U.S. Department of ENERGY

A Generic Counterfactual Greenhouse Gas Emission Factor for Life-Cycle Assessment of Manure-Derived Biogas and Renewable Natural Gas

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A. Introduction

Biogas, a methane (CH_4)-containing gas resulting from the decomposition of organic matter under anaerobic conditions, can be produced from a wide variety of organic feedstocks, including food waste, agricultural residues, and manure. The biogas can be combusted for heat/electricity or upgraded to renewable natural gas (RNG), sometimes referred to as biomethane.[1] The life-cycle greenhouse gas (GHG)-intensities of biogas and RNG are of great interest to policymakers, researchers, and industry decision-makers because GHG-intensities are in some cases tied directly to the monetary incentives received by producers.

There is particular interest in animal manure as an input for biogas production because of the potential for GHG benefits in circumstances where improved manure management practices can be implemented that reduce GHG emissions. Biogas production from animal manure occurs via anaerobic digestion, a process that breaks down organic materials in the absence of oxygen to produce biogas (a mixture of CH_4, carbon dioxide (CO_2), and other trace gases). Putting animal-derived waste materials into an anaerobic digester serves as an alternative to more conventional organic waste management practices, such as storage in open lagoons and land application, although the residual solids and liquid remaining after anaerobic digestion may still be land-applied or composted. Relative to conventional management systems, treating animal manure in a digester has the potential to reduce CH_4 emissions as it facilitates capture and productive use of the biogas. The business-as-usual management of organic waste is referred to as the counterfactual (what would have happened in the absence of a policy or other driver for sending such materials to an anaerobic digester). Life-cycle assessment (LCA) can allow for consideration of counterfactual emissions that are avoided if the organic waste is diverted to anaerobic digesters from other previous management practices. Some conventional management practices for organic wastes, such as certain manure management practices other than sending the materials to digesters, result in substantial emissions.

This white paper focuses on estimating counterfactual emissions for manure generated in the U.S., and specifically on establishing a generic average manure GHG counterfactual emissions value that is agnostic to manure management method and to animal type and can be applied broadly to biogas and RNG production from manures when prior and future manure management practices are varied or uncertain. The basic equations and underlying data needed to calculate counterfactual GHG emissions for average manure are provided, along with numeric results using the most up-to-date data available.

B. Technical Background

Manure management in the U.S. resulted in an estimated 2.31 million metric tons (MMT) of CH_4 emissions in 2022 and 64,000 metric tons (MT) of nitrous oxide (N_2O).[2] Manure is produced from livestock and poultry operations including dairy cattle, beef cattle, swine, sheep, goats, poultry, horses, mules and asses, and bison, although approximately 90% of the CH_4 emissions originate from cattle and swine operations.[1] This outsized share of total emissions is due to differences in how dairy cattle and swine are managed, compared to other livestock and poultry, and the resulting options for managing their manure. Diverting manure from business-as-usual practices by constructing anaerobic digesters to break down manure into usable biogas can avoid direct GHG and other air pollutant emissions, particularly CH_4 emitted from open storage lagoons and deep pit storage. The net impact of manure diversion to anaerobic digestion on N_2O emissions is more nuanced, as the fate of nitrogen depends on how liquid and solid manure is land-applied, and the degree to which those emissions are attributed to manure management versus the crop benefitting from manure as a supplemental fertilizer.[3] This white paper incorporates estimates of both CH_4 and N_2O emissions from manure management. The white paper does not, however, include emissions that occur if/when manure, solid digestate, and liquid digestate are collected and land-applied (e.g., on-field N_2O emissions). These emissions are not included because more data is required to accurately quantify differences between GHG emissions from untreated manure application versus land application of post-anaerobic digestion solids/liquids, as well as the expected net effects on farmers' application of synthetic fertilizers. Future iterations of this approach could include these factors.

Manure management practices vary farm-to-farm and by the type of livestock and poultry operation. It is not uncommon for individual farms to employ several different practices as part of their Manure Management Plan (MMP), which depends on the crops on which manure is eventually land-applied, type(s) and number of livestock and poultry, and systems in place for manure handling.[4] A manure management system includes:[5]

- Where, and how much manure is produced (excreted) by the livestock or poultry
- How manure is collected
- How manure is stored
- What manure treatment is used (e.g., solid-liquid separation)
- How manure is transferred and utilized (e.g., energy generation, supplemental fertilizer)

Tracking and managing manure is difficult because it can change in mass, volume, consistency, and composition during an animal's growth cycle or with a change in feed provided to the animals. Additionally, the composition of manure changes as it passes through the management system (e.g., water is added or removed, bedding may be mixed in). There are three different points at which manure flows can be tracked, and each will result in a different total mass value:

1. Manure as excreted, which includes urine and feces
2. Manure as collected, which potentially includes drinking water, wasted feed, bedding material, and flush or recharge water
3. Manure as stored, which includes any added wastewater, runoff, and direct precipitation into uncovered storage facilities

When discussing total mass of manure, this white paper refers exclusively to manure as excreted (#1 above), unless otherwise noted. However, the list above provides context for why tracking manure for the purposes of calculating avoided manure management emissions can be onerous. Dairy cattle and swine manure as excreted is 88-92% water by mass[5] (8-12% total solids) but the total mass and moisture fraction of manure will vary considerably once it is comingled with bedding, flush water, and other wastewater or runoff. At points where an inflow or outflow of manure might be simplest to track, it may have already been mixed with additional water or other solids.

Availability of data on current manure management by farm is limited because there is no national reporting requirement for MMPs, and state-level reporting requirements and regulations vary.[6] The associated emissions from manure management also vary widely by management practice. Wet methods, such as lagoon and deep pit storage, result in more uncontrolled emissions of CH_4, whereas dry methods, including solid storage, daily spread, and pasture, emit less CH_4. The practical options for controlling CH_4 emissions also vary by MMP. Lagoons can be covered to allow for the capture of biogas for combustion or upgrading to RNG, whereas the head space above deep pit storage must be adequately ventilated for health and safety reasons, meaning the CH_4 concentration at the outlet is typically too low to ignite in a flare or be upgraded cost-effectively.

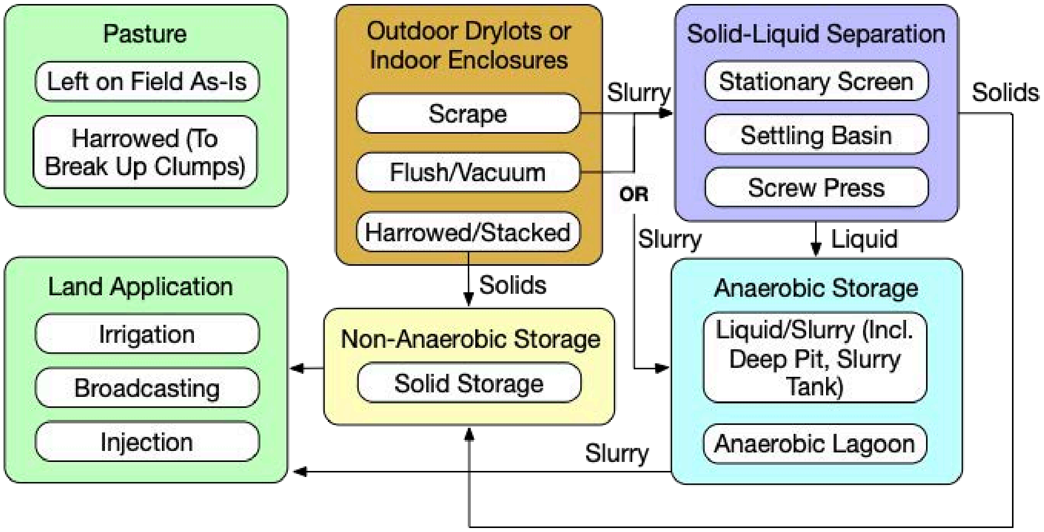

Figure 1: Overview of Common Manure Management Practices, Adapted from Greene et al. (2024)[7]

Manure can be diverted from the conventional practices, as exemplified in Figure 1, to anaerobic digesters. After processing in anaerobic digesters, the produced biogas can be captured and used, either for generation of heat/ power or for upgrading to renewable natural gas (RNG) that is suitable for a variety of uses, including fueling vehicles or electricity generators directly or injection into natural gas pipelines. RNG produced from manure digesters is not cost-competitive with natural gas, absent the availability of subsidies, and the construction of digesters in the last decade has been largely driven by government programs and incentives, such as those provided through the Renewable Fuel Standard and state Low Carbon Fuel Standards. There are manure digesters across the U.S. that currently process dairy cattle, swine, beef cattle, and poultry manure. The AgSTAR Livestock Anaerobic Digester Database[8] lists 473 digesters that are operational or under construction as of 2024, including 52 swine manure digesters, 398 dairy manure digesters, 4 beef cattle manure digesters, and 7 poultry manure digesters. Of those digesters, 104 co-digest the primary type of manure specified with one or more other wastes, including other types of manure, food waste, agricultural residues, and dairy/food processor waste. The relative quantities of different manure types and other wastes co-digested in these anaerobic digesters is not provided in any publicly available datasets. The diversity of feedstocks processed in these digesters further exacerbates the difficulty of tracking specific types of manure sent to anaerobic digestion and assigning avoided emissions values specific to the counterfactual for each type of manure (and how the manure would have otherwise been managed).

The appropriate methods for calculating life-cycle GHG footprints for manure-derived biogas and RNG remain a subject of debate, as technical LCA approaches can justifiably differ based on the specific research or policy context for the analysis. These GHG intensities, sometimes referred to as carbon intensity (CI) scores, can be driven in large part by the assumed counterfactual manure management practices, when included as part of the analysis. Analyses that assume CH_4 emissions are avoided when manure is diverted to anaerobic digestion for the generation of biogas typically apply these avoided emissions in perpetuity (as opposed to a one-time or otherwise limited avoided emissions value). As of 2024, the California Air Resources Board (CARB) had approved manure-derived RNG pathways for the LCFS with GHG intensities from -130 to -532 grams (g) CO_2-equivalent (CO_2e) per megajoule (MJ),[9] Even in the case where detailed facility-specific GHG accounting is done, and a robust verification process is in place, the resulting GHG intensities in CARB's program do not incorporate the potential for broader shifts in livestock or poultry operations and manure management or broader market impacts because of the policy incentive (or in the base case absent any policy incentive) – i.e., these GHG intensities do not take into account any emissions indirectly associated with the changes in supply of biogas or RNG under the policy. For example, one potential indirect effect of significant monetary incentives tied to avoidance of manure CH_4 emissions could be an industry-wide shift away from lower-emitting dry manure management (e.g., solid storage and pasture) toward higher-CH_4-producing wet methods that are better suited for the installation of anaerobic digestion. These types of potential shifts are not accounted for in CARB's facility-specific GHG intensity values.

This white paper discusses a simple, but technically sound approach to estimate a broadly applicable value for avoided GHG emissions for diversion of manure from conventional management practices to anaerobic digesters. Developing a broadly applicable manure counterfactual emissions value, based on a weighted average of all estimated emissions for manure management across the U.S., can be a technically sound approach at this point in time given the paucity of comprehensive and reliable data. The counterfactual emissions value is easily administered, as it assigns credit for estimated emissions avoided from typical manure management practices. If used in policy applications, this approach improves administrability by reducing or eliminating the need for farm-level tracking of historical management practices, which would be highly challenging to administer and verify. The use of a single generic counterfactual emissions value for manure also reduces accounting complexity for farms that process multiple types of manure in a single digester. Finally, this approach helps to address concerns that calculating counterfactual emissions specific to wet methods may overestimate avoided CH_4 if the indirect effects of a policy incentive include a shift from dry to wet manure management.

C. Methodology

A generic manure counterfactual GHG emissions value can be generated based on a weighted average of estimated emissions from all conventional manure management practices across the U.S., inclusive of all types of manure. If adopted for a specific application, this counterfactual GHG (CH_4 and N_2O) emissions value can be uniformly applied to all manure processed in anaerobic digesters for the purpose of generating biogas (and potentially upgrading that biogas to RNG). To simplify the application of the generic manure counterfactual emissions value, it is possible to establish an average manure-to-biogas yield factor and produce the emissions value on a per-unit biogas basis. The resulting counterfactual value can be applied for life-cycle GHG emissions modeling of manure biogas production without the need to track mass or type(s) of manure loaded into digesters. Based on the most up-to-date data available, the manure counterfactual GHG emissions translate to an abated GHG (CH_4 and N_2O) value for the *biomethane portion of untreated biogas* equal to **-53 gCO_2e/standard cubic foot (scf) biomethane in biogas (or -51 gCO_2e/MJ)**. We report this value on the basis of scf of biomethane contained in the untreated biogas, as opposed to scf of the biogas itself to avoid confusion, given that untreated biogas contains other gases including CO_2, and the CH_4 content of biogas varies. Similarly, we also provide the value per MJ lower heating value (LHV) of biomethane contained in the biogas, as the LHV of untreated biogas varies and is impacted by the concentration of other non-CH_4 gases.

This section provides additional details regarding the calculation of the generic manure counterfactual GHG (CH_4 and N_2O) emissions value and the underlying data required to generate and update this value. This value can be applied directly as an estimated emissions *avoidance* credit to any biogas (on a biomethane basis) produced from manure in the U.S. The final GHG intensity of the energy product (e.g., RNG or electricity) should account for emissions downstream of the digester as appropriate, such as biogas upgrading and compression, as well as for any GHG emissions associated with transportation or other processing of the digester inputs and outputs.

Estimated Emissions Per Unit of Manure

At the most basic level, estimation of a generic counterfactual for all manure generated in the U.S. requires that total emissions for manure management be calculated and then allocated across the total manure generated:

Equation 1: GHG emissions per unit of manure (MT= Metric Ton)

$$\left[\frac{\text{MT CO}_2\text{e}}{\text{MT Manure}}\right]$$

Quantification of the Numerator for Equation 1 (MT CO_2e): Calculating a GHG emissions footprint for manure management requires estimated values for CH_4 and N_2O emissions (numerator in Equation 1) from business-as-usual manure management practices for all animal types (dairy cattle, swine, beef cattle, poultry, sheep, goats, horses, mules and asses, and bison). There are no sector-wide reported emissions values for the livestock and poultry sectors (analogous to large-scale measurement campaigns conducted in the oil and gas sector[10]), so all published CH_4 and N_2O emissions values from manure management are based on bottom-up calculations. These calculations are done as part of the Inventory of U.S. Greenhouse Gas Emissions and Sinks (hereafter referred to as the GHG Inventory) using practice-specific emission estimation methods aligned with Intergovernmental Panel on Climate Change (IPCC) Tier 1 and Tier 2 methodologies and publicly available industry statistics and U.S. Department of Agriculture data. For the purposes of this white paper, we used the total CH_4 and N_2O emissions values for manure management from 2022 (reported in the 2024 release of the GHG Inventory[2]), which is the most up-to-date representation of the state of manure management practices and the resulting GHG emissions. The manure management emissions shown in Table 1 include CH_4 and N_2O emissions from the collection and storage of manure, as well as the CH_4 emissions from manure that is directly deposited by animals on pasture, range, or paddock lands. The emissions values in Table 1 account for all manure management practices including the portion of manure that is handled in anaerobic digesters as of 2022 (manure sent to anaerobic digestion is generally less emissions-intensive relative to manure stored in uncovered lagoons or deep pits, depending on the operating period and operating conditions of a covered anaerobic digester). The values in Table 1 do not include direct and indirect N_2O emissions that occur on fields from manure that is collected and spread as supplemental fertilizer (either via daily spread or after storage/anaerobic digestion) as this is highly variable per practice, weather, landowner and operators, biogeochemical conditions, and these GHG emissions profiles would be challenging to track and verify. Additionally, emissions from the spread of manure as supplemental fertilizer may be included as part of the life-cycle GHG footprint of the related agricultural products and omission can help avoid double counting.

Table 1: Estimated 2022 Total CH_4 and N_2O Emissions from Manure Management[11]

Animal Type	MT CH_4 emitted/year	MT N_2O emitted/year
Dairy Cattle	1,193,000	23,000
Swine	851,000	7,000
Poultry	108,000	9,000
Beef Cattle	154,000	24,000
Other (Bison, Goats, Horses, Mules, Sheep)	6,000	1,000
Total	**2,312,000**	**64,000**

The values in Table 1 can be converted to CO_2-equivalents (CO_2e) using 100-year global warming potential (GWP100) (see Table 2). This white paper uses Fifth IPCC Assessment Report (AR5) GWP100 values.[12] The AR5 GWP100 value for CH_4 is 28. The AR5 GWP100 value for N_2O is 265. The total emissions of manure management in the U.S. are estimated to be 81,696,000 MT CO_2e/year using AR5 GWP100 values, as shown in Table 2. This value is used for the numerator in Equation 1.

Table 2: 2022 GHG Emissions (CH_4 and N_2O) on a GWP100 Basis for Manure Management in the U.S.

Animal Type	AR5 GWP100[13] (MT CO_2e/year)
Dairy Cattle	39,499,000
Swine	25,683,000
Poultry	5,409,000
Beef Cattle	10,672,000
Other (Bison, Goats, Horses, Mules, Sheep)	433,000
Total	**81,696,000**

Quantification of the Denominator for Equation 1 (MT Manure): Quantities of each type of manure produced, based on the most recent data available, are required to complete an updated bottom-up calculation of generalized GHG-intensity of biogas and related manure management in the U.S. The total manure generated across all animal types must be calculated and used as the denominator in Equation 1 to produce a generic value for mass CO_2e emitted in the business-as-usual counterfactual scenario per mass of manure, which can later be converted to a per-unit-biomethane basis. For the estimate provided in this white paper, the manure production total was derived for 2022 as published in the 2024 GHG Inventory submission,[2] which provides estimates of total manure production on a volatile solids (VS) basis by combining per-animal manure production estimates with total heads by animal type. The total estimated VS production per year is shown in Table 3.

To calculate the total as-excreted manure, this paper applies the following steps. First, take the VS manure production shown in Table 3 and divide it by the VS fraction[13] of total solids (TS). This will be different for each species and will result in the TS of manure. Second, divide TS by the total solids fraction of as-excreted manure (calculated as one minus the moisture content in Equation 2) to calculate the as-excreted total manure, and then sum the resulting quantity for each species. Equation 2 depicts this method.

Equation 2 Calculation of total manure mass as excreted

$$\text{MT Manure} = \sum_{i \in livestock} \frac{\text{TS}_\text{i}}{(1 - M_i)}$$

Where: M_i is the moisture content (fraction) of as-excreted manure for each species and TS_i is the TS in metric tons. TS_i is calculated as follows:

$$\text{TS}_i = X_i \times \text{VS}_\text{i}$$

Where: X_i is the ratio of

$$\frac{\text{TS}}{\text{VS}}$$

taken from Lorimor et al. 2005.[13] This ratio will be different for each species. Table 3 shows both the TS and total manure values alongside the specific VS fraction of TS and moisture content of manure for each species.

Table 3: 2022 Total U.S. Manure Production by Animal Type on the Basis of Volatile Solids, Total Solids, and Total Mass (Including Water Content) rounded to the nearest metric ton. MT=metric tons, VS=volatile solids, TS=total solids.

Animal Type	2022 Manure Production (VS, MT/year)[14]	Volatile Solids Fraction of TS[15]	Calculated 2022 Manure Production (TS, MT/year)	Estimated Moisture Content in As-Excreted Manure[15]	Calculated As-Excreted Total Manure (MT/year)
Dairy Cattle	**34,473,946**	**-**	**40,617,184**	**-**	**338,476,533**
Dairy Cows	27,287,966	85%	32,164,166	88%	268,034,716
Dairy Heifer	5,514,470	85%	6,468,100	88%	53,900,835
Dairy Calves	1,671,510	84%	1,984,918	88%	16,540,982
Swine	**7,744,408**	**-**	**9,531,700**	**-**	**87,878,704**
Market <50 lb	880,468	81%	1,080,573	89%	9,823,392
Market 50-119 lb	1,467,045	80%	1,833,806	89%	16,670,964
Market 120-179 lb	1,930,673	79%	2,430,218	89%	22,092,893
Market >180 lb	2,266,764	80%	2,837,532	89%	25,795,748
Market Breeding	1,199,458	89%	1,349,571	90%	13,495,706
Beef Cattle	**86,527,132**	**-**	**102,749,993**	**-**	**931,812,553**
Feedlot Steers	6,195,088	82%	7,595,988	92%	94,949,844
Feedlot Heifers	3,512,418	82%	4,306,683	92%	53,833,542
NOF Bulls	3,682,950	85%	4,356,178	88%	36,301,481
NOF Calves	5,248,300	84%	6,232,356	92%	77,904,447
NOF Heifers	9,662,220	85%	11,418,987	88%	95,158,225
NOF Steers	7,602,985	85%	8,985,346	88%	74,877,881
NOF Cows	50,623,172	85%	59,854,456	88%	498,787,133
Sheep	**802,666**	**-**	**926,153**	**-**	**3,704,612**
Sheep on Feed	**193,131**	**87%**	**222,843**	**75%**	**891,372**
Sheep NOF	**609,535**	**87%**	**703,310**	**75%**	**2,813,240**
Goats	**616,050**	**87%**	**710,827**	**75%**	**2,843,307**
Poultry	**14,224,432**	**-**	**18,883,668**	**-**	**73,650,822**
Hens >1yr	2,530,489	73%	3,467,707	75%	13,870,828
Pullets	861,733	76%	1,133,859	75%	4,535,437
Other Chickens	49,209	75%	65,864	75%	263,456
Broilers	9,306,212	76%	12,245,016	74%	47,096,214
Turkeys	1,476,790	75%	1,971,222	75%	7,884,888
Horses	**2,076,991**	**85%**	**2,448,331**	**86%**	**17,488,080**
Mules and Asses	**117,182**	**85%**	**138,133**	**86%**	**986,667**
American Bison	**375,474**	**85%**	**444,110**	**88%**	**3,700,913**
TOTAL	**146,958,281**	**-**	**176,450,099**	**-**	**1,460,542,191**

Combining the total GHG emissions and total manure values in Equation 1 gives the following results (using AR5 GWP100 values):

- 0.56 kg CO_2e per kg manure (VS only)
- 0.46 kg CO_2e per kg manure (TS only)
- 0.056 kg CO_2e per kg manure (total manure mass, as excreted including moisture)

Estimated Emissions Per Unit Biomethane

There are two facility-specific factors that could impact the GHG estimates for manure-derived RNG: digester performance (e.g., yield of biogas per unit manure processed, leakage, energy requirements) and the performance of the upgrader that converts biogas to RNG by removing CO_2, water vapor, and other trace contaminants to produce a relatively pure biomethane output (e.g., RNG yield, leakage, and energy requirements). Other factors, such as transportation of manure and digestate, also impact GHG emissions and these factors are included in the white paper as well. Establishing clear system boundaries and the intended end use of the RNG is also essential, as this determines the degree to which additional RNG compression-related energy use and emissions should be included. The possible range of GHG intensities for RNG depends on whether the GHG intensity is generated for RNG from an individual facility using performance metrics specific to that facility's operations (referred to as foreground data in some LCA models) or whether industry-wide average default values for facility performance are used (referred to as background data). If biogas is *not* upgraded to RNG, but instead combusted to generate electricity and/or heat, the GHG intensity of the electricity or heat also would be affected by the digester performance and efficiency of the heat/power generation.

Digester performance (biogas yield per unit of manure input): Different digester designs, operating conditions, and feedstocks will impact biogas yields. Anaerobic digester operators may also choose to co-digest manure alongside other food wastes or wastewater to achieve the optimal carbon-to-nitrogen ratio for maximal biogas yields. Assigning appropriate facility-specific manure emissions abatement credits based on individual manure types and quantities would require operators to track each type of manure entering the digester and document the total solids in the manure separately from additional water or other materials that have been mixed with the manure prior to entering the digester. Conversely, it is possible to calculate an average biogas yield per unit manure and use this single value as background data (in place of detailed facility-specific tracking) in a life-cycle GHG model, which can simplify the GHG accounting and related tracking and verification processes if required in specific contexts.

Assuming digester performance is provided as background data in an LCA, an average biogas conversion must be developed. Units:

$$\left[\frac{\text{scf CH}_4\text{ in biogas}}{\text{MT manure}}\right]$$

When combined with the GHG calculation described above (0.056 $kgCO_2e$/kg manure as excreted), this would produce a GHG emissions estimate in units of:

$$\left[\frac{\text{gCO}_2\text{e}}{\text{scf CH}_4\text{ in biogas}}\right]$$

The average digester emissions intensity is expected to be different for each digester technology and animal species. To generate a generic digester emissions factor for the purposes of this white paper, using the values from R&D GREET 2023 (hereafter referred to as R&D GREET), the digester technology values were averaged and applied to a manure-weighted average for each species. These calculations resulted in a fixed yield of 0.61 standard cubic foot (scf) biomethane in biogas per kg manure (as excreted) used for this white paper to calculate the resulting emissions factor of -90 gCO_2e/scf biomethane in biogas (the negative value indicates GHG emissions avoidance).[15] The emissions intensity of operating the digester was calculated as a manure-weighted average of the three primary digester technologies (covered lagoon, mixed plug flow, and complete mix) from R&D GREET. The resulting emissions intensity of operating the digester is 39 gCO_2e/MJ biomethane in biogas. This value assumes grid electricity and natural gas are used to supply the energy necessary to operate the digester. It also includes a 3-mile truck hauling distance for manure processed in the digester, as well as 3-mile truck transport to backhaul digestate for application to land. If digester yield and performance are used as background data, the -90 gCO_2e/MJ and 39 gCO_2e/MJ values are summed to calculate a net GHG intensity (including the credit for counterfactual GHG emissions and positive GHG emissions from anaerobic digestion) of approximately **-53 gCO_2e/scf biomethane in biogas (or -51 gCO_2e/MJ)** for digesters exclusively processing manure. Assigning default digester performance values as background data in an LCA model based on a weighted average across different manure types is a robust technical approach, given the uncertainties and heterogeneity of underlying systems, that alleviates some of the challenges of tracking quantities and types of manure processed for the purposes of subsequently using those values to calculate GHG intensities for the resulting biogas, electricity, and/or RNG. This value does not include indirect effects, such as potential increased demand for synthetic fertilizer on farms previously land-applying manure, although solid and liquid digestate is assumed to be land applied.

Electricity and heat generation performance: Manure anaerobic digesters often use biogas for power generation or cogeneration of heat and power. Of the 473 manure digesters listed in the AgSTAR Digester Database, 90 list cogeneration as their biogas end use, 70 list electricity, 13 list boiler/furnace fuel, and 14 list co-generation as one of multiple biogas end uses. Heat may be required to maintain an optimal temperature in the digester(s), among other uses. If biogas is used exclusively to generate and export electricity, a GHG intensity can be calculated by adding any additional leakage emissions to the counterfactual emissions value and dividing by the total electricity exported, resulting in a factor with the following units:

$$\left[\frac{\mathrm{gCO_2e}}{\mathrm{MJ\ electricity}}\right]$$

For example, assuming the standard R&D GREET reciprocating engine efficiency of 30% and an additional biogas leakage rate of 2% associated with the power generation portion of the facility,[16] the GHG intensity of the electricity is calculated as -165 gCO_2e/MJ electricity (-601 gCO_2e/kWh).

RNG upgrader performance: RNG upgraders are the facilities that take in biogas and remove CO_2, water vapor, and other impurities. Upgraders require electricity and can make investments to improve their efficiency and reduce leakage rates. Upgraders may be co-located with an anaerobic digester or biogas may be transported from multiple digesters to a centralized upgrading facility. Upgrader performance (RNG yield per unit of biogas input and the upgraders' energy demand and source of energy) varies by facility but may be relatively straightforward to document and verify. Where appropriate in the context of the policy application, enabling users of an LCA tool to enter facility-specific data could provide an incentive to improve their efficiency and source clean energy to run their operations. Units of resulting RNG:

$$\left[\frac{\mathrm{gCO_2e}}{\mathrm{MJ\ RNG}}\right]$$

The standard GHG intensity from R&D GREET[16] for RNG upgraders of biogas from manure anaerobic digesters is 19.4 gCO_2e/MJ RNG at pipeline injection (including leakage and upstream emissions associated with grid electricity supply). When combined with the biogas GHG intensity **(-51 gCO_2e/MJ of biomethane in biogas**) this would result in a **GHG intensity of -31 gCO_2e/MJ RNG** when rounded to the nearest gram. This estimated GHG intensity of RNG includes the credit for avoided emissions from conventional manure management (except emissions from land application as supplemental fertilizer), all life-cycle emissions from managing manure using anaerobic digestion, and life-cycle emissions from upgrading to RNG. It does not include net GHG emissions effects associated with potential changes in nutrient management as a result of managing manure using anaerobic digestion rather than direct land application due to the heterogeneity of on-farm practices and lack of reliable data. Future iterations of this approach could incorporate these and other factors to improve the comprehensiveness of the GHG emissions estimates.

D. Summary and Potential for Future Updates

A generic manure counterfactual GHG emissions value is a simple, technically sound, and transparent option for incorporating avoided emissions credits in LCA in a manner that reduces the challenges involved in tracking the specific type(s) of manure loaded into each digester and each facility's past and expected future manure management practices in the absence of monetary incentives. The inclusion of all manure management practices, and hence all types of manure, is based on the acknowledgement that monetary incentives provided for manure RNG could cause broader shifts in manure management away from lower-emitting dry methods to wet methods that facilitate the additional production and use of biogas. This white paper provides a streamlined calculation approach based on the best-available data as of December 2024. However, future updates to this approach are possible based on updated national emissions inventories and more comprehensive, detailed, and robust reporting of manure production and management practices in the livestock and poultry industries at a national scale.

Endnotes

[1] See https://afdc.energy.gov/fuels/natural-gas-renewable

[2] EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

[3] Zhou, M., Zhu, B., Wang, S., Zhu, X., Vereecken, H., & Brüggemann, N. (2017). Stimulation of N2O emission by manure application to agricultural soils may largely offset carbon benefits: A global meta-analysis. Global Change Biology, 23(10), 4068-4083. https://doi.org/10.1111/gcb.13648.

[4] Purdue Cooperative Extensive Service (1999) "Swine Manure Management Planning" https://www.extension.purdue.edu/extmedia/id/id-205.html

[5] Varma, V. S., Parajuli, R., Scott, E., Canter, T., Lim, T. T., Popp, J., & Thoma, G. (2021). Dairy and swine manure management–Challenges and perspectives for sustainable treatment technology. Science of The Total Environment, 778, 146319. https://doi.org/10.1016/j.scitotenv.2021.146319.

[6] Rosov, K. A., Mallin, M. A., & Cahoon, L. B. (2020). Waste nutrients from US animal feeding operations: Regulations are inconsistent across states and inadequately assess nutrient export risk. Journal of Environmental Management, 269, 110738. https://doi.org/10.1016/j.jenvman.2020.110738.

[7] Greene, J. M., Wallace, J., Williams, R. B., Leytem, A. B., Bock, B. R., McCully, M., ... & Quinn, J. C. (2024). National Greenhouse Gas Emission Reduction Potential from Adopting Anaerobic Digestion on Large-Scale Dairy Farms in the United States. Environmental Science & Technology, 58(28), 12409-12419. https://doi.org/10.1021/acs.est.4c00367.

[8] U.S. EPA. Livestock Anaerobic Digester Database. https://www.epa.gov/agstar/livestock-anaerobic-digester-database

[9] California Air Resources Board. LCFS Pathway Certified Carbon Intensities. LCFS Pathway Certified Carbon Intensities | California Air Resources Board.

[10] Sherwin, E.D., Rutherford, J.S., Zhang, Z. et al. US oil and gas system emissions from nearly one million aerial site measurements. Nature 627, 328–334 (2024). https://doi.org/10.1038/s41586-024-07117-5

[11] GHG Inventory Table 5-6

[12] GWPs of GHGs are published periodically by the Intergovernmental Panel on Climate Change (IPCC). The Fifth Assessment Report GWPs are currently utilized in reporting to the United Nations Framework Convention on Climate Change (UNFCCC). See: Subsidiary Body for Scientific and Technological Advice, "Common metrics used to calculate the carbon dioxide equivalence of anthropogenic greenhouse gas emissions by sources and removals by sinks," UNFCCC; 2022, Sharm el-Sheikh. https://unfccc.int/sites/default/files/resource/sbsta2022_L25a01E.pdf

[13] Calculated based on published values for total solids and volatile solids by animal in Table 6 in Michigan State University's Manure Characteristics report: https://www.canr.msu.edu/uploads/files/ManureCharacteristicsMWPS-18_1.pdf

[14] Estimated using animal counts and volatile solids production per animal provided in Tables A-155 through A-158 the 2024 GHG Inventory submission, available in Annex 3: https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-annex-3-additional-source-or-sink-categories-part-b.pdf. Cattle VS production is reported on a statewide basis in table A-158. To get to a national VS production factor of kg/animal-year factor the statewide VS production is weighted based upon the statewide manure emissions data reported in Table A-171. All of these tables are reproduced in the Appendix of this white paper.

[15] Digester and upgrader yield and performance are generated from R&D GREET 2023. U.S. Department of Energy. R&D GREET Life Cycle Assessment Model. R&D GREET Life Cycle Analysis Model | Department of Energy.

U.S. Department of Energy. R&D GREET Life Cycle Assessment Model. R&D GREET Life Cycle Analysis Model | Department of Energy.

[16] The 2% leakage rate is the default rate for electric generator sets from biogas in R&D GREET 2023.

Appendix

Table A1 Copy of table A-155 from Annex 3 of the 2024 GHG Inventory submission[2]: Livestock Population (1,000 head)

Animal Type	1990	2005	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Dairy Cattle	**19,512**	**17,793**	**18,587**	**18,505**	**18,517**	**18,812**	**18,857**	**18,923**	**19,006**	**18,849**	**18,804**	**18,828**	**18,626**
Dairy Cows	10,015	9,004	9,236	9,221	9,209	9,312	9,312	9,369	9,432	9,353	9,343	9,442	9,377
Dairy Heifer	4,129	4,162	4,581	4,523	4,571	4,727	4,785	4,757	4,741	4,677	4,637	4,562	4,394
Dairy Calves	5,369	4,628	4,770	4,761	4,737	4,774	4,760	4,797	4,833	4,818	4,825	4,823	4,855
Swine[a]	**53,941**	**61,073**	**66,363**	**65,437**	**64,195**	**68,178**	**70,065**	**72,125**	**73,430**	**76,898**	**77,267**	**74,100**	**73,362**
Market <50 lb.	18,359	20,228	19,472	19,002	18,939	19,843	20,572	20,973	21,359	22,278	22,047	21,219	21,086
Market 50-119 lb.	11,734	13,519	17,140	16,834	16,559	17,577	18,175	18,767	19,039	20,195	20,153	19,318	19,085
Market 120-179 lb.	9,440	11,336	12,714	12,674	12,281	13,225	13,575	13,982	14,311	14,852	15,143	14,457	14,405
Market >180 lb.	7,510	9,997	11,199	11,116	10,525	11,555	11,714	12,282	12,418	13,138	13,604	12,918	12,638
Breeding	6,899	5,993	5,839	5,812	5,892	5,978	6,030	6,122	6,303	6,435	6,321	6,187	6,147
Beef Cattle[b]	**81,576**	**82,193**	**76,858**	**76,010**	**74,966**	**76,149**	**79,323**	**81,385**	**81,722**	**82,049**	**80,812**	**80,525**	**79,389**
Feedlot Steers	6,357	8,116	8,586	8,613	8,696	8,594	9,017	9,560	9,605	9,706	9,685	9,691	9,960
Feedlot Heifers	3,192	4,536	4,742	4,655	4,518	4,334	4,433	4,786	5,085	5,210	5,250	5,253	5,514
NOF Bulls	2,160	2,214	2,100	2,074	2,038	2,109	2,137	2,244	2,252	2,253	2,237	2,211	2,110
Beef Calves	16,909	16,918	15,288	14,805	14,737	14,998	15,546	15,931	16,221	16,146	15,635	15,631	15,244
NOF Heifers	10,182	9,550	8,687	8,780	8,730	9,291	9,892	9,790	9,460	9,257	9,066	9,181	8,896
NOF Steers	10,321	8,185	7,173	7,451	7,291	7,491	8,133	7,904	7,633	7,786	7,600	7,714	7,682
NOF Cows	32,455	32,674	30,282	29,631	28,956	29,332	30,164	31,171	31,466	31,691	31,339	30,844	29,983
Sheep	**11,358**	**6,135**	**5,375**	**5,360**	**5,235**	**5,270**	**5,295**	**5,270**	**5,265**	**5,230**	**5,200**	**5,170**	**5,065**
Sheep On Feed	1,180	2,976	2,669	2,658	2,588	2,587	2,624	2,618	2,623	2,616	2,611	2,596	2,550
Sheep NOF	10,178	3,159	2,706	2,702	2,647	2,683	2,671	2,652	2,642	2,614	2,589	2,574	2,515
Goats	**2,516**	**2,897**	**2,622**	**2,637**	**2,652**	**2,668**	**2,683**	**2,699**	**2,714**	**2,729**	**2,745**	**2,753**	**2,776**
Poultry[c]	**1,537,074**	**2,150,410**	**2,168,697**	**2,106,502**	**2,116,333**	**2,134,445**	**2,173,216**	**2,214,462**	**2,256,552**	**2,276,951**	**2,269,691**	**2,254,998**	**2,249,441**
Hens >1 yr.	273,467	348,203	346,965	361,403	370,637	351,656	377,299	388,006	402,536	403,102	391,010	393,078	377,606
Pullets	73,167	96,809	104,460	106,646	106,490	118,114	112,061	117,173	124,729	121,971	119,898	123,179	128,590
Chickens	6,545	8,289	6,827	6,853	6,403	7,211	6,759	6,859	6,626	7,130	7,371	6,447	6,809
Broilers	1,066,209	1,613,091	1,625,945	1,551,600	1,553,636	1,579,764	1,595,764	1,620,691	1,643,327	1,668,582	1,676,745	1,660,127	1,666,436
Turkeys	117,685	84,018	84,500	80,000	79,167	77,700	81,333	81,733	79,333	76,167	74,667	72,167	70,000

Animal Type	1990	2005	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Horses	2,212	3,875	3,621	3,467	3,312	3,157	3,002	2,847	2,692	2,538	2,383	2,233	2,073
Mules and Asses	63	212	293	298	303	308	313	318	323	328	333	337	343
American Bison	47	212	162	166	171	175	179	184	188	193	197	201	209

[a] Prior to 2008, the Market <50 lbs category was <60 lbs and the Market 50-119 lbs category was Market 60-119 lbs; USDA updated the categories to be more consistent with international animal categories.

[b] NOF - Not on Feed,

[c] Pullets includes laying pullets, pullets younger than 3 months, and pullets older than 3 months.

Note: Totals may not sum due to independent rounding.

Table A2 Copy of A-156 from 2024 GHG Inventory submission[2]: Waste Characteristics Data

	Typical Animal Mass, TAM		Total Nitrogen Excreted, Nex[a]		Maximum Methane Generation Potential, B_0		Volatile Solids Excreted, VS[a]	
Animal Group	Value (kg)	Source	Value	Source	Value (m^3 CH_4/kg VS added)	Source	Value	Source
Dairy Cows	680	CEFM[b]	Table A-158	CEFM	0.24	Morris 1976	Table A-158	CEFM
Dairy Heifers	406-408	CEFM	Table A-158	CEFM	0.17	Bryant et al. 1976	Table A-158	CEFM
Feedlot Steers	419-457	CEFM	Table A-158	CEFM	0.33	Hashimoto 1981	Table A-158	CEFM
Feedlot Heifers	384-430	CEFM	Table A-158	CEFM	0.33	Hashimoto 1981	Table A-158	CEFM
NOF Bulls	831-917	CEFM	Table A-158	CEFM	0.17	Hashimoto 1981	Table A-158	CEFM
NOF Calves	122-123	CEFM	Table A-158	USDA 1996, 2008	0.17	Hashimoto 1981	Table A-158	USDA 1996, 2008
NOF Heifers	296-407	CEFM	Table A-158	CEFM	0.17	Hashimoto 1981	Table A-158	CEFM
NOF Steers	314-335	CEFM	Table A-158	CEFM	0.17	Hashimoto 1981	Table A-158	CEFM
NOF Cows	554-611	CEFM	Table A-158	CEFM	0.17	Hashimoto 1981	Table A-158	CEFM
American Bison	578.5	Meagher 1986	Table A-158	CEFM	0.17	Hashimoto 1981	Table A-158	CEFM
Market Swine <50 lbs.	13	ERG 2010a	Table A-157	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-157	USDA 1996, 2008
Market Swine <60 lbs.	16	Safley 2000	Table A-157	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-157	USDA 1996, 2008
Market Swine 50-119 lbs.	39	ERG 2010a	Table A-157	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-157	USDA 1996, 2008
Market Swine 60-119 lbs.	41	Safley 2000	Table A-157	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-157	USDA 1996, 2008
Market Swine 120-179 lbs.	68	Safley 2000	Table A-157	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-157	USDA 1996, 2008
Market Swine >180 lbs.	91	Safley 2000	Table A-157	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-157	USDA 1996, 2008
Breeding Swine	198	Safley 2000	Table A-157	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-157	USDA 1996, 2008
Feedlot Sheep	25	EPA 1992	Table A-157	ASAE 1998, USDA 2008	0.36	EPA 1992	Table A-157	ASAE 1998, USDA 2008
NOF Sheep	80	EPA 1992	Table A-157	ASAE 1998, USDA 2008	0.19	EPA 1992	Table A-157	ASAE 1998, USDA 2008
Goats	64	ASAE 1998	Table A-157	ASAE 1998	0.17	EPA 1992	Table A-157	ASAE 1998
Horses	450	ASAE 1998	Table A-157	ASAE 1998, USDA 2008	0.33	EPA 1992	Table A-157	ASAE 1998, USDA 2008
Mules and Asses	130	IPCC 2006	Table A-157	IPCC 2006	0.33	EPA 1992	Table A-157	IPCC 2006
Hens >/= 1 yr	1.8	ASAE 1998	Table A-157	USDA 1996, 2008	0.39	Hill 1982	Table A-157	USDA 1996, 2008
Pullets	1.8	ASAE 1998	Table A-157	USDA 1996, 2008	0.39	Hill 1982	Table A-157	USDA 1996, 2008
Other Chickens	1.8	ASAE 1998	Table A-157	USDA 1996, 2008	0.39	Hill 1982	Table A-157	USDA 1996, 2008
Broilers	0.9	ASAE 1998	Table A-157	USDA 1996, 2008	0.36	Hill 1984	Table A-157	USDA 1996, 2008

	Typical Animal Mass, TAM		Total Nitrogen Excreted, Nex[a]		Maximum Methane Generation Potential, B_0		Volatile Solids Excreted, VS[a]	
Turkeys	6.8	ASAE 1998	Table A-157	USDA 1996, 2008	0.36	Hill 1984	Table A-157	USDA 1996, 2008

[a] Nex and VS values vary by year; Table A-158 shows state-level values for 2022 only. CEFM = Cattle Enteric Fermentation Model

[b] CEFM = Cattle Enteric Fermentation Model, used within the Enteric Fermentation Category of the U.S. GHG Inventory. See Chapter 5.1 and Annex 3.10.[2]

Table A3 Copy of Table A-157 from 2024 GHG Inventory submission[2]: Estimated Volatile Solids (VS) and Total Nitrogen Excreted (Nex) Production Rates by year for Swine, Poultry, Sheep, Goats, Horses, Mules and Asses, and Cattle Calves (kg/day/1000 kg animal mass)

Animal Type	1990	2005	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
VS																	
Swine, Market <50 lbs.	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8
Swine, Market 50-119 lbs.	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Swine, Market 120-179 lbs.	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Swine, Market >180 lbs.	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Swine, Breeding	2.6	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
NOF Cattle Calves	6.4	7.4	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
Sheep	9.2	8.6	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Goats	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Hens >1yr.	10.1	10.1	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Pullets	10.1	10.1	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Chickens	10.8	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
Broilers	15	16.5	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17
Turkeys	9.7	8.8	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Horses	10	7.3	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Mules and Asses	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Nex																	
Swine, Market <50 lbs.	0.6	0.84	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Swine, Market 50-119 lbs.	0.42	0.51	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Market 120-179 lbs.	0.42	0.51	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Market >180 lbs.	0.42	0.51	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Breeding	0.24	0.21	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
NOF Cattle Calves	0.3	0.41	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sheep	0.42	0.44	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Goats	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Hens >1yr.	0.7	0.77	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
Pullets	0.7	0.77	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
Chickens	0.83	1.03	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Broilers	1.1	1	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Turkeys	0.74	0.65	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63

Animal Type	1990	2005	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Horses	0.3	0.26	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Mules and Asses	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Table A4 Copy of Table A-158 from 2024 GHG Inventory submission[2]: Estimated Volatile Solids (VS) and Total Nitrogen Excreted (Nex) Production Rates by State for Cattle (other than Calves) and American Bison[a] for 2022 (kg/animal/year)

Volatile Solids										Nitrogen Excreted								
State	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison
Alabama	1,951	1,255	1,665	1,096	974	637	622	1,721	1,721	122	69	73	50	42	59	61	83	83
Alaska	1,099	1,255	1,892	1,268	1,120	637	622	1,956	1,956	84	69	59	42	33	59	61	69	69
Arizona	2,911	1,255	1,892	1,239	1,120	637	622	1,956	1,956	162	69	59	40	33	59	61	69	69
Arkansas	1,945	1,255	1,665	1,093	974	637	622	1,721	1,721	120	69	73	50	42	59	61	83	83
California	2,895	1,255	1,892	1,219	1,120	637	622	1,956	1,956	160	69	59	39	33	59	61	69	69
Colorado	3,038	1,255	1,892	1,196	1,120	637	622	1,956	1,956	167	69	59	38	33	59	61	69	69
Connecticut	2,886	1,255	1,674	1,093	980	637	622	1,731	1,731	161	69	74	50	42	59	61	84	84
Delaware	2,432	1,255	1,674	1,101	980	637	622	1,731	1,731	141	69	74	51	42	59	61	84	84
Florida	2,644	1,255	1,665	1,108	974	637	623	1,721	1,721	152	69	73	51	42	59	61	83	83
Georgia	2,803	1,255	1,665	1,105	974	637	622	1,721	1,721	159	69	73	51	42	59	61	83	83
Hawaii	1,099	1,255	1,892	1,259	1,120	637	622	1,956	1,956	84	69	59	41	33	59	61	69	69
Idaho	2,995	1,255	1,892	1,213	1,120	637	622	1,956	1,956	165	69	59	39	33	59	61	69	69
Illinois	2,702	1,255	1,589	1,014	927	637	622	1,643	1,643	153	69	75	50	43	59	61	85	85
Indiana	2,874	1,255	1,589	1,020	927	637	622	1,643	1,643	160	69	75	50	43	59	61	85	85
Iowa	2,944	1,255	1,589	993	927	637	622	1,643	1,643	163	69	75	48	43	59	61	85	85
Kansas	2,891	1,255	1,589	982	927	637	622	1,643	1,643	161	69	75	47	43	59	61	85	85
Kentucky	2,693	1,255	1,665	1,082	974	637	622	1,721	1,721	154	69	73	49	42	59	61	83	83
Louisiana	2,034	1,255	1,665	1,106	974	637	622	1,721	1,721	124	69	73	51	42	59	61	83	83
Maine	2,693	1,255	1,674	1,093	980	637	622	1,731	1,731	152	69	74	50	42	59	61	84	84
Maryland	2,635	1,255	1,674	1,095	980	637	621	1,731	1,731	150	69	74	51	42	59	61	84	84
Massachusetts	2,662	1,255	1,674	1,108	980	637	622	1,731	1,731	151	69	74	52	42	59	61	84	84
Michigan	3,151	1,255	1,589	1,009	927	637	622	1,643	1,643	172	69	75	49	43	59	61	85	85
Minnesota	2,829	1,255	1,589	1,013	927	637	622	1,643	1,643	158	69	75	49	43	59	61	85	85
Mississippi	2,115	1,255	1,665	1,098	974	637	622	1,721	1,721	129	69	73	50	42	59	61	83	83
Missouri	2,150	1,255	1,589	1,033	927	637	622	1,643	1,643	129	69	75	51	43	59	61	85	85
Montana	2,767	1,255	1,892	1,253	1,120	637	622	1,956	1,956	155	69	59	41	33	59	61	69	69
Nebraska	2,957	1,255	1,589	989	927	637	622	1,643	1,643	164	69	75	48	43	59	61	85	85
Nevada	2,955	1,255	1,892	1,247	1,120	637	622	1,956	1,956	164	69	59	40	33	59	61	69	69

Volatile Solids										Nitrogen Excreted								
New Hampshire	2,737	1,255	1,674	1,095	980	637	622	1,731	1,731	154	69	74	51	42	59	61	84	84
New Jersey	2,726	1,255	1,674	1,091	980	637	621	1,731	1,731	154	69	74	50	42	59	61	84	84
New Mexico	2,956	1,255	1,892	1,239	1,120	637	622	1,956	1,956	164	69	59	40	33	59	61	69	69
New York	2,976	1,255	1,674	1,086	980	637	622	1,731	1,731	164	69	74	50	42	59	61	84	84
North Carolina	2,903	1,255	1,665	1,098	974	637	622	1,721	1,721	163	69	73	50	42	59	61	83	83
North Dakota	2,804	1,255	1,589	1,020	927	637	622	1,643	1,643	157	69	75	50	43	59	61	85	85
Ohio	2,751	1,255	1,589	1,028	927	637	622	1,643	1,643	155	69	75	51	43	59	61	85	85
Oklahoma	2,475	1,255	1,665	1,071	974	637	622	1,721	1,721	143	69	73	48	42	59	61	83	83
Oregon	2,664	1,255	1,892	1,234	1,120	637	621	1,956	1,956	151	69	59	40	33	59	60	69	69
Pennsylvania	2,689	1,255	1,674	1,087	980	637	622	1,731	1,731	152	69	74	50	42	59	61	84	84
Rhode Island	2,595	1,255	1,674	1,086	980	637	622	1,731	1,731	148	69	74	50	42	59	61	84	84
South Carolina	2,492	1,255	1,665	1,103	974	637	622	1,721	1,721	145	69	73	51	42	59	61	83	83
South Dakota	2,828	1,255	1,589	1,019	927	637	622	1,643	1,643	158	69	75	50	43	59	61	85	85
Tennessee	2,522	1,255	1,665	1,087	974	637	622	1,721	1,721	147	69	73	50	42	59	61	83	83
Texas	3,017	1,255	1,665	1,056	974	637	622	1,721	1,721	166	69	73	47	42	59	61	83	83
Utah	2,844	1,255	1,892	1,243	1,120	637	622	1,956	1,956	159	69	59	40	33	59	61	69	69
Vermont	2,718	1,255	1,674	1,076	980	637	622	1,731	1,731	153	69	74	49	42	59	61	84	84
Virginia	2,675	1,255	1,665	1,085	974	637	622	1,721	1,721	153	69	73	49	42	59	61	83	83
Washington	2,901	1,255	1,892	1,213	1,120	637	622	1,956	1,956	161	69	59	39	33	59	61	69	69
West Virginia	2,221	1,255	1,674	1,093	980	637	622	1,731	1,731	132	69	74	51	42	59	61	84	84
Wisconsin	2,974	1,255	1,589	1,026	927	637	622	1,643	1,643	164	69	75	50	43	59	61	85	85
Wyoming	3,026	1,255	1,892	1,241	1,120	637	622	1,956	1,956	167	69	59	40	33	59	61	69	69

[a] Beef NOF Bull values were used for bison Nex and VS

Source: CEFM

Table A5 Copy of Table A-171 from 2024 GHG Inventory submission[2]: Methane Emissions by State from Livestock Manure Management for 2022 (MMT CO_2e)[a]

State	Beef OF	Beef NOF	Dairy Cow	Dairy Heifer	Swine-Market	Swine-Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Alabama	0.0006	0.0215	0.0062	0.0001	0.0074	0.0042	0.1689	0.2056	0.0002	0.0003	0.0002	0.0012	0.0001	+	0.4167
Alaska	+	0.0004	0.0001	+	0.0001	+	+	+	+	+	+	+	+	+	0.0007
Arizona	0.0403	0.0091	0.5036	0.0079	0.0571	0.0122	0.0142	+	+	0.001	0.0002	0.0022	+	+	0.6478
Arkansas	0.0021	0.0291	0.0105	0.0002	0.0233	0.037	0.024	0.1515	0.0181	0.0003	0.0001	0.001	0.0001	+	0.2972
California	0.0826	0.0355	6.7126	0.0547	0.0303	0.005	0.0267	0.0437	0.0043	0.006	0.0005	0.0019	0.0001	+	7.0039
Colorado	0.1749	0.0342	0.6186	0.0048	0.0755	0.0596	0.0248	0.0001	+	0.0035	0.0002	0.0027	0.0001	0.0003	0.9992
Connecticut	+	0.0002	0.0742	0.0005	0.0002	0.0001	0.007	+	+	0.0001	+	0.0002	+	+	0.0825
Delaware	+	0.0001	0.0104	0.0001	0.0003	0.0008	0.0035	0.0278	+	+	+	0.0001	+	+	0.0429
Florida	0.0002	0.028	0.3631	0.0024	0.0013	0.0008	0.1061	0.0117	+	0.0003	0.0003	0.002	0.0001	+	0.5166
Georgia	0.0003	0.016	0.3153	0.0019	0.0073	0.0119	0.2232	0.2233	+	0.0003	0.0003	0.0011	0.0001	+	0.8009
Hawaii	0.0001	0.0028	0.0019	0.0001	0.0017	0.0013	0.0004	+	+	0.0002	0.0001	0.0001	+	+	0.0088
Idaho	0.0192	0.0238	3.1071	0.0147	0.0025	0.0025	0.0097	+	+	0.0019	0.0001	0.0011	+	0.001	3.1836
Illinois	0.1517	0.012	0.2914	0.0018	1.2832	0.3453	0.0064	0.0002	0.0008	0.0006	0.0001	0.0008	0.0001	+	2.0944
Indiana	0.0359	0.007	0.4827	0.0027	1.2288	0.1452	0.0386	0.0052	0.0139	0.0007	0.0002	0.0018	+	+	1.9628
Iowa	0.2501	0.0397	0.9743	0.0053	5.628	0.456	0.0434	0.0027	0.0081	0.0019	0.0004	0.0012	+	0.0001	7.4113
Kansas	1.1112	0.067	1.0175	0.0074	0.8313	0.1335	0.0031	+	0.0002	0.0008	0.0002	0.001	+	0.0001	3.1734
Kentucky	0.0011	0.0318	0.1122	0.0017	0.141	0.0347	0.0205	0.0273	0.0002	0.0008	0.0002	0.0031	0.0001	0.0001	0.3748
Louisiana	0.0005	0.0144	0.0211	0.0002	0.0007	0.0003	0.0198	0.0344	+	0.0002	0.0001	0.0009	0.0001	+	0.0927
Maine	+	0.0005	0.0719	0.0006	0.0002	0.0001	0.0054	+	+	0.0002	+	0.0002	+	+	0.0792
Maryland	0.0005	0.0016	0.1341	0.0013	0.0041	0.0011	0.0084	0.0289	0.0001	0.0002	0.0001	0.0008	+	+	0.1812
Massachusetts	+	0.0003	0.0105	0.0003	0.0005	0.0003	0.0002	+	+	0.0002	+	0.0003	+	+	0.0126
Michigan	0.0542	0.0057	1.8343	0.0067	0.2616	0.0522	0.021	0.0012	0.0036	0.001	0.0001	0.0013	+	0.0001	2.243
Minnesota	0.1287	0.0164	1.2603	0.0092	1.7258	0.2326	0.009	0.0047	0.0257	0.0013	0.0001	0.0009	+	0.0001	3.4149
Mississippi	0.0004	0.0158	0.0126	0.0004	0.0338	0.048	0.1075	0.1146	+	0.0002	0.0001	0.0008	0.0001	+	0.3344
Missouri	0.0103	0.0615	0.1742	0.0014	0.9108	0.304	0.019	0.0362	0.0118	0.0012	0.0002	0.0017	0.0001	+	1.5323
Montana	0.0027	0.0504	0.0338	0.0002	0.0264	0.0194	0.0088	0.0001	+	0.0015	0.0001	0.0019	+	0.0007	0.146
Nebraska	0.2577	0.0807	0.3166	0.0013	1.0142	0.278	0.0088	0.001	0.0002	0.0009	0.0001	0.001	+	0.0008	1.9613
Nevada	0.0002	0.009	0.1959	0.0004	+	0.0001	+	+	+	0.0005	+	0.0002	+	+	0.2062
New Hampshire	+	0.0002	0.0292	0.0003	0.0003	0.0001	0.0006	+	+	0.0001	+	0.0002	+	+	0.031

State	Beef OF	Beef NOF	Dairy Cow	Dairy Heifer	Swine-Market	Swine-Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
New Jersey	+	0.0003	0.0117	0.0001	0.0009	0.0003	0.015	+	+	0.0002	+	0.0006	+	+	0.0291
New Mexico	0.0011	0.0177	0.9673	0.0054	0.0001	0.0001	0.0009	+	+	0.0007	0.0001	0.0011	+	0.0001	0.9948
New York	0.0017	0.006	2.3882	0.0153	0.0061	0.0006	0.015	0.0003	0.0002	0.001	0.0001	0.0015	+	+	2.436
North Carolina	0.0004	0.012	0.1368	0.001	3.3677	0.7817	0.1617	0.182	0.0195	0.0006	0.0002	0.0012	0.0001	+	4.6648
North Dakota	0.0152	0.0317	0.0645	0.0003	0.0186	0.017	0.0007	+	0.0005	0.0007	+	0.0004	+	0.0004	0.1502
Ohio	0.0691	0.0121	0.8559	0.0053	0.7084	0.1028	0.0398	0.0129	0.0042	0.0016	0.0002	0.0025	0.0001	+	1.815
Oklahoma	0.0456	0.0779	0.1128	0.0013	0.7342	0.494	0.0342	0.0363	0.0002	0.0009	0.0004	0.0031	0.0002	+	1.541
Oregon	0.0099	0.0207	0.2358	0.0026	0.0011	0.0006	0.0075	0.0021	+	0.0012	0.0002	0.0018	+	0.0001	0.2837
Pennsylvania	0.0052	0.0089	1.172	0.0093	0.3013	0.0684	0.0618	0.0241	0.0054	0.0012	0.0002	0.0018	0.0001	+	1.6597
Rhode Island	+	+	0.0011	+	0.0001	+	0.0001	+	+	+	+	+	+	+	0.0016
South Carolina	0.0002	0.0051	0.0302	0.0004	0.0728	0.0067	0.0378	0.0402	0.0071	0.0002	0.0002	0.0011	0.0001	+	0.202
South Dakota	0.1585	0.0574	0.885	0.0018	0.4545	0.1579	0.0025	+	0.0017	0.0028	0.0001	0.0011	+	0.0006	1.7241
Tennessee	0.0008	0.029	0.0724	0.001	0.1082	0.0246	0.0095	0.029	+	0.0009	0.0004	0.0026	0.0002	+	0.2788
Texas	0.4281	0.169	1.8206	0.0153	0.3943	0.1318	0.0718	0.1218	0.0012	0.007	0.0031	0.009	0.0012	0.0003	3.1744
Utah	0.0015	0.0132	0.2632	0.0023	0.1548	0.0264	0.0409	+	0.0032	0.0022	0.0001	0.0015	+	+	0.5094
Vermont	0.0001	0.0009	0.3469	0.0024	0.0002	0.0001	0.0004	+	+	0.0002	+	0.0002	+	+	0.3515
Virginia	0.0016	0.0201	0.188	0.0017	0.1167	0.0046	0.0048	0.0294	0.0106	0.0009	0.0002	0.0014	0.0001	+	0.3801
Washington	0.0181	0.0114	1.1536	0.0062	0.0019	0.0008	0.0098	0.0029	+	0.0004	0.0001	0.0013	+	+	1.2066
West Virginia	0.0003	0.0063	0.0095	0.0001	0.0001	0.0001	0.0047	0.0084	0.0026	0.0004	0.0001	0.0006	+	+	0.0334
Wisconsin	0.1019	0.0159	3.6958	0.0288	0.0543	0.0189	0.0065	0.0068	0.0022	0.001	0.0005	0.0015	+	0.0002	3.9343
Wyoming	0.0053	0.0263	0.0427	0.0002	0.005	0.0179	0.0001	+	+	0.0027	0.0001	0.0012	+	0.0003	0.1019

+ Does not exceed 0.0005 MMT CO_2e

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

Table A6 Copied from Table 6 of Lormior et al: Daily manure production and characteristics, as-excreted (per head per day).[13]

	Size[a]	Total Manure[b]			Water[c]	Density[c]	TS[d]	VS[c]	BOD$_5$	Nutrient content		
	lbs	lbs	ft^3	gal	%	lb/ft^3	lb/ day	lb/ day	lb/day	(lbs N)[d]	(lbs P_2O_5)[d]	lbs K_2O
Dairy Calf	150	12	0.18	1.38	88	65	1.4	1.2	0.19	0.06	0.01[c]	0.05
	250	20	0.31	2.3	88	65	2.4	2	0.31	0.11	0.02[c]	0.09
Dairy Heifer	750	45	0.7	5.21	88	65	6.7	5.7	0.69	0.23	0.08[c]	0.23
	1,000	60	0.93	6.95	88	65	8.9	7.6	0.92	0.3	0.1[c]	0.31
Lactating	1,000	111	1.79	13.36	88	62	14.3	12.1	1.67	0.72	0.37[c]	0.4
	1,400	155	2.5	18.7	88	62	20	17	2.34	1.01	0.52[c]	0.57
Dry Cow	1,000	51	0.82	6.14	88	62	6.5	5.5	0.75	0.3	0.11[c]	0.24
	1,400	71	1.15	8.6	88	62	9.1	7.7	1.04	0.42	0.15[c]	0.33
	1,700	87	1.4	10.45	88	62	11	9.3	1.27	0.51	0.18[c]	0.4
Veal	250	6.6	0.11	0.79	96	62	0.26	0.11	0.04	0.03	0.02	0.05[d]
Calf (confinement)	450	48	0.76	5.66	92	63	3.81	3.2	1.06	0.2	0.09	0.16
	650	69	1.09	8.18	92	63	5.51	4.63	1.54	0.29	0.13	0.23
Finishing	750	37	0.59	4.4	92	63	2.97	2.42[d]	0.6	0.27	0.08	0.17
	1,100	54	0.86	6.46	92	63	4.35	3.55[d]	0.89	0.4	0.12	0.25
Cow (confinement)	1,000	92	1.46	10.91	88	63	11	9.38	2.04	0.35	0.18	0.29
Nursery	25	1.9	0.03	0.23	89	62	0.21	0.17	0.06	0.02	0.01	0.01
	40	3	0.05	0.37	89	62	0.33	0.27	0.1	0.03	0.01	0.02
Finishing	150	7.4	0.12	0.89	89	62	0.82	0.65	0.23	0.09	0.03	0.04
	180	8.9	0.14	1.07	89	62	0.98	0.78	0.28	0.1	0.04	0.05
	220	10.9	0.18	1.31	89	62	1.2	0.96	0.34	0.13	0.05	0.06
	260	12.8	0.21	1.55	89	62	1.41	1.13	0.41	0.15	0.05	0.08
	300	14.8	0.24	1.79	89	62	1.63	1.3	0.47	0.17	0.06	0.09
Gestating	300	6.8	0.11	0.82	91	62	0.61	0.52	0.21	0.05	0.03	0.04
	400	9.1	0.15	1.1	91	62	0.82	0.7	0.28	0.06	0.04	0.05
	500	11.4	0.18	1.37	91	62	1.02	0.87	0.35	0.08	0.05	0.06
Lactating	375	17.5	0.28	2.08	90	63	1.75	1.58	0.58	0.17	0.11	0.13
	500	23.4	0.37	2.78	90	63	2.34	2.11	0.78	0.22	0.15	0.18
	600	28.1	0.45	3.33	90	63	2.81	2.53	0.93	0.27	0.18	0.21
Boar[c]	300	6.2	0.1	0.74	91	62	0.57	0.51	0.2	0.04	0.03	0.03
	400	8.2	0.13	0.99	91	62	0.75	0.67	0.26	0.06	0.05	0.05
	500	10.3	0.17	1.24	91	62	0.94	0.84	0.33	0.07	0.06	0.06
Broiler	2	0.19	0.003	0.023	74	63	0.05	0.038	0.011	0.0021	0.0014	0.001
Layer	3	0.15	0.002	0.017	75	65	0.037	0.027	0.008	0.0026	0.0008	0.0012
Turkey (female)	10	0.47	0.007	0.056	75	63	0.117	0.088	0.034	0.0078	0.0051	0.0034
Turkey (male)	20	0.74	0.012	0.088	75	63	0.186	0.139	0.054	0.0111	0.0074	0.0048
Duck	4	0.44	0.007	0.053	73	62	0.118	0.089	0.016	0.0043	0.0034	0.0026
Feeder lamb[c]	100	4.1	0.06	0.5	75	63	1.05	0.91	0.1	0.04	0.02	0.04
horse - Sedentary	1,000	54.4	0.88	6.56	86[d]	62	7.61	6.5	1.52	0.18	0.06	0.06[d]
Horse - Intense	1,000	55.5	0.9	6.7	86[d]	62	7.78	6.6	1.56	0.3	0.15	0.23[d]

TS = total solids; VS = volatile solids; BOD_5 = the oxygen used in the biochemical oxidations of organic matter in five days at 68° F.

[a] Use linear interpolation to obtain values for weights not listed in the table.

[b] Calculated using TS divided by the solids content percentage.

[c] Based on Manure Management Planning System (MWPS) historical data.

[d] Values calculated or interpreted using diet based formulas being considered for the ASAE Standards D384: Manure Production and Characteristics.