4 Agriculture (NIR Chapter 5)

For this methodology report, the Agriculture chapter consists of two subsectors: livestock management and other agriculture activities. More information on national-level emissions and methods is available in Chapter 5 of the national *Inventory,* available online at: https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-chapter-5-agriculture.pdf. Table 4-1 summarizes the different approaches used to estimate state-level agriculture emissions. The sections below provide more detail on each category.

Table 4-1. Overview of Approaches for Estimating State-Level Agriculture Sector GHG Emissions

Category	Gas	Approach	Completeness[a]
Enteric Fermentation	CH_4	Approach 1	Includes emissions from all states and tribal lands.[a]
Manure Management	CH_4, N_2O	Approach 1	Includes emissions from all states and tribal lands.[a]
Agricultural Soil Management	N_2O	Hybrid: 4.2.2.2 • 1990–2017: Approach 1 • 2018–2022: Approach 2	Includes emissions from all states, the District of Columbia, tribal lands, and territories.[a] Some components of Alaska and Hawaii were not estimated.
Rice Cultivation	CH_4	Hybrid: • 1990–2020: Approach 1 • 2021–2022: Approach 2	Includes emissions from all 13 states (and tribal lands) cultivating rice.[a]
Liming	CO_2	Hybrid: • 1990–2021: Approach 1 • 2022: Approach 2	Includes emissions from all states (and tribal lands) for which USGS (through Minerals Yearbook and the Mineral Industry Survey) reports limestone and dolomite consumption for agriculture in current and historical yearbooks and surveys.[a]
Urea	CO_2	Approach 1	Includes emissions from all states and territories[a] (i.e., Puerto Rico).
Field Burning of Agricultural Residues	CH_4, N_2O	Hybrid: • 1990–2014: Approach 1 • 2015–2022: Approach 2 • Sugarcane: 1990–2020 (Approach 1) • Sugarcane: 2021–2022 (Approach 2)	Includes emissions from all states except Alaska and Hawaii.[a]

[a] Emissions are likely occurring in other U.S. territories; however, due to a lack of available data and the nature of this category, this analysis includes emissions for only the territories indicated. Territories not listed are not estimated. See planned improvements discussions across Chapter 5 of the national *Inventory*. Includes tribal areas in the conterminous United States.

4.1 Livestock Management

This section presents the methodology applied to estimate the livestock management emissions, which consist of the following sources:

- Enteric fermentation (CH_4)

- Manure management (CH_4, N_2O)

4.1.1 Enteric Fermentation (NIR Section 5.1)

4.1.1.1 Background

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

4.1.1.2 Methods/Approach

EPA compiles state-level CH_4 emissions from enteric fermentation using the same methods applied in the national *Inventory*. The methods applied in the national *Inventory* are summarized below in Table 4-2. Estimates are available for all 50 states. Territories are not currently estimated, and tribal lands are not explicitly included based on USDA survey practices, which depend on the presence of the animal on the farm/operation, not the geographic area.

Table 4-2. Approaches to Estimate Enteric Fermentation Methane Across Time Series

Time Series Range	Method
1990–2022	• Cattle: IPCC Tier 2 (Cattle Enteric Fermentation Model) • Non-cattle: IPCC Tier 1 (population × default emissions factor)

Please refer to Section 5.1 and Annex 3.10 the national *Inventory* on enteric fermentation for details on the methods applied to estimate state-level emissions for the years 1990–2022 (EPA 2024). Below is a summary:

- For cattle, the Cattle Enteric Fermentation Model (CEFM) was used to estimate CH_4 emissions using the IPCC Tier 2 method. The CEFM utilizes the IPCC Tier 2 method and other analyses of cattle population, feeding practices, diet data, and production characteristics.
- For non-cattle animals, USDA state population estimates (from USDA *QuickStats* and the U.S. Census of Agriculture) were multiplied by the corresponding default IPCC emissions factors (IPCC 2006).
- Data Appendix E-1 to this report provides state-level non-cattle livestock population numbers for all inventory years. These population data serve as the activity data that are multiplied by default IPCC emission factors to estimate CH_4 emissions from enteric fermentation.
- Data Appendix E-2 to this report provides state-level cattle population numbers disaggregated by animal type for all inventory years.
- To allow for greater exploration of the underlying data that support cattle enteric fermentation emissions estimates, state-level implied emission factors for all cattle types across the time series are provided in Data Appendix E-3 to this report. These implied emission factors are calculated post-hoc from the CEFM output where emissions estimates are modeled based on data inputs regarding livestock populations, diet attributes, feeding practices, and production characteristics. The resulting enteric fermentation emissions estimates were divided by cattle population numbers to calculate the implied emission factor that describes average CH_4 produced per head of cattle in each state in a given year.

4.1.1.3 Uncertainty

The overall uncertainty associated with the 2022 national estimates of CH_4 from enteric fermentation was calculated using the 2006 IPCC Guidelines Approach 2 methodology (IPCC 2006). As described further in Chapter 5 of the national *Inventory* (EPA 2024), levels of uncertainty in the national estimates in 2022 were −11%/+18% for CH_4. State-level estimates have a higher uncertainty due to apportioning the national or default emission estimates to each state. This approach does not address state-level differences in uncertainty when applying regional diet data or factors. It is important to note that beef and dairy cattle diets can vary significantly even between states that are in similar regions because of the wide variety of forage types being grown on range and pasture land. Additionally, producers often develop unique feed for their livestock based on the availability of specific feed inputs in their area. Regionally derived data were applied at the state level because state-level data were limited or unavailable for many parameters. For more details on national-level uncertainty, see the uncertainty discussion in Section 5.1 of the national *Inventory*.

4.1.1.4 Recalculations

Changes that resulted from recalculations to the state-level estimates are the same as those presented in Section 5.1 of the national *Inventory* (page 5-10), given that improvements in the national *Inventory* will lead directly to improvements in the quality of state-level estimates as well. In particular, consistent with the national *Inventory*, EPA updated the 2021 estimates that had been previously calculated using a simplified method to use the complete method consistent with the full time series.

4.1.1.5 Planned Improvements

Planned improvements to the state-level estimates are the same as those presented in Section 5.1 of the national *Inventory* (page 5-10), given that improvements in the national *Inventory* will lead directly to improvements in the quality of state-level estimates as well. In particular, state-level livestock diet data would be of value for improving estimates of enteric fermentation.

4.1.1.6 References

EPA (U.S. Environmental Protection Agency) (2024) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*. EPA 430-R-24-004. Available online at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

IPCC (Intergovernmental Panel on Climate Change) (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Institute for Global Environmental Strategies. Available online at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

Full citations of references included in Chapter 5.1 (Enteric Fermentation) and Annex 3.10 of the national *Inventory* are available online here: https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-chapter-10-references_0.pdf and https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-annex-3-additional-source-or-sink-categories-part-b.pdf.

4.1.2 Manure Management (NIR Section 5.2)

4.1.2.1 Background

The treatment, storage, and transportation of livestock manure can produce anthropogenic CH_4 and N_2O emissions. Methane is produced by the anaerobic decomposition of manure and N_2O is produced from direct and indirect pathways through the processes of nitrification and denitrification, volatilization, and runoff and leaching. In addition, there are many underlying factors that can affect these resulting emissions from manure management. For CH_4, the type of manure management system, ambient temperature, moisture, and residency (storage) time of the manure affect bacteria growth and therefore subsequent emissions. For N_2O, the composition of the manure (manure includes both feces and urine), the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system affect the resulting emissions.

4.1.2.2 Methods/Approach

EPA compiles state-level emissions from manure management using the same methods applied in the national *Inventory* as summarized in Table 4-3. Estimates are available for all 50 states. Territories are not currently estimated, and tribal lands are not explicitly included based on USDA survey practices, which depend on the presence of the animal on the farm/operation, not the geographic area.

Table 4-3. Approaches to Estimate Manure Management Methane and N_2O Across Time Series

Time Series Range	Method
1990–2022	• Combination of IPCC Tier 1 and 2 approaches as described in the national *Inventory*.

For 1990–2022, please refer to the national *Inventory* Chapter 5, Section 5.2 and Annex 3.11, which provides additional detail on the methods to estimate state-level manure management emissions (EPA 2024). As noted in that section, the basic approach applies a combination of IPCC Tier 1 and Tier 2 methodologies. EPA applies Tier 1 default N_2O emissions factors and CH_4 conversion factors for dry systems from the IPCC (2006), U.S.-specific CH_4 conversion factors for liquid systems, and U.S.-specific values for the volatile solids production rate and the nitrogen excretion rate for some animal types, including cattle values from the CEFM (see Section 4.1.1 Enteric Fermentation).

4.1.2.3 Uncertainty

The overall uncertainty associated with the 2022 national estimates of CH_4 and N_2O from manure management were calculated using the 2006 IPCC Guidelines Approach 2 methodology (IPCC 2006). As described further in Chapter 5 of the national *Inventory* (EPA 2024), levels of uncertainty in the national estimates in 2022 were −18%/+20% for CH_4 and −16%/+24% for N_2O. State-level estimates have a higher uncertainty due to apportioning the national or default emission estimates to each state. This approach does not address state-level differences in uncertainty when applying regional waste management system distributions or factors. These assumptions were applied because state-level data are limited or unavailable for many parameters. For more details on national-level uncertainty, see the uncertainty discussion in Section 5.2 of the national *Inventory* (EPA 2024).

4.1.2.4 Recalculations

Changes that resulted from recalculations to the state-level estimates are the same as those presented in Section 5.2 of the national *Inventory* (page 5-19), given that improvements in the national *Inventory* lead directly to improvements in the quality of state-level estimates as well. In particular, consistent with the national *Inventory*, EPA updated the 2021 estimates that had been previously calculated using a simplified method to use the complete method consistent with the full time series. EPA updated waste management system distribution data for poultry broilers and layers and for beef feedlot animal types and also updated the direct N_2O emission factor for solid storage waste management systems pursuant to guidance in the IPCC *2019 Refinement to the 2006 IPCC Guidelines*. EPA also updated anaerobic digester usage for poultry manure management and for swine manure management and improved the representation of livestock characteristics such as calf typical animal mass and urinary energy for feedlot cattle within the CEFM.

4.1.2.5 Planned Improvements

Planned improvements to the state-level estimates are the same as those presented in Chapter 5, Section 5.2 of the national *Inventory* (page 5-20), given that improvements in the national *Inventory* will lead directly to improvements in the quality of state-level estimates as well.

4.1.2.6 References

EPA (U.S. Environmental Protection Agency) (2024) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*. EPA 430-R-24-004. Available online at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

IPCC (Intergovernmental Panel on Climate Change) (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Institute for Global Environmental Strategies. Available online at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

Full citations of references included in Chapter 5.2 (Manure Management) and Annex 3.11 of the national *Inventory* are available online here: https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-chapter-10-references_0.pdf and https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-annex-3-additional-source-or-sink-categories-part-b.pdf.

4.2 Other (Agriculture)

This section presents the methodology applied to estimate the other agricultural activity emissions, which consist of the following source categories:

- Rice cultivation (CH_4)
- Agricultural soil management (N_2O)
- Liming (CO_2)
- Urea fertilization (CO_2)
- Field burning of agricultural residues (CH_4, N_2O)

4.2.1 Rice Cultivation (NIR Section 5.3)

4.2.1.1 Background

Most of the world's rice is grown on flooded fields that create anaerobic conditions, leading to CH_4 production through a process known as methanogenesis. Approximately 60% to 90% of the CH_4 produced by methanogenic bacteria in flooded rice fields is oxidized in the soil and converted to CO_2 by methanotrophic bacteria. The remainder is emitted to the atmosphere or transported as dissolved CH_4 into groundwater and waterways. Methane is transported to the atmosphere primarily through the rice plants, but some CH_4 also escapes via ebullition (i.e., bubbling through the water) and to a much lesser extent by diffusion through the water.

4.2.1.2 Methods/Approach

EPA compiles state-level CH_4 emissions from rice cultivation using the same methods applied in the national *Inventory*. Rice is currently cultivated in 13 states: Arkansas, California, Florida, Illinois, Kentucky, Louisiana, Minnesota, Mississippi, Missouri, New York, South Carolina, Tennessee, and Texas. This is described in Chapter 5, Section 5.3 (pages 5-21 through 5-28), of the national *Inventory*. Additional information on the methodologies and data is also provided in Annex 3.12.

As described in the national *Inventory*, the methodology used to estimate CH_4 emissions from rice cultivation is based on a combination of IPCC Tier 1 and 3 approaches. The IPCC Tier 3 method utilizes the DayCent process-based model to estimate CH_4 emissions from rice cultivation. DayCent is used to simulate hydrological conditions and thermal regimes, organic matter decomposition, root exudation, rice plant growth and its influence on oxidation of CH_4, as well as CH_4 transport through the plant and via ebullition (Cheng et al. 2013). This method captures the influence of organic amendments and rice straw management on methanogenesis in the flooded soils, and ratooning of rice crops with a second harvest during the growing season. In addition to CH_4 emissions, DayCent simulates soil carbon stock changes and N_2O emissions and allows for a seamless set of simulations for crop rotations that include both rice and non-rice crops (EPA 2024).

The IPCC Tier 1 method is applied to estimate CH_4 emissions from rice when grown in rotation with crops that are not simulated by DayCent, such as vegetable crops. The Tier 1 method is also used for areas converted between agriculture (i.e., cropland and grassland) and other land uses such as forest land, wetland, and settlements. In addition, the Tier 1 method is used to estimate CH_4 emissions from organic soils (i.e., Histosols) and from areas with very gravelly, cobbly, or shaley soils (greater than 35% by volume). The Tier 3 method using DayCent has not been fully tested for estimating emissions associated with these conditions (EPA 2024). The most recent national *Inventory* includes state-level emissions for the 13 states mentioned above for the years 1990–2018, which were used for this report (Approach 1). Cultivated rice areas for the 13 rice-cultivating states are determined from land-use and cropping history information derived from the National Resources Inventory (NRI) for the 1990–2017 period (USDA 2020), and the time series is extended from 2018 to 2020 using crop data provided in the USDA National Agricultural Statistics Service Cropland Data Layer (USDA-NASS CDL) (USDA 2021). Within the national *Inventory*, EPA does not currently directly estimate state-level emissions from rice cultivation for the years 2021–2022, so it is not possible to develop state-level estimates for those years using the same approach. The national-level emissions for 2021–2022 are estimated using a surrogate data method, and were disaggregated to the state level in a two-step process for this report (Approach 2). First, the average proportion of the total national emissions was computed for each state for the years 2018–2020, which are the last three years for which state-level emissions have been estimated. Second, the state-level proportions were multiplied by the total national emissions to approximate the emissions occurring in each state from 2021 to 2022. Data Appendix E-4 to this report lists the total rice cultivated areas of each of the 13 states with rice cultivation across the 1990–2020 time period. State-level rice cultivated areas are disaggregated to show the land area in each state for which the Tier 3 and Tier 1 methods were used to estimate CH_4 emissions from rice cultivation. State-level total rice harvested areas, which account for land area on which a second rice crop is harvested, are also provided in Data Appendix E-4 to this report.

4.2.1.3 Uncertainty

The overall uncertainty associated with national estimates of CH_4 from rice cultivation was calculated using the IPCC Approach 2 (i.e., Monte Carlo simulation). As described in Chapter 5 of the national *Inventory* (EPA 2024), sources of uncertainty include incomplete information on management practices, uncertainties in model structure (i.e., algorithms and parameterization), emissions factors, and variance associated with the NRI sample. Levels of uncertainty in the national CH_4 rice cultivation estimates in 2022 were −34%/+34% of total emissions estimated using the Tier 1 method and −86%/+86% of total emissions estimated using the Tier 3 method, with a combined uncertainty of −73%/+73% of national CH_4 emissions from rice cultivation. Uncertainty will be greater for the years 2021–2022, where a surrogate data method is used to extend the time series past the period over which NRI data and direct emissions estimates are available.

4.2.1.4 Recalculations

Changes that resulted from recalculations to the state-level estimates are the same as those presented in Section 5.3 of the national *Inventory* (page 5-28), given that improvements in the national *Inventory* will lead directly to improvements in the quality of state-level estimates as well. Included in the latest *Inventory* were improvements to the characterization of rice cultivated land areas in the land representation activity data, an extension of crop history data using CDL as described above, and improvements to the characterization of rice cultivation practices (e.g., ratooning, winter flooding) and inputs (e.g., fertilizer and organic amendment additions, crop residue inputs).

4.2.1.5 Planned Improvements

Planned improvements to the state-level estimates are anticipated to be the same as those presented in Section 5.3 of the national *Inventory,* given that improvements in the national *Inventory* will lead directly to improvements in the quality of state-level estimates as well.

4.2.1.6 References

Cheng, K., S.M. Ogle, W.J. Parton, and G. Pan (2013) Predicting Methanogenesis from Rice Paddies Using the DAYCENT Ecosystem Model. *Ecological Modelling*, 261–262(Suppl.): 19–31. Available online at: https://doi.org/10.1016/j.ecolmodel.2013.04.003.

EPA (U.S. Environmental Protection Agency) (2024) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990‑2022*. EPA 430-R-24-004. Available online at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

USDA (U.S. Department of Agriculture) (2020) *2017 National Resources Inventory: Summary Report*. USDA Natural Resources Conservation Service and Center for Survey Statistics and Methodology, Iowa State University. Available online at: https://www.nrcs.usda.gov/sites/default/files/2022-10/2017NRISummary_Final.pdf.

USDA (2021) *CropScape‒Cropland Data Layer*. Accessed July 2021. Available online at: https://nassgeodata.gmu.edu/CropScape/.

Full citations of references included in Chapter 5.3 (Rice Cultivation) and Annex 3.12 of the national *Inventory* are available online here: https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-chapter-10-references_0.pdf and https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-annex-3-additional-source-or-sink-categories-part-b.pdf.

4.2.2 Agricultural Soil Management (NIR Section 5.4)

4.2.2.1 Background

N_2O is naturally produced in soils through the microbial processes of nitrification and denitrification that are driven by the availability of mineral nitrogen. Mineral nitrogen is made available in soils through decomposition of soil organic matter and plant litter, asymbiotic fixation of nitrogen from the atmosphere, and agricultural management practices, which are discussed below.

Several agricultural activities increase mineral nitrogen availability in soils that lead to direct N_2O emissions at the site of a management activity. These activities include synthetic nitrogen fertilization; application of managed livestock manure; application of other organic materials such as biosolids (i.e., treated sewage sludge); deposition of manure on soils by domesticated animals in pastures, range, and paddocks (PRP) (i.e., unmanaged manure); retention of crop residues (nitrogen-fixing legumes and non-legume crops and forages); and drainage of organic soils (i.e., Histosols) (IPCC 2006). Additionally, agricultural soil management activities, including irrigation, drainage, tillage practices, cover crops, and fallowing of land, can influence nitrogen mineralization from soil organic matter and plant litter, as well as levels of asymbiotic nitrogen fixation.

Indirect emissions of N_2O occur when nitrogen is transported from a site and is subsequently converted to N_2O. There are two pathways for indirect emissions: (1) volatilization and subsequent atmospheric deposition of applied/mineralized nitrogen and (2) surface runoff and leaching of applied/mineralized nitrogen into groundwater and surface water.

4.2.2.2 Methods/Approach

EPA compiles state-level N_2O emissions from Agricultural Soil Management using the same methods applied in the national *Inventory*. Please see the methodologies described in Chapter 5, Section 5.4 (pages 5-28 through 5-47), of the national *Inventory*.

For this report, a hybrid of Approach 1 and 2 was applied in developing state-level estimates. Estimates are available for all 50 states and the District of Columbia, with emissions occurring on tribal lands implicitly captured in the estimates for the states within which these lands occur; however, some components of this category are not estimated for Alaska and Hawaii, as described in the national *Inventory*. Specifically, Alaska and Hawaii only have estimates of N_2O emissions that result from applying nitrogen to soils in the form of biosolid waste and livestock manure, including managed manure and manure deposited onto pasture/range/paddock, which is not managed. Soil N_2O emissions in Hawaii are also estimated from crop residue additions to soils. Therefore, soil N_2O emissions associated with synthetic fertilization, mineralization of nitrogen from soil organic matter, and drainage of organic soils (i.e., *Histosols*) are not estimated for Alaska or Hawaii.

Estimates of N_2O emissions from managed croplands and grasslands are not available for Alaska and Hawaii except for managed manure nitrogen, PRP nitrogen, and biosolid additions for Alaska and managed manure and PRP nitrogen, biosolid additions, and crop residue for Hawaii.

Additional information on methodologies and data is also provided in Annex 3.12 of the national *Inventory*.

4.2.2.3 Uncertainty

The overall uncertainty associated with national estimates of N_2O from agricultural soil management is described in Chapter 5 of the national *Inventory* (EPA 2024. Uncertainty is estimated for each of the following five components of N_2O emissions from agricultural soil management: (1) direct emissions simulated by DayCent, (2) the components of indirect emissions (nitrogen volatilized and leached or runoff) simulated by DayCent, (3) direct emissions estimated with the IPCC Tier 1 method, (4) the components of indirect emissions (nitrogen volatilized and leached or runoff) estimated with the IPCC (2006) Tier 1 method, and (5) indirect emissions estimated with the IPCC Tier 1 method.

Levels of uncertainty in the national N_2O agricultural soil management emissions estimates in 2022 were −28%/+28% of the emissions estimate for direct N_2O and −51%/+123% of the emissions estimate for indirect N_2O across all methodologies at the national scale.

4.2.2.4 Recalculations

Changes that resulted from recalculations to the state-level estimates are the same as those presented in Section 5.4 of the national *Inventory* (pages 5-46 and 5-47), given that improvements in the national *Inventory* will lead directly to improvements in the quality of state-level estimates as well. These improvements include an updated time series of land representation data; re-calibration of the soil carbon module in the DayCent model (see Annex 3.12); a more accurate output variable to estimate asymbiotic nitrogen fixation in the Tier 3 method; corrections associated with manure deposited on pasture, range, and paddock; and estimation of leaching based on irrigation status.

4.2.2.5 Planned Improvements

Planned improvements to the state-level estimates are anticipated to be the same as those presented in Section 5.4 (page 5-47) of the national *Inventory,* given that improvements in the national *Inventory* will lead directly to improvements in the quality of state-level estimates as well.

4.2.2.6 References

EPA (U.S. Environmental Protection Agency) (2024) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990*–*2022*. EPA 430-R-24-004. Available online at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

IPCC (Intergovernmental Panel on Climate Change) (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Institute for Global Environmental Strategies. Available online at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

Full citations of references included in Chapter 5.4 (Agricultural Soil Management) and Annex 3.12 of the national *Inventory* are available online here: https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-chapter-10-references_0.pdf and https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-annex-3-additional-source-or-sink-categories-part-b.pdf.

4.2.3 Liming (NIR Section 5.5)

4.2.3.1 Background

Crushed limestone (calcium carbonate) and dolomite ($CaMg[CO_3]_2$) are added to soils by land managers to increase soil pH (i.e., to reduce acidification). CO_2 emissions occur as these compounds react with hydrogen ions in soils. The rate of degradation of applied limestone and dolomite depends on the soil conditions, soil type, climate regime, and whether limestone or dolomite is applied. Emissions from limestone and dolomite that are used in industrial processes (e.g., cement production, glass production) are reported under the IPPU chapter.

4.2.3.2 Methods/Approach

EPA compiles state-level CO_2 emissions from liming using the same methods applied in the national *Inventory*. The national method is a Tier 2 approach based on the amount of limestone and dolomite applied to agricultural soils, multiplied by a country-specific emissions factor. This is described in Chapter 5, Section 5.5 (pages 5-47 through 5-50), of the national *Inventory*.

The current national *Inventory* includes state-level emissions for the years 1990–2021. For this report, a hybrid Approach 1 and Approach 2 was used to extend state-level estimates across the time series. The national estimates for 2022, which were estimated using a linear extrapolation method, are disaggregated to the state level based on the proportion of total CO_2 emissions from carbonate lime application occurring in each state for 2021. Estimates are currently available for all 50 states as well as the District of Columbia and implicitly include emissions from liming occurring on tribal lands.

Within the national activity data that leverage statistics on the application rates of crushed limestone and dolomite for agricultural purposes, a portion of total limestone and dolomite applied nationally are "withheld" and not allocated to specific states to avoid the disclosure of company proprietary data related to poultry grit and mineral food. In order to allocate this withheld pool of limestone and dolomite to states so that the sum of all limestone and dolomite applied to all states and the District of Columbia, the withheld pools of limestone and dolomite were allocated to states relative to the proportion of total limestone/dolomite consumed by each state.

Data Appendix E-5 to this report provides state-level limestone and dolomite agricultural application rates for all 50 states as well as the District of Columbia across the time series. Separate tables are provided where withheld pools of limestone and dolomite are retained as discrete categories and where the withheld pools of limestone and dolomite are allocated to states using the assumptions and methodology described above.

4.2.3.3 Uncertainty

The overall uncertainty associated with national estimates of CO_2 from liming is described in Chapter 5 of the national *Inventory* (EPA 2024). A Monte Carlo uncertainty analysis was applied, and the analysis was performed on the amount of limestone and dolomite applied to soils. The emissions factors included the fraction of lime dissolved by nitric acid versus the fraction that reacts with carbonic acid, as well as the portion of bicarbonate that leaches through the soil and is transported to the ocean. Uncertainty regarding the time associated with leaching and transport is not addressed in the national *Inventory* uncertainty analysis. The overall level of uncertainty in the national CO_2 liming estimates in 2022 was −85%/+89% of national emissions estimates.

4.2.3.4 Recalculations

Limestone and dolomite application data for 2020 and 2021 were updated with the recently acquired data from the U.S. Geological Survey. Changes that resulted from recalculations to the state-level estimates are the same as those presented in Section 5.5 of the national *Inventory* (page 5-50), given that improvements in the national *Inventory* will lead directly to improvements in the quality of state-level estimates as well.

4.2.3.5 Planned Improvements

Planned improvements to the state-level estimates are anticipated to be the same as those presented in Section 5.5 (page 5-50) of the national *Inventory,* given that improvements in the national *Inventory* will lead directly to improvements in the quality of state-level estimates as well. As noted, there are no specific improvements identified at this time for CO_2 emissions from liming.

4.2.3.6 References

EPA (U.S. Environmental Protection Agency) (2024) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990*–*2022*. EPA 430-R-24-004. Available online at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

Full citations of references included in Chapter 5.5 (Liming) of the national *Inventory* are available online here: https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-chapter-10-references_0.pdf.

4.2.4 Urea Fertilization (NIR Section 5.6)

4.2.4.1 Background

The use of urea, or $CO(NH_2)_2$, as a fertilizer leads to GHG emissions through the release of CO_2 that was fixed during the production of urea. In the presence of water and urease enzymes, urea that is applied to soils as fertilizer is converted into ammonium, hydroxyl ion, and bicarbonate. The bicarbonate then evolves into CO_2 and water.

4.2.4.2 Methods/Approach

EPA compiles state-level CO_2 emissions from urea fertilization using the same IPCC Tier 1 methods applied in the national *Inventory* (Approach 1). With this approach, state-level fertilizer sales data are multiplied by the default IPCC emissions factor. This approach is described in Chapter 5, Section 5.6 (pages 5-50 through 5-52), of the national *Inventory*. Estimates are currently available for all 50 states and Puerto Rico and implicitly include emissions from urea applied on tribal lands. Data Appendix E-6 to this report provides seasonal and annual urea fertilizer consumption data by state across the time series, which serve as the underlying activity data used to calculate state-level CO_2 emissions from urea application.

4.2.4.3 Uncertainty

The overall uncertainty associated with national estimates of CO_2 from urea fertilization is described in Chapter 5 of the national *Inventory* (EPA 2024). A Monte Carlo uncertainty analysis was applied. The largest source of uncertainty is the default emissions factor, which assumes that 100% of the carbon in $CO(NH_2)_2$ applied to soils is emitted as CO_2. The overall level of uncertainty in the national CO_2 urea fertilization estimates in 2022 was −43%/+3%.

4.2.4.4 Recalculations

Changes that resulted from recalculations to the state-level estimates are the same as those presented in Section 5.6 of the national *Inventory* (page 5-52), given that improvements in the national *Inventory* will lead directly to improvements in the quality of state-level estimates as well. Updated fertilizer consumption statistics led to time series recalculations at the state level.

4.2.4.5 Planned Improvements

Planned improvements to the state-level estimates are anticipated to be the same as those presented in Section 5.6 (page 5-52) of the national *Inventory,* given that improvements in the national *Inventory* will lead directly to improvements in the quality of state-level estimates as well.

4.2.4.6 References

EPA (U.S. Environmental Protection Agency) (2024) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2022*. EPA 430-R-24-004. Available online at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

Full citations of references included in Chapter 5.6 (Urea Fertilization) of the national *Inventory* are available online here: https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-chapter-10-references_0.pdf.

4.2.5 Field Burning of Agricultural Residues (NIR Section 5.7)

4.2.5.1 Background

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

In the United States, field burning of agricultural residues is more common in southeastern states, the Great Plains, and the Pacific Northwest. The primary crops that are managed with residue burning include corn, cotton, lentils, rice, soybeans, sugarcane, and wheat.

4.2.5.2 Methods/Approach

EPA compiles state-level CH_4 and N_2O emissions from field burning of agricultural residues using the same methods applied in the national *Inventory*. The national *Inventory* applies a country-specific Tier 2 methodology. This is described in Chapter 5, Section 5.7 (pages 5-53 through 5-62), of the national *Inventory*.

The most recent national *Inventory* includes state-level emissions for 1990–2014, but not for 2015–2022. The exception is sugarcane, for which emissions have been estimated for 1990–2020, with 2021 to 2022 emissions estimated using a data splicing method. State estimates were developed using Approach 1 for 1990–2014 and Approach 2 for disaggregating 2015–2022 national estimates. National-level emissions for 2015–2022 are estimated using a linear extrapolation of the pattern from the previous years in the national *Inventory*. For this report, these national totals were disaggregated to the state level in a two-step process. First, the average proportion of the total national emissions was computed for each state for the years 2012–2014, which are the last three years in which state-level emissions had been estimated. Second, the state-level proportions were multiplied by the total national emissions to approximate the amount of emissions occurring in each state from 2015 to 2022. Estimates are currently available for all states excluding Alaska and Hawaii, consistent with the national *Inventory*, because these two states are not captured in the current analysis. Field burning of agricultural residues does not occur in the District of Columbia and as such is not estimated for this area. Emissions from field burning of agricultural residues occurring on tribal lands located in the conterminous United States are implicitly captured in national and state-level estimates. No estimates are included for U.S. territories. See Data Appendix E-7 to this report for the underlying state-level activity data detailing the mass of residue burned and the agricultural area burned by crop type from 1990 to 2014.

4.2.5.3 Uncertainty

The overall uncertainty associated with national estimates of CH_4 and N_2O from field burning of agricultural residues is described in Chapter 5 of the national *Inventory* (EPA 2024). As described in the national *Inventory*, emissions are estimated using a linear regression model with autoregressive moving-average errors for the 2015–2021 period. The linear regression autoregressive moving-average model also produced estimates of the upper and lower bounds to quantify uncertainty.

Because of data limitations, there are additional uncertainties in agricultural residue burning, particularly the potential omission of burning associated with Kentucky bluegrass (produced on farms for turf grass installation). EPA is aware that some agricultural residue burning is not currently captured in the national *Inventory* analysis; please see national *Inventory* planned improvements information. Overall levels of uncertainty in the national CH_4 and N_2O field burning of agricultural residue estimates in 2020 were −11%/+11% for CH_4 and −13%/+13% for N_2O.

4.2.5.4 Recalculations

Changes that resulted from recalculations to the state-level estimates are the same as those presented in Section 5.7 of the national *Inventory* (page 5-62), given that improvements in the national *Inventory* will lead directly to improvements in the quality of state-level estimates as well. Recalculations have been conducted for this *Inventory* to account for field burning of sugarcane residue, which was not included in the previous *Inventory*.

4.2.5.5 Planned Improvements

Planned improvements to the state-level estimates are anticipated to be the same as those presented in Section 5.7 (page 5-62) of the national *Inventory,* given that improvements in the national *Inventory* will lead directly to improvements in the quality of state-level estimates as well.

4.2.5.6 References

EPA (U.S. Environmental Protection Agency) (2024) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990‑2022*. EPA 430-R-24-004. Available online at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

Full citations of references included in Chapter 5.7 (Field Burning of Agricultural Residues) of the national *Inventory* are available online here: https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-chapter-10-references_0.pdf.