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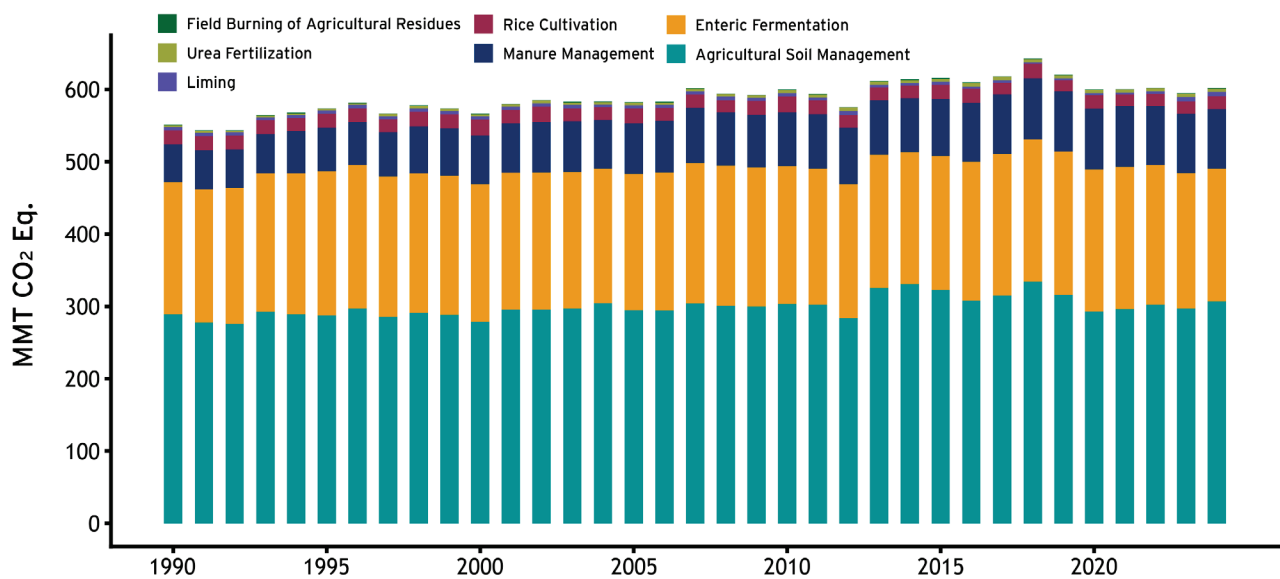


Chapter 5. Agriculture

Agricultural management activities including livestock production, crop cultivation, and agricultural land management produce greenhouse gas (GHG) emissions of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O).¹

In 2024, emissions from this sector were 602.1 million metric tons of carbon dioxide equivalent (MMT CO₂ Eq.), accounting for approximately 9.7 percent of total gross U.S. GHG emissions (see Table 5-1). Emissions in 2024 represent an increase of 9.3 percent since 1990 when the sector made up 8.4 percent of total gross emissions (see Figure 5-1).

Figure 5-1: Trends in Agriculture Sector Greenhouse Gas Emission Sources



Enteric fermentation represents not only the largest source of CH₄ in the agriculture sector, making up 68.7 percent of agricultural CH₄, but also the largest source of CH₄ in the *Greenhouse Gas Inventory and Analysis for the United States (GHGIA)* account for 26.8 percent of total U.S. CH₄ emissions. Recent enteric fermentation trends have largely followed trends in livestock populations. In 2024, enteric fermentation decreased by 1.7 percent relative to 2023, driven primarily by a decrease in beef and dairy cattle populations. Manure management represented 13.6 percent of total agriculture emissions. Together, enteric fermentation and manure management make up the “livestock management” sector, which makes up 44.1 percent of total agriculture emissions and 36.2 percent of total national CH₄ emissions.

¹ Consistent with Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006), additional CO₂, CH₄, and N₂O fluxes from land use and land-use conversion activities, such as cultivation of cropland, management on grasslands, grassland fires, aquaculture, and conversion of forest land to cropland, are presented in Chapter 6, *Land Use, Land-Use Change, and Forestry*. CO₂ emissions from stationary and mobile on-farm energy use and CH₄ and N₂O emissions from stationary on-farm energy use are reported in Chapter 3, *Energy*. CH₄ and N₂O emissions from mobile on-farm energy use are reported in Chapter 3 under mobile fossil fuel combustion emissions (EPA, 2025).

Agricultural soil management is the largest overall source of emissions in the agriculture sector, accounting for 50.9 percent of total sector emissions, and the largest N₂O source in the *GHGIA* (77.1 percent of total U.S. N₂O emissions) primarily from fertilizer application and increased nitrogen in soils.

Rice cultivation represents a smaller agricultural source category at 3 percent of total sectoral emissions, in part due to the limited geographic extent of rice cultivation in the United States. Rice cultivation emissions in 2024 are approximately equal to those in 1990.

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

Gas/Source	1990	2005	2020	2021	2022	2023	2024
CO₂	7.0	7.9	7.6	6.9	8.1	10.1	10.6
Liming	4.7	4.4	2.9	2.4	3.2	5.4	5.6
Urea Fertilization	2.3	3.6	4.7	4.5	4.8	4.7	5.1
CH₄	241.4	264.4	282.5	279.9	274.8	270.5	267.8
Enteric Fermentation	182.8	188.2	196.3	196.5	192.6	187.2	184.1
Manure Management	39.1	55.0	66.9	66.4	64.7	65.1	65.0
Rice Cultivation	18.9	20.6	18.6	16.3	16.8	17.5	18.1
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.6	0.6	0.6	0.6
N₂O	302.7	310.2	310.1	313.8	319.7	314.3	323.7
Agricultural Soil Management	289.1	294.7	293.0	296.5	302.5	297.3	306.7
Manure Management	13.4	15.2	16.9	17.1	17.0	16.8	16.8
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	551.0	582.5	600.2	600.6	602.5	594.9	602.1

Note: Totals may not sum due to independent rounding.

Unless otherwise noted, all estimates in this chapter are provided in MMT CO₂ Eq. Consistent with GHG inventories from other countries, this *GHGIA* uses 100-year Global Warming Potential values from Table 8.A.1 in Appendix 8.A of the *IPCC Fifth Assessment Report* for calculating CO₂ Eq. emissions. Supplemental data tables published with this *GHGIA* for download include all the tables presented in this chapter as well as tables with unweighted units reported as kilotons (kt).

Methodological Framework

Emissions are estimated based on Volume 4 (Agriculture, Forestry and Other Land Use [AFOLU]) of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Intergovernmental Panel on Climate Change [IPCC], 2006) and the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2019), using country-specific data and management practices where available. Unless otherwise noted, methods are consistent with those used in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (Environmental Protection Agency [EPA], 2025), as noted in Table 5-2. Consistent with IPCC good practices, the inventory applies higher tier methods and approaches for more significant sources (e.g., Tier 2 and Tier 3 methods, which include use of country-specific methods and models, emission factors and other site-specific information) and as data allow for smaller sources.

To fill gaps in activity data typically occurring in the most recent years of the time series, several types of statistical techniques are used to extrapolate emission estimates (see Volume 1, Chapter 5 of IPCC, 2006). See Box 5-1 for more details on the specific extrapolation techniques used to forecast emissions estimates in the agriculture and land use, land-use change, and forestry sectors, as well as discussions within category Methods sections.

Table 5-2: Summary of Methods in the Agriculture Chapter

Category (CRT Code ^a)	Gases	IPCC Methodological Tier	Methodological Refinements Compared to 1990–2023 Inventory (EPA, 2025)
Enteric Fermentation (3A)	CH ₄	Tier 1 (other livestock), Tier 2 (cattle)	No change
Manure Management (3B)	CH ₄ , N ₂ O	Tier 1 (other livestock), Tier 2 (cattle)	No change
Rice Cultivation (3C)	CH ₄	Tier 1, Tier 3	No change
Agricultural Soil Management (3D)	N ₂ O	Tier 1, Tier 3	No change
Liming (3G)	CO ₂	Tier 2	No change
Urea Fertilization (3H)	CO ₂	Tier 1	Updated primary activity data source
Field Burning of Agricultural Residues (FBAR) (3F)	CH ₄ , N ₂ O	Tier 2	No change

^a Codes in parentheses represent common reporting table (CRT) codes. CRT codes are a classification system to organize quantitative reporting of detailed emission and removal data in standardized data tables (i.e., CRTs) to facilitate comparison of national inventory data and trends. The code reflects classification levels (e.g. sector, subsector, category, subcategory). Translating 3A: 3 = agriculture sector, A = enteric fermentation.

Box 5-1: AFOLU Extrapolation Techniques

To fill gaps in activity data typically occurring in the most recent years of the time series, several types of statistical techniques are used to extrapolate emission estimates (see Volume 1, Chapter 5 of IPCC, 2006). When possible, surrogate data that capture historical trends in activity data or emissions can be used to fill time series gaps. A correlation between the surrogate or proxy data and historical activity data or emissions estimates is built, and then the surrogate data is used to predict emissions during the time series gap using this statistical relationship. For example, to extrapolate agricultural soil management N₂O emissions for the latter part of the time series when management information from the U.S. Department of Agriculture (USDA) National Resource Inventory (NRI) is not available, a linear model correlating historical N₂O emissions prior to 2021 with total national nitrogen fertilizer consumption, annual precipitation data, and planted acreage of corn and soybeans is used to predict N₂O emissions using these surrogate data.

When suitable surrogate data are not available, an autoregressive moving average technique (ARMA) can be applied to forecast emission estimates for years in which key data are unavailable. Forecasted estimates are based on oscillations around a historical mean across the time series of existing emission estimates. Where a trend can be identified, an autoregressive integrated moving average (ARIMA) approach is applied to predict emissions based on recent trends in addition to underlying movement around the mean. In some cases, both a linear regression using surrogate data and ARMA errors are used in combination to more accurately fill time series gaps by explicitly incorporating known emission trend drivers via inclusion of the surrogate data (EPA, 2025). In other cases, statistical tests indicate that a simple linear trend extrapolation is the best fit model to explain historical variation in emissions, and recent emission trends alone were used to complete the time series (Brockwell & Davis, 2016).

Quality Assurance/Quality Control

For all categories, the IPCC general and category-specific quality assurance/quality control (QA/QC) procedures were implemented. These procedures involved checks specifically focused on the activity data and methodology used for estimating each source of emissions from the agriculture sector. Emission trends were investigated to determine whether any corrective actions were needed. Minor corrective actions were taken as necessary.

Uncertainty

The same uncertainty bounds from the *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2023* (EPA, 2025) were applied for each category and subcategory (as applicable); see Table 5-16. A qualitative description of the uncertainties, along with the total category uncertainty estimate, is provided within each category. Future iterations and versions of this *GHGIA* will review and update the quantified uncertainty associated with activity data, emission factors, and other input parameters.

Future Areas for Improvement

Continuous improvement efforts are important for reflecting the latest science and reducing uncertainties in estimating emissions from agricultural management activities, especially for significant categories such as CH₄ emissions from livestock and N₂O emissions from agricultural soil management; to the extent practicable. For categories where the methodology has not changed in this *GHGIA* and remains consistent with previous analyses, improvements identified in EPA's assessment (EPA, 2025) will be reviewed. Any improvements that have been incorporated into this *GHGIA* will be discussed in the Methods and Recalculations sections of those respective categories.

There are categories where additional methodological improvements will be needed, mostly due to challenges with data availability. A thorough review of alternative data sources and methods/models will also consider time-series consistency and recalculations. These will likely occur in the following categories where additional analysis and/or modeling that relies on proprietary data (e.g., USDA NRI data used in the DayCent model) had previously been used:

- Rice Cultivation
- Agricultural Soil Management
- Field Burning of Agricultural Residues (FBAR)

Future versions of this *GHGIA* will specify more on scope, timing, and plans for phasing in improvements.



5.1 Enteric Fermentation (Source Category 3A)

CH₄ is generated during animal digestion as microbes present in livestock digestive tracts ferment food consumed by livestock, a process known as enteric fermentation. CH₄ produced during enteric fermentation is dependent on livestock characteristics like the size, growth stage, and type of digestive system and also varies with the quantity and quality of feedstock in an animal's diet.

In the United States, enteric fermentation is the largest source of CH₄ emissions across all Inventory sectors. The amount of CH₄ emitted by an individual animal depends mainly on its digestive physiology and the type and quantity of feed consumed. In the absence of changes in feeding practices, animal diets or productivity, livestock populations (herd sizes) are the primary driver of enteric fermentation emission trends.

In 2024, enteric fermentation resulted in emissions of 184.1 MMT CO₂ Eq. Enteric fermentation emissions in 2024 across all livestock types decreased by 1.7 percent relative to 2023, driven primarily by a decrease in beef cattle populations that led to a 2.0 percent decrease in beef cattle enteric fermentation emissions. Dairy cattle enteric fermentation emissions also declined in 2024 relative to 2023 (0.9 percent decrease) and trends in cattle populations generally drive overall enteric fermentation emissions, the following livestock types also experienced declines in enteric fermentation emissions in 2024: horses, sheep, American bison, and mules and asses. Enteric fermentation emissions from swine and goats saw marginal emission increases in 2024 relative to 2023 (0.4 percent increase and 0.2 percent increase, respectively).

Across the time series, total enteric fermentation emissions peaked in 1995 (199.2 MMT CO₂ Eq.) and then fluctuated over time, with two other notable highs occurring in 2007 (194.5 MMT CO₂ Eq.) and 2019 (197.3 MMT CO₂ Eq.), as shown in Table 5-3. Emissions in 2024 were 0.7 percent lower than total enteric fermentation emissions in 1990 (182.8 MMT CO₂ Eq.).



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

Livestock Type	1990	2005	2020	2021	2022	2023	2024
Beef Cattle	132.8	139.6	140.5	140.3	137.0	131.7	129.0
Dairy Cattle	43.3	41.3	48.8	49.4	48.9	48.8	48.3
Swine	2.3	2.6	3.2	3.1	3.1	3.1	3.2
Horses	0.8	2.0	1.3	1.3	1.2	1.2	1.1
Sheep	2.9	1.5	1.3	1.3	1.3	1.3	1.3
Goats	0.6	0.7	0.7	0.6	0.6	0.6	0.6
American Bison	0.1	0.5	0.4	0.4	0.4	0.4	0.4
Mules and Asses	+	0.1	0.1	0.1	0.1	0.1	0.1
Total	182.8	188.2	196.3	196.5	192.6	187.2	184.1

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Methods

Methods used in this *GHGIA* are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2023* (EPA, 2025). The "Simplified Approach" utilized and documented by EPA (2025) to estimate 2023 emission estimates was applied in this *GHGIA* to estimate 2024 enteric fermentation emission estimates for cattle populations. In this method, national cattle population data from the USDA National Agricultural Statistical Service (USDA-NASS) QuickStats database of annual survey data was pulled according to the cattle subpopulation categories used in USDA-NASS surveys listed in Table 5-4 for the years 2022 and 2024 (USDA, 2022a, 2022b, 2024a, 2024b, 2024c). Percent change in 2024 cattle populations reported by the survey relative to 2022 populations were used to project 2024 cattle populations based on the modeled average annual populations estimated using the most recent implementation of the Cattle Enteric Fermentation Model (CEFM) (ICF, 2006). Cattle populations were then multiplied by implied emission factors for each cattle subcategory, resulting in a national estimate of CH₄ emitted annually per head of cattle.

Table 5-4: Cattle Subpopulation Categories for 2024 Population Estimates

CEFM Cattle Category	USDA-NASS QuickStats Cattle Category
Dairy Calves	Cattle, Calves
Dairy Cows	Cattle, Cows, Milk
Dairy Replacements 7-11 months	Cattle, Heifers, GE 500 lbs, Milk Replacement
Dairy Replacements 12-23 months	Cattle, Heifers, GE 500 lbs, Milk Replacement
Bulls	Cattle, Bulls, GE 500 lbs
Beef Calves	Cattle, Calves
Beef Cows	Cattle, Cows, Beef
Beef Replacements 7-11 months	Cattle, Heifers, GE 500 lbs, Beef Replacement
Beef Replacements 12-23 months	Cattle, Heifers, GE 500 lbs, Beef Replacement
Steer Stockers	Cattle, Steers, GE 500 lbs
Heifer Stockers	Cattle, Heifers, GE 500 lbs, Excl. Replacement
Steer Feedlot	Cattle, On Feed
Heifer Feedlot	Cattle, On Feed

For non-cattle livestock categories, national livestock population estimates for 2024 were downloaded from USDA-NASS QuickStats from a combination of USDA-NASS annual surveys and the USDA Census of Agriculture. See Table 5-5 for details regarding the source of population data for each non-cattle livestock type. Swine populations in 2024 are based on averaging reported hog inventories from each quarterly hog survey published by USDA-NASS (USDA, 2024a 2024d, 2024e, 2024f, 2024g).

For livestock populations derived from the USDA Census of Agriculture, updated population estimates from the 2022 Census of Agriculture were newly incorporated into livestock estimates in this *GHGIA* (USDA, 2024h). USDA Census of Agriculture estimates are available for 1987, 1992, 1997, 2002, 2007, 2012, 2017, and 2022 (USDA, 2024a). Population estimates are linearly interpolated between census years and extrapolated from 2022 to 2024 to complete the time series using an autoregressive moving average (ARMA) extrapolation. See Box 5-1 for more information on this statistical technique. Livestock populations were then multiplied by IPCC Tier 1 emission factors to estimate enteric fermentation emissions for each livestock type (IPCC, 2019).

Table 5-5: Data Sources for Non-Cattle Livestock Population Estimates

Livestock Type	Population Data Source	USDA-NASS QuickStats Query
Swine	USDA-NASS Quarterly Survey (USDA, 2024d, 2024e, 2024f, 2024g)	Hogs, Breeding Hogs, Market, less than 50 lb. Hogs, Market, 50 to 119 lb. Hogs, Market, 120 to 179 lb. Hogs, Market, GE 180 lb.
Horses	USDA Census of Agriculture (USDA, 2024h)	Equine, Horses, and Ponies
Sheep	USDA-NASS Annual Survey (USDA, 2024h)	Sheep, Including Lambs
Goats	USDA Census of Agriculture (USDA, 2024h)	Goats
American Bison	USDA Census of Agriculture (USDA, 2024h)	Specialty, Bison
Mules and Asses	USDA Census of Agriculture (USDA, 2024h)	Equine, Mules & Burros & Donkeys

Recalculations

Recalculations to estimates presented in this *GHGIA* were implemented to incorporate the most recent population estimates for horses, goats, American bison, and mules and asses from the 2022 USDA Census of Agriculture (USDA, 2024h). As a result, emissions for these livestock types were recalculated from 2018 to 2023. Population data for these livestock types were interpolated between the 2017 and 2022 Census of Agriculture reports and extrapolated from 2022 using an ARMA forecasting technique (see Box 5-1) to estimate populations for 2023 and 2024 to complete the time series. Across all animal types, this recalculation resulted in an average annual increase in enteric fermentation emissions of 0.02 percent (0.045 MMT CO₂ Eq.) over the 2018-2023 recalculation interval.

In addition to the recalculations above, a corrective recalculation was implemented after quality control checks identified an issue with the extrapolation of horse populations from the 1992 Census of Agriculture dating back to 1990. The issue was addressed for the current estimates, resulting in a small recalculation to the 1990 and 1991 enteric fermentation emission estimates for horses. On an average annual basis, 1990-1991 emissions decreased by 12.9 percent (-0.2 MMT CO₂ Eq.) relative to 1990-1991 emissions reported by EPA (2025).

Uncertainty

An uncertainty analysis for enteric fermentation emissions was last conducted for estimates reported by EPA (2003) for the inventory report covering the 1990-2001 time series using the 2006 Guidelines Approach 2 methodology (ICF, 2003; IPCC, 2006). This analysis revealed that beef cattle represent the largest source of CH₄ emissions while also resulting in the largest degree of uncertainty associated with those estimates. The largest uncertainty in beef cattle emission estimates originates from the high degree of uncertainty in beef cattle diet characteristics, especially for the grazing portion of the beef cattle population. The uncertainty bounds used by EPA (2003) at the 95% confidence level continued to be applied to new emission estimates for all reports published through EPA (2025), as the same underlying sources of information regarding cattle population demography, diet characteristics, and ruminant nutrition models continued to be used in subsequent reports.

For this current *GHGIA*, the overall uncertainty associated with enteric fermentation is assumed to be similar to prior estimates (EPA, 2025) given the use of the same basic methodology and data sources for most years, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). In 2024, enteric fermentation CH₄ emissions were estimated to fall between 11 percent below and 18 percent above the total enteric fermentation CH₄ estimate of 184.1 MMT CO₂ Eq. (between 163.9 MMT CO₂ Eq. and 217.2 MMT CO₂ Eq.). This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.



5.2 Manure Management (Source Category 3B)

Manure treatment, storage, and transport generate CH₄ and N₂O emissions. CH₄ is generated through the anaerobic decomposition of manure, while direct and indirect N₂O arises through nitrification and denitrification, including emissions from volatilization, runoff, and leaching.² Structural characteristics of the U.S. livestock production industry and climatic conditions affect biological processes, which influence CH₄ and N₂O potential. For CH₄, the manure management system, ambient temperature, moisture levels, and storage duration affect emissions. For N₂O, emissions vary based on manure composition and the type of storage system or treatment, which influences the amount of oxygen and liquid present within the system (IPCC, 2006).

Emissions in the United States vary by animal type, regional climates, and manure management systems in use. Increased use of liquid systems influences CH₄ trends, while nitrogen content and handling practices drive N₂O emissions. Similar to enteric fermentation emissions, trends in CH₄ and N₂O emissions from manure management mirror trends in livestock populations, particularly cattle and swine populations, as livestock population sizes determine the amount of manure produced and managed annually.

In 2024, manure management CH₄ emissions across all livestock types totaled 65.0 MMT CO₂ Eq., and manure management N₂O emissions totaled 16.8 MMT CO₂ Eq., as shown in Table 5-6. Relative to 2023 emissions, manure management CH₄ emissions decreased by 0.2 percent (0.2 MMT CO₂ Eq.), while N₂O emissions increased by 0.1 percent.

² The N₂O emissions generated by manure in the system pasture, range, and paddock lands occur directly and indirectly from the soil and are therefore reported under N₂O emissions from agricultural soil management (IPCC, 2006).

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

Gas/Livestock Type	1990	2005	2020	2021	2022	2023	2024
CH₄	39.1	55.0	66.9	66.4	64.7	65.1	65.0
Dairy Cattle	16.0	26.4	34.7	34.3	33.4	33.5	33.2
Swine	17.4	22.7	24.9	24.6	23.8	24.3	24.3
Poultry	3.8	3.4	3.0	3.0	3.0	3.0	3.0
Beef Cattle	1.8	2.2	4.2	4.4	4.3	4.2	4.2
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N₂O	13.4	15.2	16.9	17.1	17.0	16.8	16.8
Beef Cattle	5.2	6.0	6.1	6.4	6.4	6.2	6.3
Dairy Cattle	5.5	5.5	6.2	6.3	6.2	6.1	6.0
Swine	1.1	1.5	1.9	1.8	1.8	1.8	1.8
Poultry	1.3	1.8	2.3	2.3	2.3	2.3	2.3
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
American Bison	NA	NA	NA	NA	NA	NA	NA
Total	52.5	70.2	83.8	83.6	81.7	81.9	81.8

+ Does not exceed 0.05 MMT CO₂ Eq.

NA (Not Applicable).

Note: Totals may not sum due to independent rounding.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2023* (EPA, 2025). All livestock population data used to estimate manure management emissions are consistent with those used to estimate enteric fermentation. See description in Section 5.1 above for more information.

In addition to the population data for cattle, swine, horses, mules and asses, American bison, sheep, and goats used in the estimation of enteric fermentation emissions, an estimate of poultry populations is necessary to estimate manure management emissions from this animal type. Consistent with the method used to estimate 2023 poultry populations (EPA, 2025), 2024 poultry populations were collected from USDA-NASS annual production and inventory surveys (USDA, 2024a, 2024b, 2024c). See Table 5-7 for details regarding the source of population data for each poultry subcategory. Turkey and broiler populations are estimated from annual production data, where production data must be adjusted to account for a production interval that incorporates the average lifespan of each animal in the production cycle. Annual production data for turkeys are divided by a production interval of 3.0 to estimate average annual population, while annual production data for broilers are divided by a production interval of 5.5 to yield average annual broiler population.

Table 5-7. Data Sources for Poultry Population Estimates

Livestock Type	Population Data Source	USDA-NASS QuickStats Query
Hens (> 1 year)	USDA-NASS Annual Survey (USDA, 2024g)	Chickens, Layers
Pullets	USDA-NASS Annual Survey (USDA, 2024g)	Chickens, Pullets, Replacement
Chickens	USDA-NASS Annual Survey (USDA, 2024g)	Chickens, Roosters and Other
Broilers	USDA-NASS Annual Production Summary (USDA, 2024h)	Chickens, Broilers – Production
Turkeys	USDA-NASS Annual Production Summary (USDA, 2024h)	Turkeys – Production

To estimate 2024 manure management CH₄ and N₂O emissions, the Simplified Approach used by EPA (2025) was applied. National population estimates in 2024 were multiplied by 2022 animal-specific implied emission factors for CH₄ and N₂O emissions (a combined emission factor that encompasses both direct and indirect N₂O emissions per animal type) (EPA, 2025). Use of this method ensures time series consistency across the 1990-2024 emission estimates, in line with guidance provided in IPCC (2006).

Recalculations

As with enteric fermentation emission estimates presented in this *GHGIA*, recalculations were implemented due to incorporation of USDA-NASS 2022 Census of Agriculture data to replace population estimates from 2018 to 2023 that were extrapolated from the 2017 census for horses, goats, American bison, and mules and asses (USDA, 2024d).

Across all animal types, these implemented recalculations resulted in an average annual increase in manure management CH₄ emissions of 0.01 percent (0.006 MMT CO₂ Eq.) and a 0.01 percent increase in N₂O emissions (0.001 MMT CO₂ Eq.) over the 2018–2023 recalculation interval.

Uncertainty

For this current *GHGIA*, the overall uncertainty associated with manure management is assumed to be similar to prior estimates (ERG, 2003; EPA, 2003, 2025) given the use of the same basic methodology and data sources for most years, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC 2006). This confidence level indicates a range of approximately 18 percent below (53.3 MMT CO₂ Eq.) and 20 percent above (78.0 MMT CO₂ Eq.) the manure management CH₄ emission estimate of 65.0 MMT CO₂ Eq. in 2024. The uncertainty range surrounding the manure management N₂O emission estimate was 16 percent below (14.1 MMT CO₂ Eq.) and 24 percent above (20.8 MMT CO₂ Eq.) the 2024 estimate of 16.8 MMT CO₂ Eq. This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.



5.3 Rice Cultivation (Source Category 3C)

All rice produced in the United States is grown in irrigated fields (USDA ERS, 2025) that create anaerobic conditions, leading to CH₄. Water management plays a significant role in CH₄ production from rice cultivation, as well as factors such as drainage and aeration, amendment application (including fertilizer use), rice variety, and soil attributes.

In the United States, only a handful of states cultivate rice, with Arkansas, California, Louisiana, and Texas representing the states with the largest share of rice cultivation areas and emissions, in that order. Most farmers in these states apply fertilizers and, in Texas and Louisiana in particular, some farmers can reflood their fields after harvest and achieve a partial second or “ratoon” crop, which often leads to higher methane emissions (USDA ERS, 2025).

Emissions from rice cultivation in the United States were 18.1 MMT CO₂ Eq. in 2024 (see Table 5-8). Although there have been annual changes across the time series, emission estimates in 2024 were similar to those in 1990, with approximately the same amount of rice area being planted during those 2 years (USDA-NASS, 2026).

Table 5-8: CH₄ Emissions from Rice Cultivation (MMT CO₂ Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Rice Cultivation	18.9	20.6	18.6	16.3	16.8	17.5	18.1

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2023* (EPA, 2025).

To estimate rice methane emissions for years beyond the available USDA NRI data, a linear regression model with autoregressive integrated moving average (ARIMA) errors was used to forecast emissions estimates from 2021 to 2024, since the Tier 3 estimates from 1990 to 2020 were based on prior runs from the DayCent model, as described in Box 5-1. Rice methane emissions were forecasted as a function of planted rice area (surrogate data), as shown in Table 5-9 (USDA-NASS, 2026). Estimates from 1990 to 2020 are consistent with estimates from EPA (2025).

Table 5-9: Rice Area Planted (1,000 Acres)

Year	1990	2005	2020	2021	2022	2023	2024
Rice Area Planted	2,897	3,384	3,036	2,531	2,219	2,895	2,919

Recalculations

With the application of the updated forecasting approach, recalculations to the 2021-2023 time series ranged from -2.2 MMT CO₂ Eq. (-12 percent) to -1.2 MMT CO₂ Eq. (-6.6 percent). There were no recalculations implemented to 1990-2020 estimates.

Uncertainty

Uncertainty in rice cultivation CH₄ emission estimates stems from uncertainty associated with the management practice activity data, emission factors, uncertainty in the DayCent model structure, and variance in the underlying NRI sampling.

For this current *GHGIA*, the overall uncertainty of rice cultivation CH₄ is assumed to be similar to EPA findings (2025) given the use of the same basic methodology and data sources for most years, calculated using the 2006 IPCC Guidelines Approach 1 (for Tier 1 emissions and total emissions) and Approach 2 (for Tier 3 emissions) methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). There will be increased uncertainties associated with the use of the ARIMA forecasting approach that are not currently reflected in the uncertainty estimates above. This confidence level indicates a range of approximately 75 percent below and 75 percent above the total rice cultivation methane emissions in 2024. This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.



5.4 Agricultural Soil Management (Source Category 3D)

Agricultural soil management includes N₂O emissions resulting from nitrogen inputs to managed agricultural soils. The application of nitrogen leads to direct N₂O emissions as N₂O is emitted from agricultural soils as an intermediary during the microbial processes of nitrification and denitrification. Management of agricultural soils also leads to indirect N₂O emissions when nitrogen inputs are transported off-site either via volatilization or leaching and runoff before ultimately being transformed to N₂O through the same microbial processes of nitrification and denitrification.

The methodology used to estimate the N₂O emissions from agricultural soil management incorporates nitrogen inputs from the following sources (IPCC, 2006):

- Synthetic nitrogen fertilizer
- Managed livestock manure
- Other organic materials (e.g., application of treated sewage sludge or other biosolids)
- Manure deposited directly on pasture, rangeland, or paddock soils by grazing livestock (i.e., unmanaged manure; see Section 5.2)
- Crop residue retention on crop fields

Other activities such as drainage of organic soils, tillage, and grazing management practices can alter N₂O emissions from agricultural soils. Trends in agricultural soil management emissions fluctuate across the time series and are predominantly influenced by the type, amount, and timing of nitrogen fertilizer applied to agricultural soils, cropping systems and cropland and rangeland management practices, and seasonal weather patterns. As estimated by EPA (2025), across the 1990-2023 time series, cropland accounted for 68 percent of total direct N₂O emissions and 79 percent of indirect N₂O emissions from agricultural soil management, while grassland accounted for 32 percent of direct N₂O emissions and 21 percent of indirect N₂O emissions.

Emissions of N₂O from agricultural soil management is the largest source of emissions in the agricultural sector across all gases, as well as the largest source of N₂O across all inventory sectors in the United States. In 2024, agricultural soil management direct N₂O emissions totaled 265.4 MMT CO₂ Eq. across both cropland and grassland soils, and indirect N₂O emissions totaled 28.5 MMT CO₂ Eq. (Table 5-10). Relative to 2023 emissions, direct N₂O emissions increased by 3.6 percent (9.5 MMT CO₂ Eq.) in 2024, while indirect N₂O emissions decreased by 0.3 percent (0.1 MMT CO₂ Eq.).



Table 5-10: N₂O Emissions from Agricultural Soil Management (MMT CO₂ Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Direct	259.2	266.2	263.5	264.9	271.0	265.9	275.4
Indirect	29.9	28.5	29.5	31.6	31.5	31.4	31.3
Total	289.1	294.7	293.0	296.5	302.5	297.3	306.7

Note: Totals may not sum due to independent rounding.

Methods

Historically, the majority of N₂O emissions from agricultural soil management have been estimated using Tier 3 methods that leverage the DayCent model, a process-based model that tracks carbon and nitrogen dynamics through a mass-balanced approach through daily iterations of simulated microbial decomposition and plant productivity. The DayCent model incorporates numerous data products to accurately capture the impact of climate, land use and land management, fertilizer application, and geospatial variation in biogeochemical properties on nitrogen dynamics and N₂O emissions in agricultural systems across the United States. Tier 1 methods (IPCC, 2006) are used to estimate N₂O emissions from agricultural soils in systems where DayCent has not been parameterized to accurately model emissions from certain soil types (e.g., Histosols) or specialty crop types. This *GHGIA* leverages the 1990-2020 emissions estimates using the most recent DayCent model results and Tier 1 methods reported by EPA (2025). See EPA (2025) for more details regarding the DayCent model, Tier 1 estimation methodology, and activity data used to estimate 1990-2020 N₂O emissions from agricultural soil management.

To complete the time series and estimate agricultural soil management N₂O emissions from 2021 to 2024, this *GHGIA* leveraged an extrapolation approach that uses a linear model incorporating trends in surrogate data variables for national fertilizer consumption, planted acreage of corn and soybeans, and state-level precipitation data, as described in Box 5-1. This extrapolation technique is similar to that employed by EPA (2025) to extrapolate 2021-2023 N₂O emissions from agricultural soil management, but it incorporates national nitrogen fertilizer consumption data from the International Fertilizer Association (IFA) with 2024 total nitrogen fertilizer consumption extrapolated using a linear model to forecast fertilizer consumption based on the historical relationship between total national planted corn and soybean acres from 1990 to 2023 (USDA, 2024a, 2024b) and national fertilizer consumption from 1990 to 2023 (IFA, 2026a). In addition to national nitrogen fertilizer consumption data, a weighted national annual precipitation variable was created by weighting average state annual precipitation by each state's share of national planted soybean and corn acres (PRISM, n.d.; USDA, 2024a, 2024b). A linear model was then created where national precipitation data (from state precipitation data weighted by planted acreage) and national total nitrogen fertilizer consumption variables were used as surrogate data to explain historical variation in direct N₂O emissions from 1990 to 2020, and this linear model was used to extrapolate direct N₂O emissions from 2021 to 2024. Indirect N₂O emissions from 2021 to 2024 were extrapolated using an ARMA approach.

Recalculations

The implementation of a modified extrapolation technique to estimate direct N₂O emissions from 2021 to 2023 resulted in an average increase in emissions of 0.4 percent (1.1 MMT CO₂ Eq.) across the 2021-2023 recalculation interval relative to the estimates presented by EPA (2025). The modified extrapolation approach resulted in an average increase in emissions of 6.9 percent (2.0 MMT CO₂ Eq.) across the same recalculation interval relative to EPA (2025) results.

Uncertainty

For this current *GHGIA*, the overall uncertainty surrounding direct and indirect N₂O emissions from agricultural soil management is assumed to be similar to those presented by EPA (2025) given the use of the same basic methodology and data sources for most years. Uncertainty estimates presented by EPA (2025) incorporate uncertainty from DayCent model structure and assumptions, IPCC (2006) Tier 1 default emission factors, and additional error introduced through the use of extrapolation techniques to complete the time series. A Monte Carlo simulation (2006 IPCC Guidelines Approach 2 using 95 percent confidence intervals) was used to estimate the components of direct and indirect N₂O emissions derived from the DayCent model, while Approach 1, error propagation, from IPCC (2006), was used to estimate uncertainty associated with direct N₂O emissions estimated using the Tier 1 approach, the proportion of nitrogen that is volatilized, leached, or lost via runoff, and indirect N₂O emissions. This analysis indicates a range of approximately 28 percent above and below the 2024 direct N₂O emission estimate of 275.4 MMT CO₂ Eq. (i.e., between 198.3 MMT CO₂ Eq. and 352.54 MMT CO₂ Eq.) and 52 percent below to 124 percent above the 2024 indirect N₂O emission estimate of 31.3 MMT CO₂ Eq. (i.e., between 15.0 MMT CO₂ Eq. and 70.2 MMT CO₂ Eq.). This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.

5.5 Liming (Source Category 3G)

Agricultural liming is the practice of applying limestone (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$), to agricultural soils. As these materials dissolve, they release CO_2 into the atmosphere. These materials help reduce soil acidity, creating better conditions for plant growth and improving crop yields.

Emissions from limestone and dolomite that are used in industrial processes (e.g., cement production, glass production) are reported in Chapter 4, *Industrial Processes and Product Use*.

Emissions from liming of agricultural soils in the United States were 5.6 MMT CO_2 Eq. in 2024 (see Table 5-11), with time-series trends following patterns in the amount of minerals applied to soils.

Table 5-11: CO_2 Emissions from Liming (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Limestone	4.1	3.9	2.5	2.0	3.0	5.1	5.3
Dolomite	0.6	0.5	0.4	0.4	0.3	0.3	0.3
Total	4.7	4.4	2.9	2.4	3.2	5.4	5.6

Note: Totals may not sum due to independent rounding.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2023* (EPA, 2025). Total crushed stone data for 2022 and 2023 were available from the U.S. Geological Survey (USGS, 2025) (see Table 5-12), but disaggregated data on agricultural uses of crushed stone were not available at the time of this analysis and thus the proportions from 2023 were applied to 2024.

Table 5-12: Applied Minerals (MMT)

Mineral	1990	2005	2020	2021	2022	2023	2024
Limestone	19.0	18.1	11.6	9.3	13.7	23.6	24.5
Dolomite	2.4	1.9	1.6	1.6	1.1	1.2	1.4

Recalculations

With the incorporation of updated USGS activity data, recalculations were implemented in 2022 and 2023, resulting in a 0.03 MMT CO_2 Eq. and 0.1 MMT CO_2 Eq. increase, respectively, compared to EPA (2025). There were no recalculations to estimates from 1990 to 2021.

Uncertainty

Uncertainty stems from data on the amount of crushed stone applied to agricultural soils and the fraction of lime dissolved by nitric acid versus carbonic acid, as well as the portion of bicarbonate that leaches through the soil and is transported to the ocean (EPA, 2025).

For this current *GHGIA*, the overall uncertainty of liming emissions is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 85 percent below and 89 percent above the CO₂ emissions from liming estimate in 2024. This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.



5.6 Urea Fertilization (Source Category 3H)

Urea is applied to soils primarily as a nitrogen fertilizer to support crop growth and improve yields. The use of urea (CO(NH₂)₂) as a fertilizer leads to GHG emissions through the release of CO₂ that was fixed during the industrial production process (IPCC, 2006).

Emissions from urea fertilization in the United States were 5.1 MMT CO₂ Eq. in 2024, as shown in Table 5-13.³ CO₂ emissions increased by 121 percent between 1990 and 2024. This trend follows the overall trend of increased use of urea in the United States as a substitute for other nitrogen fertilizers.

Table 5-13: CO₂ Emissions from Urea Fertilization (MMT CO₂ Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Urea Fertilization	2.3	3.6	4.7	4.5	4.8	4.7	5.1

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2023* (EPA, 2025). The primary activity data source was updated to the IFA (2026b). This dataset covers the entire 1990-2024 time series, which is presented in Table 5-14, replacing the linear regression model with ARMA errors that was previously applied to the 2017 through present time series by EPA (2025).

Table 5-14: Applied Urea (MMT)

Source	1990	2005	2020	2021	2022	2023	2024
Urea Fertilizer	3.1	4.9	6.5	6.1	6.6	6.4	6.9

Recalculations

The IFA activity data is approximately 3.5 percent different, on average, compared to the prior datasets used over the time series. From an emissions perspective, this resulted in an average decrease in emissions across the time series by 0.1 MMT CO₂ Eq., with the greatest differences coming during the years in which prior analysis (EPA, 2025) used an ARMA forecasting method.

³ CO₂ emissions associated with urea used for non-agricultural purposes are reported in Chapter 4.

Uncertainty and QA/QC

When reviewing the IFA activity data source, statistical comparisons against the prior activity data were conducted for the whole time series.

Uncertainty in the urea fertilization estimates stems from the activity data and the IPCC default emission factor. For this current *GHGIA*, the overall uncertainty of urea fertilization is assumed to be similar to those presented by EPA (2025) given the use of the same basic methodology and data sources for most years, which were calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 43 percent below and 3 percent above the CO₂ estimate from urea fertilization in 2024. This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.



5.7 Field Burning of Agricultural Residues (Source Category 3F)

The burning of agricultural residues in fields is one way farmers manage the large amounts of residues left over from crop production and leads to emissions of CH₄, N₂O, carbon monoxide (CO), and nitrogen dioxide (NO_x)⁴. In the United States, residue burning occurs on a limited scale and is often subject to state and local air quality regulations.

Total emissions from field burning of agricultural residues in the United States were 0.8 MMT CO₂ Eq. in 2024, an 18.4 percent increase since 1990 (see Table 5-15). The increase in emissions since 1990 is driven in part by higher-yielding crop varieties that generate more residue, as well as by an expansion in the area where residue burning is practiced for certain crops such as wheat in the Pacific Northwest and sugarcane in Florida.

Table 5-15: CH₄ and N₂O Emissions from Field Burning of Agricultural Residues (MMT CO₂ Eq.)

Gas/Crop Type	1990	2005	2020	2021	2022	2023	2024
CH₄	0.5	0.6	0.6	0.6	0.6	0.6	0.6
Sugarcane	0.1	0.2	0.1	0.2	0.2	0.2	0.2
Wheat	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Maize	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
Soybeans	+	+	+	0.1	0.1	0.1	0.1
Cotton	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+

(continued)

⁴ The 2006 IPCC Guidelines does not consider field burning of annual crop residues to be a net source of CO₂ emissions because it is assumed that the carbon released to the atmosphere as CO₂ during burning is reabsorbed during the next growing season by the crop (IPCC, 2006).

**Table 5-15: CH₄ and N₂O Emissions from Field Burning of Agricultural Residues (MMT CO₂ Eq.)
(continued)**

Gas/Crop Type	1990	2005	2020	2021	2022	2023	2024
Oats	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Vegetables	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Sugar Beets	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Chickpeas	+	+	+	+	+	+	+
N₂O	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Wheat	0.1	0.1	+	+	+	+	+
Maize	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+

(continued)

Table 5-15: CH₄ and N₂O Emissions from Field Burning of Agricultural Residues (MMT CO₂ Eq.) (continued)

Gas/Crop Type	1990	2005	2020	2021	2022	2023	2024
Oats	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Sugar Beets	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Vegetables	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Chickpeas	+	+	+	+	+	+	+
Total	0.7	0.8	0.8	0.8	0.8	0.8	0.8

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2023* (EPA, 2025).

For field burning of agricultural residues, a linear regression model with ARIMA errors, was used to forecast emissions from 2015 to 2024 (2021-2024 for sugarcane), as described in Box 5-1. Estimates from 1990 to 2014 (through 2020 for sugarcane) are consistent with estimates from prior analysis (EPA, 2025).

Recalculations

Using the updated forecasting approach resulted in minimal recalculations to the 2015-2023 time series. These recalculations range from -0.03 MMT CO₂ Eq. to 0.03 MMT CO₂ Eq. for CH₄ and less than -0.01 MMT CO₂ Eq. for N₂O compared to the 1990-2023 inventory (EPA, 2025). There were no recalculations implemented to estimates from 1990 to 2014.

Uncertainty

Uncertainty in the estimates of field burning of agricultural residues stems from multiple sources, including the use of an analysis of burned areas across six states that is extrapolated to the rest

of the United States, potential omission of burning associated with Kentucky bluegrass, and the underlying burned area and crop data products.

For this current *GHGIA*, the overall uncertainty of field burning of agricultural residues is assumed to be similar to those found by EPA (2025) given the use of the same basic methodology and data sources for most years, which were calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 14 percent below and 14 percent above the CH₄ estimate and 18 percent below and 18 percent above the N₂O estimate for field burning of agricultural residue emissions in 2024. This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.



5.8 Agriculture Uncertainty Summary

Table 5-16 shows the uncertainty summary for each agriculture sector source. A discussion of the uncertainty ranges is included in each source category's respective chapter section.

Table 5-16: Quantitative Uncertainty Summary by Agricultural Source

Source	Gas	2024 Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO ₂ Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Enteric Fermentation	CH ₄	184.1	163.8	217.2	-11%	18%
Manure Management	CH ₄	65.0	53.3	78.0	-18%	20%
Manure Management	N ₂ O	16.8	14.1	20.8	-16%	24%
Rice Cultivation	CH ₄	18.1	4.5	31.7	-75%	75%
Direct Soil N ₂ O Emissions from Agricultural Soil Management	N ₂ O	275.4	198.3	352.5	-28%	28%
Indirect Soil N ₂ O Emissions from Agricultural Soil Management	N ₂ O	31.3	15.0	70.2	-52%	124%
Liming	CO ₂	5.5	0.8	10.5	-85%	89%
Urea Fertilization	CO ₂	5.1	2.9	5.2	-43%	3%
Field Burning of Agricultural Residues	CH ₄	0.6	0.6	0.7	-14%	14%
Field Burning of Agricultural Residues	N ₂ O	0.2	0.2	0.2	-18%	18%

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Please see the *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2023* (EPA, 2025) for additional references.

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