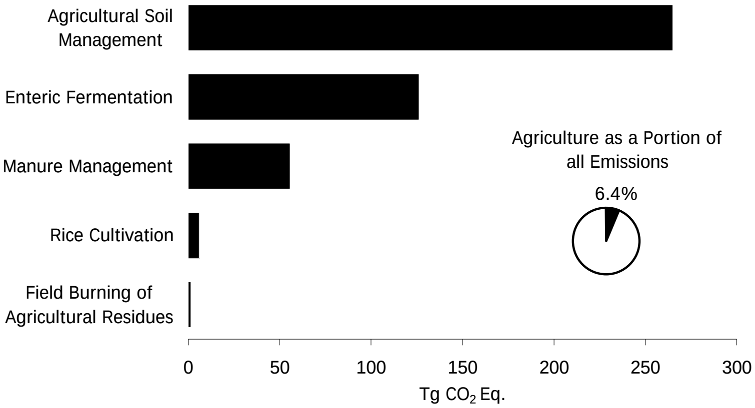
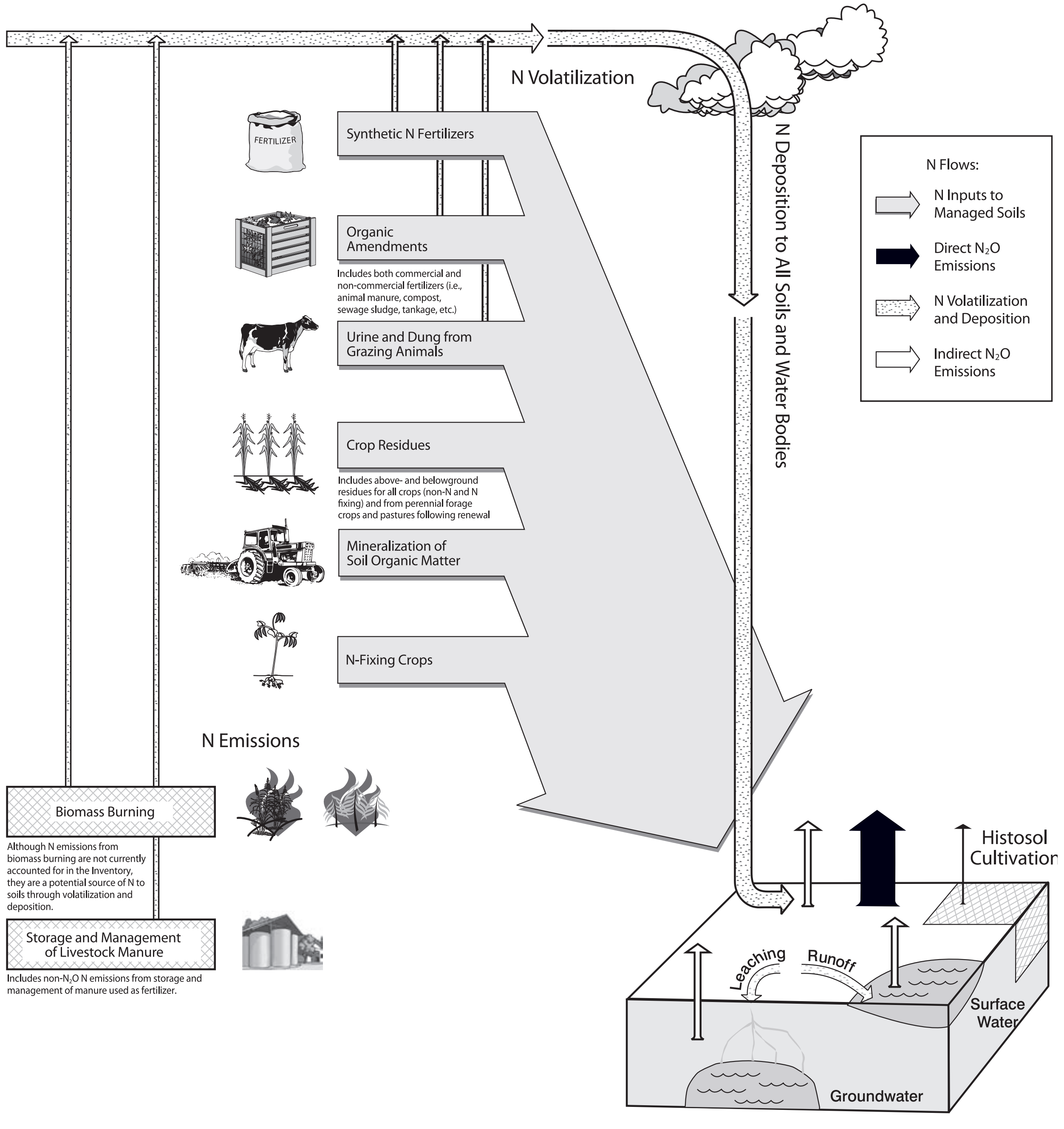


Figure 6-1: 2006 Agriculture Chapter GHG Sources

Figure 6-2

Agricultural Sources and Pathways of N that Result in N_2O Emissions



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from soils in the United States. Sources of nitrogen applied to, or deposited on, soils are represented with arrows on the left-hand side of the graphic. Emission pathways are also shown with arrows. On the lower right-hand side is a cut-away view of a representative section of a managed soil; histosol cultivation is represented here.

Figure 6-3

Major Crops, Average Annual Direct N_2O Emissions Estimated Using the DAYCENT Model, 1990–2006 (Tg CO_2 Eq./state/year)

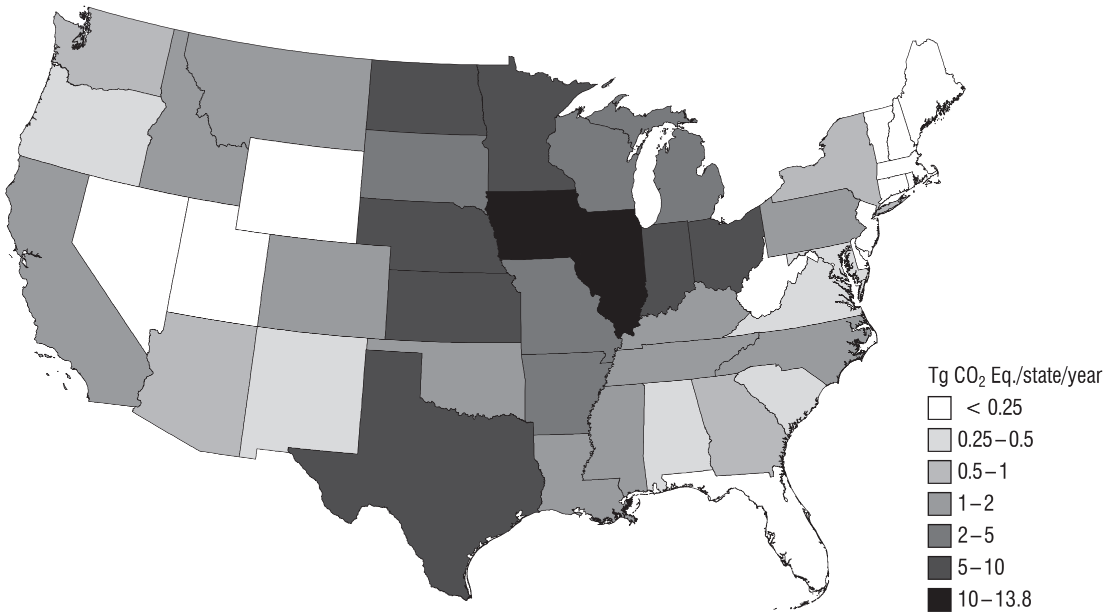


Figure 6-4

Grasslands, Average Annual Direct N_2O Emissions Estimated Estimated Using the DAYCENT Model, 1990–2006 (Tg CO_2 Eq./state/year)

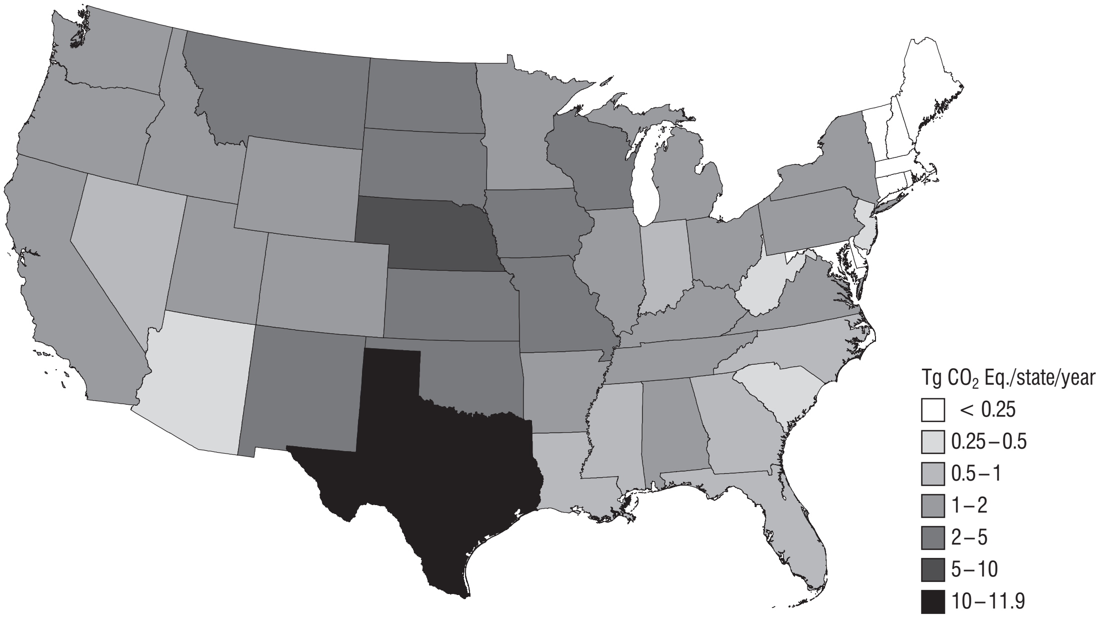


Figure 6-5

Major Crops, Average Annual N Losses Leading to Indirect N_2O Emissions Using the DAYCENT Model, 1990–2006 (Gg N/state/year)

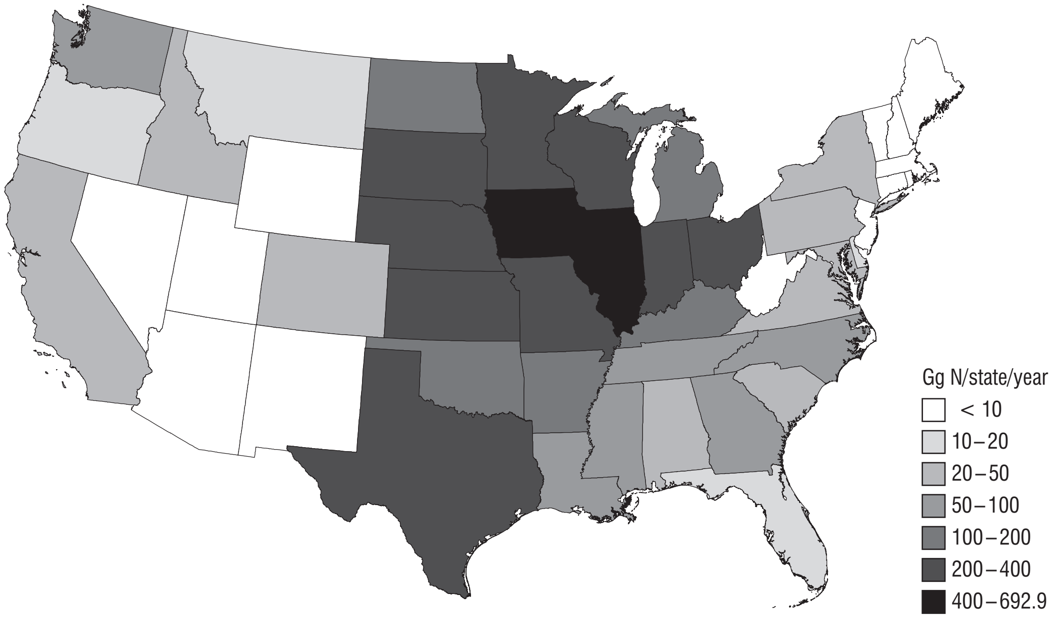


Figure 6-6

Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions Using the DAYCENT Model, 1990–2006 (Gg N/state/year)

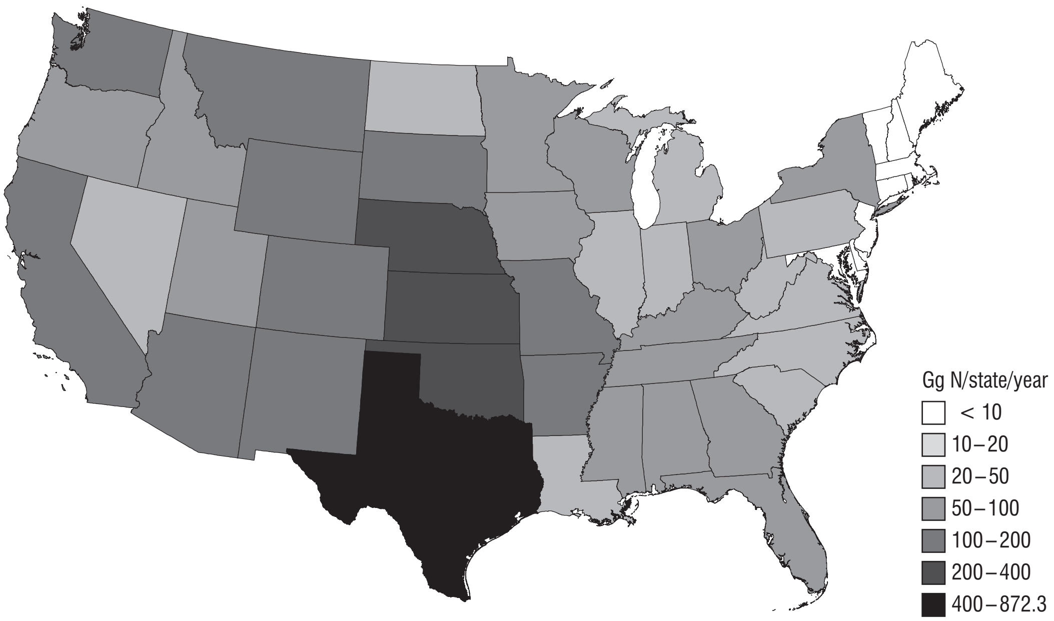


Figure 6-7

Comparison of measured emissions at field sites with modeled emissions using the DAYCENT simulation model