# Chapter 4
# Quantifying Greenhouse Gas Sources and Sinks in Animal Production Systems


## Authors:

April Leytem, USDA, Agricultural Research Service (Lead Author)
Shawn Archibeque, Colorado State University
N. Andy Cole, USDA, Agricultural Research Service
Stacey A. Gunter, USDA, Agricultural Research Service
Alexander Hristov, The Pennsylvania State University
Kristen Johnson, Washington State University
Ermias Kebreab, University of California, Davis
Rich Kohn, University of Maryland
Wei Liao, Michigan State University
Crystal Toureene, Colorado State University
Juan Tricarico, Dairy Innovation Center


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## Acronyms, Chemical Formulae, and Units

| | |
|---|---|
| 3-NOP | 3-nitrooxypropanol |
| ADF | acid detergent fiber |
| ASABE | American Society of Agricultural and Biological Engineers |
| $B_0$ | maximum methane production capacity |
| bLS | backward Lagrangian stochastic |
| BW | body weight |
| $CH_4$ | methane |
| $CO_2$ | carbon dioxide |
| $CO_2$-eq | carbon dioxide equivalents |
| CP | crude protein |
| CSTR | continuous stirred tank reactor |
| DE | digestible energy |
| DFM | direct-fed microbials |
| DGS | distillers grains with solubles |
| DM | dry matter |
| DMI | dry matter intake |
| EE | ether extract |
| EF | emission factor |
| g | gram |
| GEI | gross energy intake |
| GHG | greenhouse gas |
| GWP | global warming potential |
| IPCC | Intergovernmental Panel on Climate Change |
| kg | kilogram |
| lb(s) | pound(s) |
| LCA | life cycle analysis |
| LU | livestock unit |
| m | meters |
| MCal | megacalorie |
| MCF | methane conversion factor |
| MF | milk fat concentration |
| mg | milligram |
| MGA | melengestrol acetate |
| MJ | megajoule |
| N | nitrogen |
| $N_2O$ | nitrous oxide |
| NDF | neutral detergent fiber |
| NE | net energy |
| $N_{ex}$ | nitrogen excretion |
| NFC | nonfiber carbohydrate |
| $NH_3$ | ammonia |
| $O_2$ | oxygen |
| ppm | parts per million |
| RDP | ruminal degradable protein |
| RMSPE | residual mean square prediction error |

| | |
|---|---|
| $SF_6$ | sulfur hexafluoride |
| TDN | total digestible nutrients |
| UASB | upflow anaerobic sludge blanket |
| U.S. EPA | U.S. Environmental Protection Agency |
| VS | volatile solids |
| $Y_m$ | methane conversion factor: percent of gross energy in feed converted to methane |

# 4. Quantifying Greenhouse Gas Sources and Sinks in Animal Production Systems

This chapter provides methodologies and guidance for reporting greenhouse gas (GHG) emissions associated with entity-level fluxes from animal production systems. It focuses on methods for estimating emissions from dairy cattle, beef cattle (cow-calf, stocker, and feedlot systems), sheep, swine, and poultry (e.g., layers, broilers, and turkeys). This chapter summarizes animal management practices and their associated GHG emissions, then describes the methods for estimating GHG emissions from enteric fermentation, housing, and manure management. This chapter and its appendixes provide insight into the current state of the science and serves as a starting point for future assessments:

- Section 4.1 provides the background to the emissions discussion, interactions, and boundaries for the methods.
- Section 4.2 provides the methods for estimating GHGs from enteric fermentation (resulting from animal digestive processes).
- Section 4.3 provides the methods for estimating GHGs from housing.
- Section 4.4 provides the methods for estimating GHGs from manure management systems, including solid manure storage, composting, aerobic lagoons, anaerobic lagoons or other liquid systems, and anaerobic digestion.

This chapter has six appendixes:

- Appendix 4-A provides overviews of dairy cattle, beef cattle, sheep, swine, and poultry production systems and background information related to enteric fermentation, housing, and manure management emissions.
- Appendix 4-B provides the rationale and technical documentation for the methods. It includes discussion on data gaps for uncertainty quantification.
- Appendix 4-C summarizes research gaps for estimating GHG emissions in animal production systems that could provide a basis for future development of the methods presented in this chapter.
- Appendix 4-D discusses management factors not used in adjusting the methane conversion factor ($Y_m$) for feedlot cattle but that affect GHG emissions per unit of production in feedlot cattle.
- Appendix 4-E provides information on nutritional content of animal feedstuffs (Dairy One, 2021; Ewan, 1989; NASEM, 2016; Preston, 2013).
- Appendix 4-F provides relevant equations and tables from IPCC (2019) to assist with calculations.

## 4.1 Overview

This section describes the key practices in animal management and the resulting GHG emissions that are discussed in detail in this chapter. The agricultural practices discussed include those required to breed and house animals, along with the management of the resulting manure.

This section also discusses options for management changes that may result in changes in GHG emissions.

### 4.1.1 Description of Sector

Animal production systems include agricultural practices that involve breeding and raising animals for meat, eggs, milk, and other animal products such as leather, wool, fur, and industrial products like glue or oils. Animals considered in this sector include cattle, swine, and poultry, along with other animals such as sheep, goats, American bison, llamas, alpacas, deer, horses, mules and asses, rabbits, and fur-bearing animals.

Farmers and other facility owners raise animals in either confined, semi-confined, or unconfined spaces. They also use different practices to raise the animals, depending on animal type, region, land availability, and individual preferences (e.g., conventional or organic standards). See appendix 4-A for more background information on animal production systems.

The magnitude of GHG emissions from animal management depends primarily on the quality of the diet, the animals' physiological status and nutrient requirements (e.g., grazing, pregnant, lactating, doing work), feed intake, and the systems in place to house animals and manage manure.

This chapter considers the following manure storage and treatment practices:

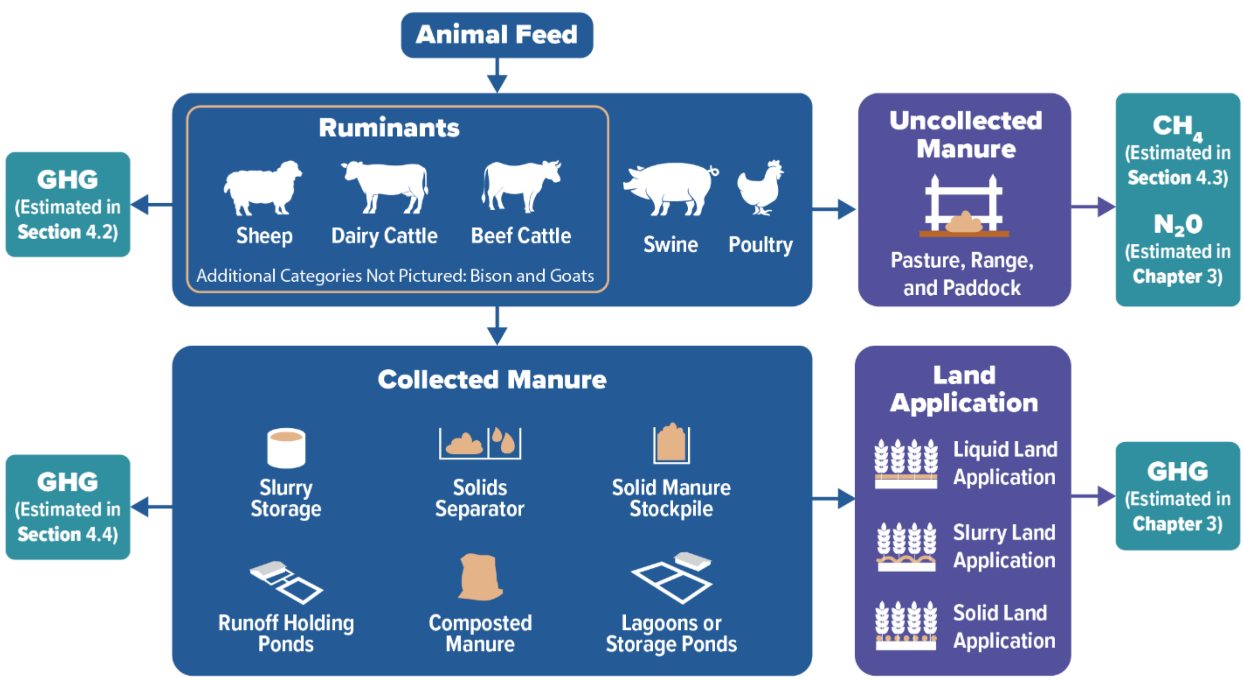
Solid manure:

- Temporary stack and long-term stockpile
- Composting

Liquid manure:

- Aerobic lagoons
- Anaerobic lagoons/runoff holding ponds/storage tanks
- Anaerobic digestion

Figure 4-1 provides an overview of the connections between feed, animals, manure, and GHG emissions in an animal production system.




Note: See section 4.5 for land application inputs to chapter 3, if applicable.

**Figure 4-1. Connections Between Feed, Animals, Manure, and GHG for Animal Agriculture**

### 4.1.2 Resulting GHG Emissions

The primary GHG emissions from animal production systems are $CH_4$ and $N_2O$. The emission of ammonia ($NH_3$) from manure and leaching of manure N from housing and storage also contribute to indirect $N_2O$ emissions when this N is either deposited in the landscape or transferred to surface waters. Figure 4-2 generally depicts these sources and their interactions. This chapter divides methods for estimating GHG emissions into three categories: emissions from enteric fermentation, emissions from housing, and emissions from manure management systems. The housing category includes GHG emissions from manure deposited in the housing unit and manure that is managed inside those areas (such as interior stockpiles). The manure management category includes GHG emissions from manure handling, treatment, and storage.[1]

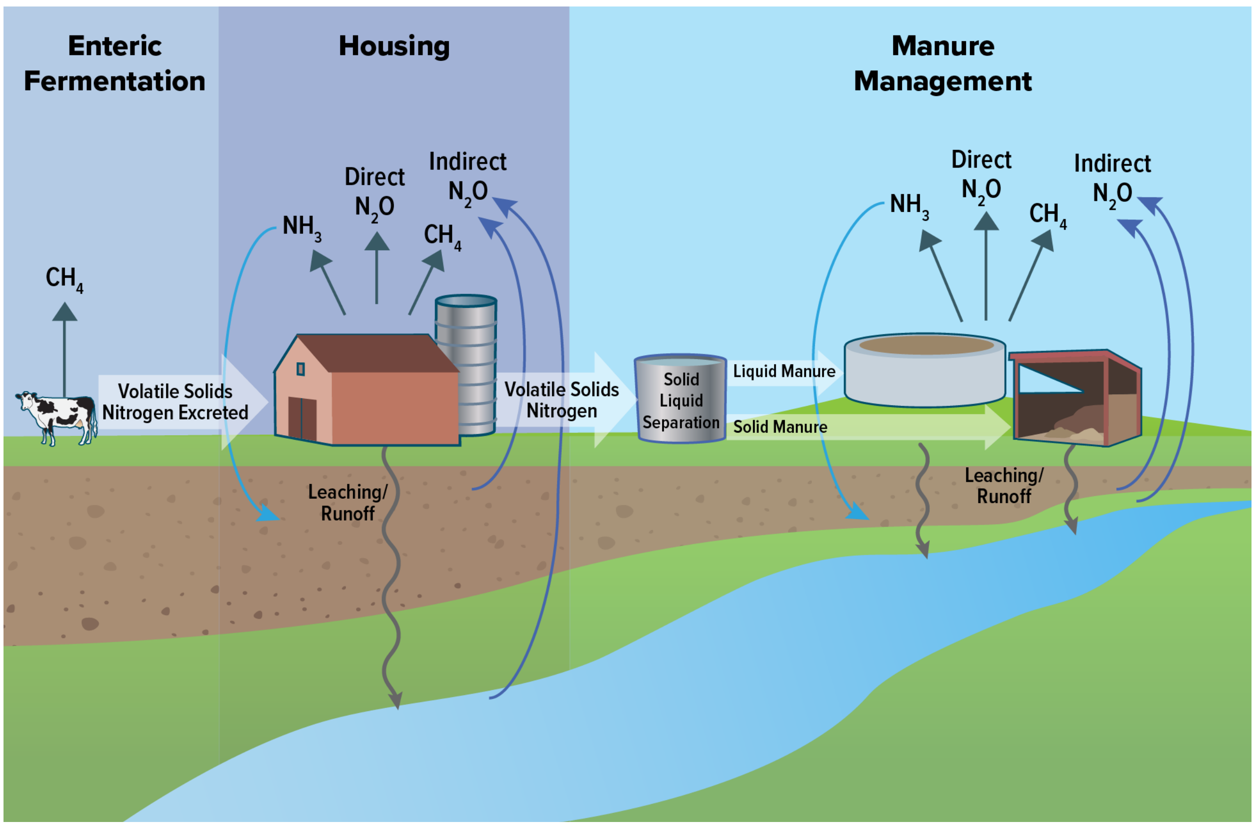



**Figure 4-2. Animal Production Emission Sources and Interactions**

The main source of $CH_4$ emissions from ruminant animal production systems is enteric fermentation, which is the result of normal bacterial fermentation as ruminant animals digest feed. Nonruminant animals such as swine also emit $CH_4$ through their digestive processes, but significantly less than ruminant animals do (~2.3 percent of total enteric $CH_4$ emissions in the United States). For simplicity, this chapter uses enteric fermentation to refer to $CH_4$ emissions from the digestive process of both ruminant and nonruminant animals.

The largest source of $N_2O$ emissions—and, in some cases, a significant source of $CH_4$ emissions—is the management of animal manure. Manure management is the collection, storage, transfer, and treatment of animal urine and feces. Storage of animal manure has become increasingly popular: it

[1] Emissions from manure deposited on grazing lands are addressed in chapter 3, "Croplands and Grazing Lands."

allows synchronization of land application of manure nutrients with crop needs, reduces the need for purchased commercial fertilizer, and reduces potential for soil compaction due to poor timing of manure application. Direct $N_2O$ emissions occur via combined nitrification and denitrification of nitrogen in the manure; indirect emissions result from volatile nitrogen losses, mainly in the forms of $NH_3$ and nitrogen oxides (IPCC, 2019). This chapter considers both direct and indirect emissions; total emissions are the summation of these sources.

The methodology used to estimate emissions from manure and bedding in housing is similar to the method described for manure handling and storage systems. Manure generated by animals, along with bedding used in some systems, may release $N_2O$ and $CH_4$ into the atmosphere during the decomposition process. Manure from grazing animals is left on fields or paddocks. Manure from dry lots and barns may be collected to be treated, stored, and applied to croplands. Methane emissions from grazing lands are covered in the housing section (section 4.3), while $N_2O$ emissions from manure deposited on grazing lands and croplands are addressed in chapter 3.

#### 4.1.2.1 Enteric Fermentation Emissions

$CH_4$-producing microorganisms, called methanogens, exist in the gastrointestinal tracts of many animals. However, ruminants emit a much higher volume of $CH_4$ than nonruminant animals because of the fermentative capacity of the rumen. In the rumen, $CH_4$ formation is a mechanism for disposing of excess hydrogen from the anaerobic fermentation of dietary carbohydrate. Control of hydrogen ions through methanogenesis helps maintain efficient microbial fermentation by reducing the partial pressure of hydrogen to levels that allow normal functioning of microbial energy transfer enzymes (Morgavi et al., 2010).

The only GHG of concern resulting from enteric fermentation is $CH_4$. Respiration chambers with $N_2O$ analyzers indicate that enteric fermentation does not result in the production of $N_2O$ (Reynolds et al., 2010). When cattle diets contain moderately high concentrations of nitrates, small amounts of enteric $N_2O$ may be produced (Parker et al., 2018). However, enteric $N_2O$ makes up less than 0.2 percent of enteric emissions, in terms of $CO_2$ equivalents (Cole et al., 2020a). $CH_4$ can also arise from hindgut fermentation, but the levels associated with hindgut fermentation (~6–14 percent of daily $CH_4$ production), are much lower than those of foregut fermentation (Johnson and Johnson, 1995; Immig, 1996).

Enteric $CH_4$ emissions are a significant contributor to many countries' GHG emissions, and decades of research have gone into characterizing, understanding, modeling, and attempting to mitigate enteric $CH_4$ emissions. Enteric $CH_4$ emissions vary with the amount of feed intake as well as diet and stage of production in both beef and dairy cattle, with lactating cows having the highest emission rates. For more information about enteric $CH_4$ emissions, see appendix 4-A.

#### 4.1.2.2 Housing Emissions

Housing can be a source of GHG and $NH_3$ when manure accumulates or is stored in housing systems, or when nitrogen accumulates in soils when animals are housed in earthen lots, commonly referred to as dry lots. Differences in populations, regional practices, and climate mean there is a wide variety of animal housing systems—which can lead to differences in both GHG and $NH_3$ emissions. Housing emissions can also have daily and seasonal trends. Table 4-1 provides an overview of the housing systems considered in this chapter. Emissions of $CH_4$ from manure deposited on pasture/range are included in the housing section, while $N_2O$ emissions from manure deposited on grazing lands are addressed in chapter 3.

**Table 4-1. Overview of Methods Included for GHG Emissions From Animal Housing Systems**

| Animal Housing Systems | | Estimation Method | | Description |
|---|---|---|---|---|
| | | $CH_4$ | $N_2O$ | |
| Dairy | Barn floors | ✓ | | Manure in freestall barns accumulates on the barn floor. |
| | Dry lot | ✓ | ✓ | A paved or unpaved open confinement area without any significant vegetative cover and manure accumulates. |
| | Deep bedded pack | ✓ | ✓ | Bedding material such as straw is added frequently in layers. These become compacted with manure and straw, leading to anaerobic fermentation. |
| | Liquid/slurry and pit storage below animal confinement | ✓ | ✓ | Slatted floors allow manure to accumulate in a pit below the animal confinement. |
| | Compost barn | ✓ | ✓ | Bedding material such as sawdust and manure is composted using an aerobic process, leading to aerobic decomposition of the manure deposited in the housing. |
| | Pasture/range | ✓ | | Manure is deposited directly to grazing lands. |
| Beef | Dry lot | ✓ | ✓ | A paved or unpaved open confinement area without any significant vegetative cover and manure accumulates. |
| | Deep bedded pack | ✓ | ✓ | Bedding material such as straw is added frequently in layers. These become compacted with manure and straw, leading to anaerobic fermentation. |
| | Compost barn | ✓ | ✓ | Bedding material such as sawdust and manure is composted using an aerobic process, leading to aerobic decomposition of the manure deposited in the housing. |
| | Pasture/range | ✓ | | Manure is deposited directly to grazing lands. |
| Swine | Deep bedding | ✓ | ✓ | Straw-bedded hoop houses allow manure to accumulate in the straw bedding. As the straw and manure accumulate, the pack begins to compost. |
| | Liquid/slurry and pit storage below animal confinement | ✓ | ✓ | Slatted floors allow manure to accumulate in a pit below the animal confinement. |
| | Pasture | ✓ | | Manure is deposited directly to pasture. |
| Poultry | Housing litter | ✓ | ✓ | Bedding material such as wood shavings, sawdust, and straw absorb poultry manure. |
| | Pit storage below animal confinement | ✓ | ✓ | Birds are kept in wire cages. Manure collects below the cages in a pit before being applied or moved to storage. |

#### 4.1.2.3 Manure Management Emissions

Manure is managed in a wide variety of systems. The resulting GHG emissions differ by GHG and magnitude of emissions per quantity of manure. Table 4-2 provides an overview of the liquid and solid manure systems considered in this report and the resulting GHGs.

**Table 4-2. Methods Included for GHG Emissions From Manure Management Systems**

| Storage and Treatment Practices | | Estimation Method | | Description |
|---|---|---|---|---|
| | | $CH_4$ | $N_2O$ | |
| Solid Manure | Solid manure storage (stacked) | ✓ | ✓ | Manure is stored in stockpiles that are not disturbed prior to land application. |
| Solid Manure | Composting | ✓ | ✓ | Composting involves the controlled aerobic decomposition of organic material and can occur in different forms. Estimation methods are provided for in-vessel, static pile, intensive windrow, and passive windrow composting. |
| Liquid Manure | Aerobic lagoon | ✓ | ✓ | In aerobic lagoons, manure undergoes biological oxidation as a liquid with natural or forced aeration. |
| Liquid Manure | Anaerobic lagoon/ runoff holding ponds/storage tanks | ✓ | ✓ | Anaerobic lagoons are earthen basins that store animal manure and provide an environment for anaerobic digestion. Lagoons may be covered or uncovered and have a crust or no-crust formation. Multistage lagoons as well as earthen settling basins/weeping walls in combination with lagoons are treated as one lagoon system. Runoff and holding ponds are constructed to capture and store runoff from feedlots and dry lots. In some cases, wash water from dairy parlors may be stored in holding ponds. Storage tanks typically store slurry or wastewater that was scraped or pumped from housing systems. Includes adjustments to estimates due to the use of solid-liquid separation (via mechanical separation like screens or pressing). |
| Liquid Manure | Anaerobic digester | ✓ | | Anaerobic digesters are manure treatment systems designed to maximize conversion of organic wastes into biogas. These can range from covered anaerobic lagoons to highly engineered systems. $CH_4$ gas leakage is the main source of GHG emissions; $NH_3$ and $N_2O$ leakage is negligible. |

## 4.1.3 Management Interactions

The influence of animal production system management practices on GHG emissions is not typically the simple sum of each practice's effect. The influence of one practice can depend on another practice. For example, a change in animal diets can impact both the enteric fermentation and manure management emissions. Because of these interactions, estimating GHG emissions will depend on a complete and accurate description of the management practices used in the operation. As a cross-sectoral example, the available nitrogen after manure storage and treatment impacts emissions expected from land applying manure on croplands. See section 4.5 for more on this interaction.

## 4.1.4 Mitigation

Changes in animal production system management practices can influence $CH_4$ and $N_2O$ emissions.

- **Enteric fermentation:** $CH_4$ emissions can be reduced through diet manipulations, or the use of feed additives or drugs added to feed.[2] Examples of diet manipulations are the

[2] USDA here follows the Food and Drug Administration (FDA) definition of "drug" which includes substances "intended for use in the diagnosis, cure, mitigation, treatment, or prevention of disease." (FDA, 2023).

inclusion of supplemental fat or a different grain type. Diet manipulations may increase or decrease expected emissions. Feed additives or drugs may include 3-nitrooxypropanol (3-NOP), nitrates, or lipid supplementation.

- **Housing:** $CH_4$ emissions can be reduced by decreasing the time manure is stored in the housing area, particularly during warmer periods of the year. Reducing nitrogen inputs into housing (i.e., via changes in feeding) will reduce $N_2O$ emissions. Some housing strategies emit less $N_2O$ than others, but the choice of strategy may be limited by on-farm factors.
- **Manure management:** In general, decreasing the amount of time manure is stored will decrease both $CH_4$ and $N_2O$ emissions as there is less time for emissions to occur in this phase of production. Changing from a liquid manure management system to a dry manure management system will reduce $CH_4$ emissions. $CH_4$ can also be reduced by covering liquid systems and capturing methane (e.g., a covered lagoon or anaerobic digester). $N_2O$ emissions can be mitigated by covering manure and in some cases adding storage additives/bulking agents.

Emissions from manure can also be affected by dietary factors that affect the quantity and composition of volatile solids (VS) and nitrogen excreted. For example, steam flaking of grains in feedlots increases digestibility and thus decreases the quantity of VS and nitrogen excreted and alters the composition of the VS (less starch vs. more undigestible fiber). By reducing the starch content of the manure there is less available carbon for conversion to $CH_4$ during storage. These changes potentially decrease manure $CH_4$ and $N_2O$ emissions compared to dry-rolled corn-based diets (Cole et al., 2020b).

Recognizing the complexities associated with management, the net impact of management changes on emissions can be estimated and the amount of mitigation quantified using the methods described in section 4.2 through section 4.4.

### 4.1.5 System Boundaries and Temporal Scale

System boundaries are defined by the coverage, extent, and resolution of the estimation methods. The methods in this chapter can be used to estimate GHG emission sources within the production area of an animal production system, including the animals; animal housing; and manure handling, treatment, and storage.

- This chapter considers $CH_4$ emissions from enteric fermentation, as well as the $CH_4$ and $N_2O$ emissions from manure management systems or manure stored in housing, as well as indirect $N_2O$ from N losses ($NH_3$ volatilization and N leaching) from housing and manure management systems that are deposited on the landscape or transported to surface waters.
- Emissions from vehicle transport are not included in the scope of this chapter. These emissions are affected by many variables—age of vehicle, type, fuel efficiency, idle time—that are not direct agricultural emissions; they could instead be considered part of the transport sector (off-road).
- This chapter does not encompass a full life cycle analysis (LCA) of GHG emissions from animal production systems. See chapter 2 for more information on what is and is not included in the scope of the report.
- Emissions that result from grazing ($N_2O$ only) and manure land application are addressed in chapter 3.

The methods in this chapter have a resolution of individual herds within an entity's operation. A herd is defined as a group of animals that are the same species, are housed similarly or graze on the same parcel of land (same diet composition) and use the same manure management system. Emissions are estimated for each individual herd within an operation, then summed to estimate the total animal production emissions for an entity. Animal production totals are then combined with emissions from croplands, grazing lands, and forestry to determine the overall emissions from the operation based on the methods provided in this document. Emissions are estimated on an annual basis. See chapter 2 as needed for additional details on accounting boundaries.

### 4.1.6 Summary of Selected Methods/Models Sources of Data

The Intergovernmental Panel on Climate Change (IPCC, 2006, 2019) has developed a system of methodological tiers related to the complexity of different approaches for estimating GHG emissions. The methods provided in this chapter range from simple Tier 1 approaches to more complex Tier 2 and 3 approaches. Higher-tier methods are expected to reduce uncertainties in the emission estimates if sufficient activity data and testing are available. See chapter 1 for more information on IPCC tiers.

Table 4-3 summarizes proposed methods and models for estimating GHG emissions from animal production systems. Appendix 4-B summarizes the rationale for the chosen methods. Box 4-1 contains important notes on how to consider all elements within this chapter.

**Box 4-1. Important Considerations for Calculating Total Animal Production Systems Emissions**

Total emissions estimates for an entity may differ depending on the animal types and management practices employed.

- Consider the units for final estimates. For example, if the calculated emissions units are by head (e.g., kg $CH_4$/head/day) then multiply by the total number of head, 365 days/year, and the GWP of $CH_4$ to obtain results in kg $CO_2$-eq..
- Emissions from each animal type, feed regime, housing, manure storage, and treatment should be converted to $CO_2$-eq and summed to determine the total entity emissions.
- Ammonia emissions, although not a GHG, as well as N losses via leaching contribute to indirect $N_2O$ emissions and must be estimated. See appendix 4-C.3 for a discussion on the inclusion of these estimates.
- As stated in section 4.1.3, management practices have implications for emissions from different sources which includes implications for other chapters within this guidance. Land application of manure requires inputs noted in section 4.5.

**Table 4-3. Overview of Sources and Selected GHG Estimation Methods for Animal Production Systems**

| Section | Source | Gas | Method |
|---|---|---|---|
| **Enteric Fermentation** | | | |
| 4.2.1.1 | Dairy cattle | $CH_4$ | Niu et al. (2018) and Moraes et al. (2014) equations |
| 4.2.2.1 | Beef cattle | $CH_4$ | Modified IPCC Tier 2 for all beef cattle classes. IPCC Tier 2 for grazing cattle if more specific values are wanted for cow-calf, bulls, and stockers |
| 4.2.3.1 | Sheep | $CH_4$ | Howden et al. (1994) equation used when intake data are known and IPCC Tier 2 (2019) when intake data are unknown |

| Section | Source | Gas | Method |
|---|---|---|---|
| 4.2.4.1 | Swine | $CH_4$ | IPCC (2006) Tier 1 |
| 4.2.5.1 | Goats, American bison, llamas, alpacas, and deer | $CH_4$ | IPCC (2019) Tier 1 |
| **Housing Emissions** | | | |
| 4.3.2.1 | Dairy production systems | $CH_4$ | IPCC (2019) Tier 2 for housing; Chianese et al. (2009) for barn floors |
| | | $N_2O$ | IPCC (2019) Tier 2 using nitrogen excretion ($N_{ex}$) from Bougouin et al. (2022), Johnson et al. (2016), and Reed et al. (2015) |
| 4.3.3.1 | Beef production systems | $CH_4$ | IPCC (2019) Tier 2 |
| | | $N_2O$ | IPCC (2019) Tier 2 using $N_{ex}$ from Johnson et al. (2016) and Dong et al. (2014) |
| 4.3.4.1 | Swine production systems | $CH_4$ $N_2O$ | IPCC (2019) Tier 2 |
| 4.3.5.1 | Poultry production systems | $CH_4$ $N_2O$ | IPCC (2019) Tier 2 |
| 4.3.6.1 | Other animals | $CH_4$, $N_2O$ | Includes sheep, goats, American bison, deer, horses, mules and asses, rabbits, and fur bearing animals using IPCC Tier 1 and 2 (2019) |
| **Manure Storage and Treatment** | | | |
| 4.4.1.1 | Solid manure storage (stacked) | $CH_4$ $N_2O$ | IPCC (2019) Tier 2 |
| 4.4.2.1 | Composting | $CH_4$ | IPCC (2019) Tier 2 with monthly data |
| | | $N_2O$ | IPCC (2019) Tier 2 |
| 4.4.3.1 | Aerobic lagoon | $CH_4$ | Methane conversion factor (MCF) for aerobic treatment is negligible and was designated as 0% in accordance with IPCC Tier 1 (2019) |
| | | $N_2O$ | IPCC Tier 2 using IPCC (2019) EFs |
| 4.4.4.1 | Anaerobic lagoon, runoff holding pond, storage tanks | $CH_4$ | IPCC (2019) Tier 2 using spreadsheet for determination of MCF developed by IPCC. Also provides guidance on including solid-liquid separation. |
| | | $N_2O$ | Function of the exposed surface area and U.S.-based emission factors |
| 4.4.5.1 | Anaerobic digesters | $CH_4$ | IPCC Tier 2 using Clean Development Mechanism EFs for digester types to estimate $CH_4$ leakage from digesters |

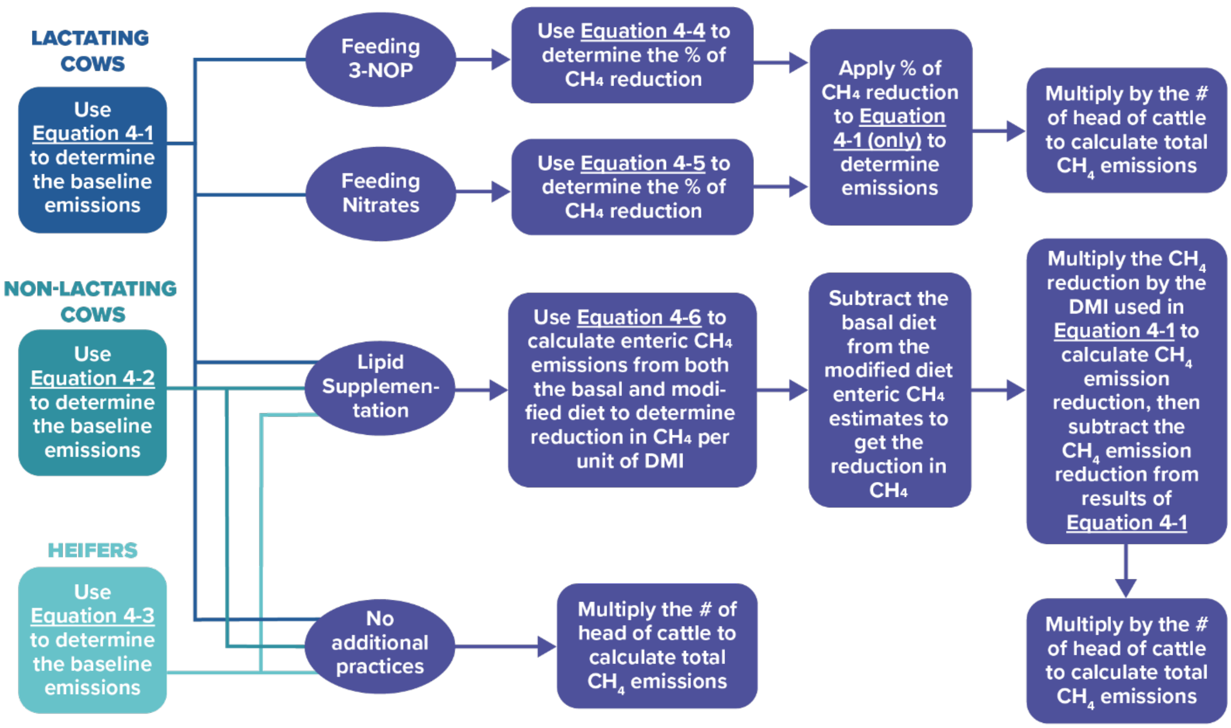
## 4.2 Enteric Fermentation Estimation Methods

This section provides the recommended method for estimating $CH_4$ from enteric fermentation. Quantitative methods are provided for dairy, beef, sheep, swine, and other animals (i.e., goats, American bison, llamas, alpacas, and deer). Review considerations for total animal production emissions in box 4-1.

### 4.2.1 Enteric $CH_4$ From Dairy Cows

**Method for Estimating $CH_4$ Emissions From Enteric Fermentation in Dairy Cows**

- Use Niu et al. (2018) equations for lactating populations and Moraes et al. (2014) for nonlactating adult and heifer populations. Data sources are user input on milk fat, body weight, and dietary intake, as well as dietary composition that, when unavailable, can be calculated from the feedstuffs composition table in appendix 4-E.
- Use equations from Kebreab et al., 2023; Feng et al., 2020; Benaouda et al., n.d. to reflect use of select drugs or diet manipulation practices.




Note: Feeding nitrates is not recommended, and 3-NOP is currently not used within the United States but is under review by the FDA; see box 4-2.

**Figure 4-3. Roadmap for Dairy Cattle Emissions Calculations**

#### 4.2.1.1 Description of Method

Equation 4-1 presents the recommended method to estimate enteric $CH_4$ produced by lactating dairy cows. This equation is based on Niu et al. (2018) and was selected because it performed best for North America as compared to other evaluated equations. The recommended methods to estimate enteric $CH_4$ emissions from dry cows and heifers are based on Moraes et al., 2014 (equation 4-2 and equation 4-3). Review considerations for total animal production emissions in box 4-1.

**Equation 4-1: Estimating Enteric Fermentation $CH_4$ Emissions From Lactating Cows**

$$CH_4 = -126 + 11.3 \times DMI + 2.30 \times NDF + 28.8 \times MF + 0.148 \times BW$$

Where:

| | | |
|---|---|---|
| $CH_4$ | = | enteric methane emissions (g $CH_4$/head/day) |
| $DMI$ | = | dry matter intake (kg/head/day) |
| $NDF$ | = | dietary neutral detergent fiber concentration (% of DM) |
| $MF$ | = | milk fat concentration (%) |
| $BW$ | = | body weight (kg) |

**Equation 4-2: Estimating Enteric $CH_4$ Emissions From Dry Cows**

$$CH_4 = \frac{CH_{4,MJ}}{0.0554}$$

Where:

| | | |
|---|---|---|
| $CH_4$ | = | enteric methane emissions (g $CH_4$/head/day) |
| $CH_{4,MJ}$ | = | enteric methane emissions per day (MJ/head/day) |
| 0.0554 | = | conversion of MJ $CH_4$ to g $CH_4$ |

and

$$CH_{4,MJ} = 2.381 + 0.053 \times GEI$$

Where:

| | | |
|---|---|---|
| $CH_{4,MJ}$ | = | enteric methane emissions (MJ/head/day) |
| $GEI$ | = | gross energy intake (MJ/head/day) |

and

$$GEI = DMI \times [CP \times 0.056 + Fat \times 0.094 + (100 - CP - Fat - Ash) \times 0.042] \times 4.184$$

Where:

| | | |
|---|---|---|
| $DMI$ | = | dry matter intake (kg/head/day) |
| $CP$ | = | dietary crude protein concentration (% of DM) |
| $Fat$ | = | dietary fat concentration measured as ether extract (% of DM) |
| $Ash$ | = | dietary ash concentration (% of DM) |
| 4.184 | = | conversion from megacalories to megajoules |

**Equation 4-3: Estimating Enteric $CH_4$ Emissions From Dairy Heifers**

$$CH_4 = \frac{CH_{4,MJ}}{0.0554}$$

Where:

$CH_4$ = enteric methane emissions (g $CH_4$/head/day)
$CH_{4,MJ}$ = enteric methane emissions per day (MJ/head/day)
0.0554 = conversion of MJ $CH_4$ to g $CH_4$

and

$$CH_{4,MJ} = 1.289 + 0.051 \times GEI$$

Where:

$CH_{4,MJ}$ = enteric methane emissions per day (MJ/head/day)
$GEI$ = gross energy intake (MJ/head/day)

and

$$GEI = DMI \times [CP \times 0.056 + Fat \times 0.094 + (100 - CP - Fat - Ash) \times 0.042] \times 4.184$$

Where:

$DMI$ = dry matter intake (kg/head/day)
$CP$ = dietary crude protein concentration (% of DM)
$Fat$ = dietary fat concentration measured as ether extract (% of DM)
$Ash$ = dietary ash concentration (% of DM)
4.184 = conversion from megacalories to megajoules

### *Dietary Management Practices*

The reductions in enteric $CH_4$ emissions resulting from drugs or feed additives (e.g., 3-NOP or nitrate) or dietary manipulation (e.g., inclusion of oils and oilseeds) require estimation through application of reduction coefficients or dose-response equations. Recommended management practices for reducing enteric $CH_4$ production (g/head/day) from lactating dairy cows include feeding 3-NOP, nitrate, and lipid supplementation or inclusion of oilseeds (Arndt et al., 2020). See appendix 4-A.7.4 for more information on these practices.

**Box 4-2. Important Caveats**

Feed additive impacts to emissions should not be summed as there are not sufficient data to conclude if combined practices would be effective.

Feed additive impacts to emissions past the duration of the literature/studies cited (60–180 days) is unknown; therefore, emission reductions should not be considered in perpetuity.

While studies exist showing the potential to reduce emissions, it is important to note that the drugs mentioned do not claim, nor may they claim, emissions reductions.

Use of nitrates can contribute to higher probability of animal fatalities and should only be done under the supervision of a trained and certified nutritionist.

Use of 3-NOP is currently prohibited in the United States, but under review as an animal drug by the FDA.

See appendix 4-C for research gaps.

Use equation 4-4, equation 4-5, and equation 4-6 to estimate the effect of dietary management practices on enteric $CH_4$ emissions (Kebreab et al., 2023; Feng et al., 2020; Benaouda et al., n.d.). Note that equation 4-4 and equation 4-5 estimate the $CH_4$ reduction as a percentage; equation 4-6 estimates the $CH_4$ emissions from the practice and is for diets containing ether extract from 2.5 to 11 percent on a DM basis. Physical bounds of reasonable maximum reductions are presented within each equation, based on the authors' expert opinion.

**Equation 4-4: Estimating Effect of 3-NOP on Enteric $CH_4$ of Lactating Dairy Cattle**

$$CH_4\ reduction = -32.4 - 0.282 \times (3\text{-}NOP - 70.5) + 0.915 \times (NDF - 32.9) + 3.080 \times (Fat - 4.2)$$

Where:

| | | |
|---|---|---|
| *$CH_4$ reduction* | = | enteric $CH_4$ reduction per day (%) *(a 40% reduction at most is feasible)* |
| *3-NOP* | = | 3-nitroxypropanol dose (mg/kg of DM) |
| *NDF* | = | dietary neutral detergent fiber concentration (% of DM) |
| *Fat* | = | dietary crude fat (% of DM) |

**Equation 4-5: Estimating Effect of Nitrate on Enteric $CH_4$ of Lactating Dairy Cattle**

$$CH_4\ reduction = -20.4 - 0.911 \times (Nitrate - 16.7) + 0.691 \times (DMI - 11.1)$$

Where:

| | | |
|---|---|---|
| *$CH_4$ reduction* | = | enteric methane reduction per day (%) (*a 28% reduction at most is feasible*) |
| *Nitrate* | = | nitrate dose (g/kg of DM) |
| *DMI* | = | dry matter intake (kg/head/day) |
| 16.7 | = | mean nitrate dose (g/kg of DM) |
| 11.1 | = | mean dry matter intake (kg/day) |

**Equation 4-6: Estimating $CH_4$ Enteric Emissions From Lipid Supplementation in Dairy Cows**

$$CH_4\ yield = 25.0 - 0.08 \times EE$$

Where:

| | | |
|---|---|---|
| *$CH_4$* | = | enteric methane yield (g $CH_4$/kg DMI) |
| *EE* | = | dietary ether extract concentration (g/kg of DMI) |

This equation is applicable for diets containing ether extract from 25 to 114 g/kg DMI. See box 4-3 for an example of how methane emissions are calculated.

**Box 4-3. Example of Lipid Supplementation**

Emissions reductions from lipid supplementation are estimated using equation 4-6. Both the basal diet lipid concentration and the supplementation concentration are needed for the equation.

The example below is based on a baseline enteric methane yield of 401 g/head/d (equation 4-1, DMI = 22.8 kg/head/d).

An operator supplementing 20 g lipid/kg DMI on top of a basal diet with 25 g lipid/kg DMI has a total of 45 g lipid/kg DMI.

Methane yield from the modified diet:

$$CH_4\ yield = 25.0 - 0.08\ \times 45 = 21.4\ g\ CH_4/kg\ DMI$$

Methane yield from the basal diet:

$$CH_4\ yield = 25.0 - 0.08\ \times 25 = 23.0\ g\ CH_4/kg\ DMI$$

Subtract the modified diet from the basal diet to determine reduced $CH_4$ yield:

$$Reduced\ CH_4\ yield = 23.0 - 21.4 = \ 1.6\ g\ CH_4/kg\ DMI$$

Multiply the reduced $CH_4$ yield by the DMI to determine the total methane reduction (g $CH_4$/day):

$$CH_4\ yield\ reduction = 1.6\ g\ CH_4/kg\ DMI\ \ \times 22.8\ kg/DMI/head/day\ \ = 36.5\ g/head/day$$

Subtract the $CH_4$ reduction from the methane emissions in equation 4-1:

$$CH_4\ emissions = 401\ g/head/day\ - 36.5\ g/head/day\ = 364.5\ g/head/day$$

#### 4.2.1.2 Activity Data

Type of cattle (lactating dairy cow, nonlactating dairy cow, and dairy heifer), daily dry matter intake (DMI), dietary fat, and lipid supplementation dosage (where applicable) are needed to estimate enteric $CH_4$ emissions for all dairy cattle categories. Body weight (BW), milk fat concentration (MF), dietary neutral detergent fiber content (NDF), and 3-NOP or nitrate dosage (where applicable) are needed to calculate enteric $CH_4$ emissions for lactating dairy cows. Estimating enteric $CH_4$ emissions for nonlactating dairy cows and heifers also requires an estimate of daily gross energy intake (GEI) to be computed from dietary ancillary data. Population is needed if herd or animal group estimates are to be computed from the individual animal results obtained with the recommended equations.

#### 4.2.1.3 Ancillary Data

Dietary concentrations of crude protein (CP) and ash are required to estimate GEI for enteric $CH_4$ emissions from nonlactating dairy cows and heifers.

#### 4.2.1.4 Limitations and Uncertainty

See appendix 4-B.1 for a discussion of current available information on uncertainties for dairy cattle and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

As noted in box 4-2 there are several limitations for the drugs and feed additives equations presented. See appendix 4-C for additional information on current research gaps. While nitrates have been studied for emissions reduction it is important to note the potential for overdoses which are fatal to cattle. Similarly, while 3-NOP has been studied, its use is prohibited within the United

States (as of December 2022). In addition, there are limits to the application and subsequent calculation of emissions from multiple feed additives, and practices used over several months.

## 4.2.2 Enteric $CH_4$ From Beef Cattle

**Method for Estimating $CH_4$ Emissions From Enteric Fermentation in Beef Cattle**

- Use the IPCC Tier 2 approach (IPCC, 2019) for all beef cattle classes, with some adjustment factors based on GEI, diet nutrient composition, and grain processing in feedlot cattle.
- Use the IPCC Tier 2 approach (IPCC, 2019) for grazing cattle if more specific values are wanted for cow-calf, bulls, and stockers on pasture/range.
- Data sources are user inputs on dietary feed intake, grain processing, and the feedstuffs composition table in appendix 4-E. Although the equations used are based on existing inventory methods, the method for feedlot cattle considers a large database of feed types (found in appendix 4-E).
- Use of drugs or feed additives can be addressed by applying calculation factors shown in table 4-6.

### 4.2.2.1 Description of Method

The recommended method to estimate enteric fermentation $CH_4$ from beef cattle uses the IPCC Tier 2 equation (equation 4-7) to calculate daily emissions as well as an emission factor (DayEmit). The GEI, or daily gross energy intake per animal, must be calculated to determine this emission factor, which can be estimated using the IPCC Tier 2 equation (equation 4-8). Both equations are presented below. The digestible energy should be weighted based on portion of total feed intake from a particular feed type. The digestible energy data for particular feedstuffs can be found in appendix 4-E. The IPCC (2019) equations required to calculate the inputs to equation 4-11 are provided in appendix 4-F. The recommended $Y_m$ (methane conversion factor) for beef replacement heifers, steer stockers, heifer stockers, beef cows, and bulls, which are raised on pasture/rangeland, is 6.5 percent for all regions of the country. Review considerations for total animal production emissions in box 4-1.

**Equation 4-7: Modified IPCC Tier 2 Equation for Calculating Enteric $CH_4$ Emissions for Beef Cattle**

$$CH_4 = DayEmit \times Pop_i$$

Where:

| | | |
|---|---|---|
| $CH_4$ | = | methane emissions (g $CH_4$/day) |
| $DayEmit$ | = | emission factor (g $CH_4$/head/day) |
| $Pop_i$ | = | number of animals with same diet (head) |

$$DayEmit = \frac{GEI \times (Y_m \div 100)}{0.056}$$

Where:

| | | |
|---|---|---|
| $DayEmit$ | = | emission factor (g $CH_4$/head/day) |
| $GEI$ | = | gross energy intake (MJ/head/day) |
| $Y_m$ | = | $CH_4$ conversation factor: fraction of gross energy in feed converted to $CH_4$ (%) |
| 0.056 | = | factor for the energy content of methane (MJ/kg $CH_4$) |

**Equation 4-8: IPCC Tier 2 Equation for Calculating Gross Energy Requirements for Beef Cattle**

$$GEI = \frac{\left[\left(NE_m + NE_a + NE_l + NE_{work} + NE_p\right) \div REM\right] + \left(NE_g \div REG\right)}{DE \div 100}$$

Where:

| | | |
|---|---|---|
| *GEI* | = | gross energy intake (MJ/head/day) |
| $NE_m$ | = | net energy required by the animal for maintenance (MJ/day), calculated using equation 10.3 in IPCC (2019) based on body weight (*"Weight"*). *See appendix 4-F for IPCC (2019) equations.* |
| $NE_a$ | = | net energy for animal activity (MJ/day), calculated using equation 10.4 in IPCC (2019) based on $NE_m$ and feeding situation. |
| $NE_l$ | = | net energy for lactation (MJ/day), calculated using equation 10.8 in IPCC (2019) based on milk production (*"Milk"*) and milk fat (*"Fat"*) |
| $NE_{work}$ | = | net energy for work (MJ/day), calculated using equation 10.11 in IPCC (2019) based on information on daily hours of work (*"Hours"*) |
| $NE_p$ | = | net energy required for pregnancy (MJ/day), calculated using equation 10.13 in IPCC (2019) based on $NE_m$ and pregnancy status |
| *REM* | = | ratio of net energy available in a diet for maintenance to digestible energy consumed, calculated using equation 10.14 in IPCC (2019) based on *DE* |
| $NE_g$ | = | net energy needed for growth (MJ/day), calculated using equation 10.6 in IPCC (2019) based on body weight (*"BW"*), mature weight (*"MW"*), and daily weight gain (*"WG"*) |
| *REG* | = | ratio of net energy needed for growth in a diet to digestible energy consumed, calculated using equation 10.15 in IPCC (2019) based on *DE* |
| *DE* | = | digestible energy expressed as a percent of gross energy (%) |

### *Feedlot Cattle*

Feedlot cattle have a baseline $Y_m$ of 3 percent; however, this value varies based on the diet the cattle receive. Correction factors to $Y_m$ for feedlot cattle for different scenarios, i.e., diet modifications, are provided in table 4-4 below (see appendix 4-B.2.2 for more details).

**Table 4-4. Determination of Adjusted $Y_m$ for Feedlot Cattle**

| Variable | Reference | Item | Change in $Y_m$ Compared to Baseline $Y_m$ (Base Diet 3%, IPCC 2006, 2019) | Resulting $Y_m$ |
|---|---|---|---|---|
| Ionophore in diet[a] | Guan et al., 2006; Tedeschi et al., 2003 | Ionophore in diet (baseline diet assumes monensin is included at recommended levels) | No change | 3% |
| | | Ionophore not in diet | Increase $Y_m$ by 0.30 units[b] | 3.3% |
| Fat content[c] | Beauchemin et al., 2008; Hales and Cole, 2017; | 0% supplemental fat | Increase $Y_m$ by 12%[d] | 3.36% |
| | | 1% supplemental fat | Increase $Y_m$ by 8% | 3.24% |
| | | 2% supplemental fat | Increase $Y_m$ by 4% | 3.12% |

| Variable | Reference | Item | Change in $Y_m$ Compared to Baseline $Y_m$ (Base Diet 3%, IPCC 2006, 2019) | Resulting $Y_m$ |
|---|---|---|---|---|
| | Martin et al., 2010; Zinn and Shen, 1996 | 3% or more added fat (baseline diet assumes 3% supplemental fat and 6% total fat) | No change | 3% |
| Grain type and grain processing | Archibeque et al., 2006; Beauchemin and McGinn, 2005; Hales et al., 2012 | Grain in animal diet is steam-flaked or high-moisture corn or sorghum (baseline diet) | No change | 3% |
| | | Grain in animal diet is unprocessed or dry-rolled corn or sorghum | Increase $Y_m$ by 20% | 3.6% |
| | | Grain in diet is either dry-rolled or steam-flaked barley (baseline diet) | No change | 3% |
| Diet starch: NDF ratio[e] | Beauchemin and McGinn, 2005; Hales et al., 2012, 2013, 2014 | Diet has a starch:NDF ratio of 4 (baseline diet is approximately 60% starch and 15% NDF for a starch:NDF ratio of 4) | No change | 3% |
| | | Diet starch:NDF ratio is less than 4 (a maximum of 20% forage in the diet DM) | Increase $Y_m$ 0.453 units for each 1 unit less than a diet starch:NDF ratio of 4 | Depends on starch:NDF ratio |
| | | Diet starch:NDF ratio is more than 4 | Decrease $Y_m$ 0.453 units for each 1 unit greater than a diet starch:NDF ratio of 4 | Depends on starch:NDF ratio |

The $Y_m$ of 3% for feedlot cattle is adjusted based on deviations from a specified baseline diet. Cattle are assumed to be fed for 90–220 days and diets are balanced for CP, ruminal degradable protein, vitamins, and minerals.

[a] Ionophore compounds are not feed additives, rather drugs that allow the transport of ions across the lipid membrane with cells.

[b] For example, if $Y_m$ = 3% add 0.30 units to get 3.3% of GEI. May also subtract the units to decrease $Y_m$.

[c] For each percent of added fat (as supplemental fat or in byproducts such as distillers grain that contain about 10 percent fat), decrease by 4% to a maximum of a 12% decrease.

[d] For example, if $Y_m$ = 3% multiply by 1.12 to get 3.36%.

[e] Baseline diet is assumed to contain about 75% grain and has a starch content of about 60%. Diet contains about 8% forage and a total NDF of about 15%.

### *Cow-Calf, Bulls, and Stockers*

If more specific values are wanted for grazing cattle, the most appropriate predictions available for cow-calf, bulls, and stocker entity-scale estimation are IPCC Tier 2 methods for grazing cattle, presented below in equation 4-9. Review considerations in box 4-1.

**Equation 4-9: IPCC Tier 2 Equation for Calculating Enteric $CH_4$ Emissions for Grazing Beef Cattle (if Detailed Feed Information is Unknown)**

$$CH_4 = DMI \times \frac{MY}{1{,}000}$$

Where:

| | | |
|---|---|---|
| $CH_4$ | = | daily methane emissions (kg $CH_4$/head/day) |
| $DMI$ | = | dry matter intake (kg/day) |
| $MY$ | = | methane yield (kg $CH_4$/kg DMI) (from IPCC table 10.12; see appendix 4-F or table reproduced below) |
| 1,000 | = | conversion from g $CH_4$ to kg $CH_4$ |

| Livestock Category | Description | Feed quality (%) | MY g $CH_4$/kg DMI |
|---|---|---|---|
| Nondairy and multi-purpose cattle and buffalo | > 75% forage | DE ≤ 62 | 23.3 |
| | Rations of > 75% high quality forage and/or mixed rations, forage of between 15 and 75% the total ration mixed with grain, and/or silage | DE 62–71 | 21.0 |

Source: IPCC, 2019.

Critical variables to define DMI include measurements or estimations of feed intake and feed quality (chemical composition) for pasture or rangelands. If the intake is unknown, guidelines proposed by Lalman (2004) can be used to determine DMI, as shown in table 4-5 (NASEM, 2016). In this case, the average quality of the grazed forage is estimated to be low, medium, or high.

**Table 4-5. Estimated DMI of Beef Cattle Grazing Low-, Medium-, or High-Quality Pastures**

| Forage Type | Total Digestible Nutrients (%) | Example Forages | Forage DMI as % of BW | |
|---|---|---|---|---|
| | | | Dry | Lactating |
| Low quality | < 52 | Dry winter forage, mature legume and grass hay, straw | 1.8 | 2.2 |
| Medium quality | 52–59 | Dry summer pasture, dry pasture during the fall, late-bloom legume hay, boot stage and early bloom grass hay | 2.2 | 2.5 |
| High quality | > 59 | Mid-bloom, early bloom, prebloom legume hay, pre-boot-stage grass hay, lush, growing pasture, silages | 2.5 | 2.7 |

Source: Lalman, 2004, as cited by NASEM, 2016. DMI is determined based on forage quality and is calculated as a percent of BW. For example, a lactating cow consuming medium quality forage would consume 2.5% of her BW. Assuming a BW of 600 kg, her DMI (used in equation 4-9) is 15 kg/day.

### *Dietary Management Practices*

Potential practices for reducing enteric $CH_4$ production (g/head/day) from beef cattle in the United States include feeding 3-NOP, nitrate, lipid supplementation, forage supplementation, monensin, and altering the forage to concentrate ratio. Note that there are limitations for some of these practices, as described in box 4-2. Table 4-6 provides information for adjusting enteric $CH_4$

emissions from beef cattle via these different strategies. If used, multiply the result by emissions determined in equation 4-7 or equation 4-9, for only the number of animals with the same diet.

Importantly, for feedlot cattle combining dietary strategies to reduce enteric $CH_4$ can have a cumulative effect, but the overall $Y_m$ value should be 2.5–4.5 percent. For grazing cattle, combining dietary strategies to reduce enteric $CH_4$ can have a cumulative effect, but the overall $Y_m$ value should be 5.5–8 percent (no more or less).

### Box 4-4. Example of Applying Dietary Management Practices

Table 4-6 summarizes emissions adjustments from various practices for beef cattle. Use either equation 4-7 or equation 4-9 to estimate baseline emissions and then review the strategies and adjustments in table 4-6 to appropriately adjust. This math will vary slightly depending on if the strategy may increase or decrease the management practice scenario emissions.

For example, if baseline emissions from feedlot finishing cattle are 25 kg $CH_4$/day and cattle are fed nitrates, <u>subtract</u> the adjustment from 100% of the baseline emissions:

$$CH4_{management\ practice} = 25\ \times \frac{(100\% - 6.5\%)}{100} = 23.4\ kg\,\frac{CH_4}{day}$$

Whereas, if dietary roughage is increased by 2%, <u>add</u> the adjustment to 100% of the baseline emissions:

$$CH4_{management\ practice} = 25\ \times \frac{(100\% + 2.25\%\ \times 2)}{100}\ =\ 26.1\ kg\,\frac{CH_4}{day}$$

As always, these emissions can be multiplied by 365 days/year to determine annual emissions as well multiplied by GWP to get to $CO_2$-eq.

**Table 4-6. Effects of Management Practices on Beef Cattle Enteric $CH_4$ Production**

| Strategy/Technology | Caveats | Enteric Fermentation $CH_4$ Emission Adjustment | |
|---|---|---|---|
| | | Forage Fed[k] Cows and Stocker Cattle | Feedlot Finishing |
| Lipid (ether extract, EE) supplementation | NA | Emission decreased 4.7 ± 0.9% for each 1% increase in dietary ether extract concentration[a,b] (assuming a baseline diet of 3% EE) | Emission decreased 4.1 ± 0.9% for each 1% increase in dietary EE concentration |
| 3-NOP | Not currently approved for use in the United States | Decrease 17.7 ± 1.93%[c] (inclusion of 100–200 mg NOP/kg DM or 1–2 g/head/day) | Decrease 43.0 ± 22.1%[d] (inclusion of 100–200 mg NOP/kg DM or 1–2 g/head/day) |
| Nitrates | Recommended with caution (see box 4-2) | Decrease 10.1 ± 1.52% | Decrease 8.95 ± 1.764%[f] |
| Forage supplementation (hay supplied when pasture/range forage is deficient to meet needs) | NA | Increase in $CH_4$ g/day 16 ± 5% and decrease of $Y_m$ 14 ± 8%[g] | — |

| Strategy/Technology | Caveats | Enteric Fermentation $CH_4$ Emission Adjustment | |
|---|---|---|---|
| | | Forage Fed[k] Cows and Stocker Cattle | Feedlot Finishing |
| Monensin | Following manufacturer label or stated inclusion rates | Decrease 14 ± 6 g $CH_4$/day or a decrease 8%[h] | Decrease 20 ± 10% for 30 days[i] |
| Forage to concentrate ratio | NA | — | Emission increased 2.25 ± 0.32% for each 1% increase in dietary roughage[j] |

[a] Beauchemin et al., 2007.

[b] Hales and Cole, 2017.

[c] Vyas et al., 2016, 2018; Kim et al., 2019; Martinez-Fernandez et al., 2014; Romero-Perez et al., 2014, 2015.

[d] Vyas et al., 2016, 2018; Alemu et al., 2021; Kim et al., 2019.

[e] Feng et al., 2020; Duthie, 2018; Rebelo et al., 2019; Lee et al., 2015, 2017a; Troy et al., 2015; Hulshof et al., 2012; Alemu et al., 2019; Newbold et al., 2014.

[f] Feng et al., 2020; Lee et al., 2017b; Troy et al., 2015.

[g] Shreck et al., 2017, 2021, Cole et al., 2020a.

[h] Appuhamy et al., 2013; McGinn et al., 2004; Hemphill et al., 2018; Vyas et al., 2018.

[i] Appuhamy et al., 2013; Thornton and Owens, 1981; Guan et al., 2006; Vyas et al., 2018.

[j] Roughage is defined here following the international feed numbering system classification with particle sizes in excess of 1.9 centimeters. Studies used to obtain the 2.25% value used alfalfa hay or grass silage as the forage.

[k] Forage-fed differs from grazing.

#### 4.2.2.2 Activity Data

Type of cattle and stage of production (cow, stocker, feedlot), daily DMI, and/or GEI, as well as type and dosage of drugs or feed additive (where applicable) are required to estimate enteric $CH_4$ emissions. For estimating emissions from enteric fermentation, the activity data are the same for all animal types.

#### 4.2.2.3 Ancillary Data

Ancillary data include the properties of the diets (e.g., gross energy, digestible energy, starch, fat, NDF) and grain processing methods in the case of feedlot cattle. The feedstuff characteristics needed to calculate $CH_4$ emissions from beef cattle are included in appendix 4-E (Dairy One, 2021; Ewan, 1989; NASEM, 2016; Preston, 2013).

#### 4.2.2.4 Limitations and Uncertainty

See appendix 4-B.2.2 for additional detail on the analysis and associated uncertainty.

As noted in box 4-2 there are several limitations for the drugs and feed additive equations presented. While nitrates have been studied for emissions reductions it is important to note the potential for overdoses which are fatal to cattle. Similarly, while 3-NOP has been studied, its use is prohibited in the United States (as of December 2022).

## 4.2.3 Enteric $CH_4$ From Sheep

**Method for Estimating Enteric Fermentation $CH_4$ Emissions From Sheep**

- Use the Howden equation (Howden et al., 1994) if DMI is known.
- Use the IPCC Tier 2 (2019) equation if DMI is unknown.

### 4.2.3.1 Description of Method

There are two possible methods for estimating enteric $CH_4$ emissions for sheep. If DMI data are available, use the Howden equation presented in equation 4-10 (Howden et al., 1994). If DMI is unavailable, use the IPCC Tier 2 (2019) equation, equation 4-11, based on new data from pasture-fed sheep. This new equation uses a $Y_m$ value from recent literature of 6.7 percent and assumes the average DMI per day for sheep ranges from 0.6 to 0.8 kg/day. The $Y_m$ value is increased to 7.0 percent if DMI is thought to be less than 0.6 kg/day and is reduced to 6.5 percent if intakes are thought to be greater than 0.8 kg/day (IPCC, 2019). Review considerations for total animal production emissions in box 4-1.

**Equation 4-10: Equation for Enteric Fermentation $CH_4$ Emissions From Sheep**

$$CH_4 = DMI \times 0.0188 + 0.00158$$

Where:

| | | |
|---|---|---|
| $CH_4$ | = | enteric methane emissions (kg $CH_4$/head/day) |
| $DMI$ | = | dry matter intake (kg/head/day) |

**Equation 4-11: IPCC Tier 2 Equation for Enteric Fermentation Emission Factor and Emissions From Sheep If Intake Is Not Known**

$$CH_4 = [GEI \times (Y_m \div 100)] \div 55.65$$

Where:

| | | |
|---|---|---|
| $CH_4$ | = | methane emission (kg $CH_4$/head/day) |
| $GEI$ | = | gross energy intake (MJ/head/day) *(calculated using IPCC equation 10.16; see appendix 4-F)* |
| $Y_m$ | = | methane conversion factor (% of gross energy in feed converted to $CH_4$) |
| 55.65 | = | energy content of $CH_4$ (MJ/kg) |

### 4.2.3.2 Activity Data

An estimate of DMI or GEI is needed to estimate emissions from enteric $CH_4$ fermentation.

### 4.2.3.3 Limitations and Uncertainty

The Howden equation was developed from measurements from sheep grazing tropical forages. This equation has not been verified in animals grazing temperate forages. See appendix 4-B.3 and appendix 4-C.4 for a brief discussion of uncertainty and data gaps for sheep.

## 4.2.4 Enteric $CH_4$ From Swine

**Method for Estimating Enteric Fermentation $CH_4$ Emissions From Swine**

- Use the IPCC Tier 1 approach, with a U.S. emission factor of 1.5 kg $CH_4$/head/year (IPCC, 2006).

### 4.2.4.1 Description of Method

The IPCC (2006) Tier 1 equation for estimating enteric $CH_4$ from swine multiples the population by an emission factor, as shown in equation 4-12. Review considerations for total animal production emissions in box 4-1.

**Equation 4-12: Equation for Enteric Fermentation Emissions From Swine**

$$CH_4 = Pop \times \frac{1.5}{365}$$

Where:

| | | |
|---|---|---|
| $CH_4$ | = | methane emissions (kg $CH_4$/day) |
| $Pop$ | = | number of animals (head) |
| 1.5 | = | emission factor (kg $CH_4$/head/year) |
| 365 | = | days in year (days/year) |

### 4.2.4.2 Activity Data

Swine population is required for estimating emissions from enteric $CH_4$ fermentation.

### 4.2.4.3 Limitations and Uncertainty

See appendix 4-B.4 for current available default values and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

## 4.2.5 Enteric $CH_4$ From Other Animals

Although most enteric fermentation emissions from animals in the United States are from cattle, sheep, and swine, emissions from other animals can also be important to consider, particularly at the entity level. Overall, the animals discussed in this section (goats, American bison, llamas, alpacas, and deer) have much smaller populations than the animals discussed in prior sections. At the entity level, these populations may be significant enough to warrant calculating their emissions, and the availability of research on emissions from these animals allows for at least an introductory level of exploration. Review considerations for total animal production emissions in box 4-1.

### 4.2.5.1 Description of Method

#### *Goats*

Calculate enteric $CH_4$ emissions from goats as shown in equation 4-13, using the IPCC (2019) $Y_m$ value (5.5 percent) for goats.

**Equation 4-13: IPCC Tier 2 Equation for Calculating Enteric Fermentation From Goats**

$$CH_4 = [GEI \times (Y_m \div 100) \times 365] \div 55.65$$

Where:

| | | |
|---|---|---|
| $CH_4$ | = | methane emission (kg $CH_4$/head/year) |
| $GEI$ | = | gross energy intake (MJ/head/day) *(calculated using IPCC equation 10.16; see appendix 4-F)* |
| $Y_m$ | = | methane conversion factor (% of gross energy in feed converted to $CH_4$) |
| 55.65 | = | energy content of $CH_4$ (MJ/kg) |

### *American Bison, Llamas, Alpacas, and Deer*

The U.S. EPA (2020) uses IPCC Tier 1 methodologies to estimate American bison emissions, as currently Tier 1 is the best option to estimate enteric $CH_4$ emissions from bison.

Use equation 4-14 for estimating enteric $CH_4$ emissions from American bison, deer, llamas, and alpacas. Table 4-7 provides available emission factors, including a modified factor for American bison as recommended by IPCC (2019) to account for average weight.

**Equation 4-14: Tier 1 Equation for Calculating Enteric $CH_4$ Emissions From Other Animals**

$$CH_4 = Pop \times EF_i$$

Where:

| | | |
|---|---|---|
| $CH_4$ | = | methane emissions per day (kg $CH_4$/day) |
| $Pop$ | = | number of animals (head) |
| $EF_i$ | = | emission factor for other animal (kg $CH_4$/head/day). See table 4-7. |

## 4.2.5.2 Activity Data

**Table 4-7. Enteric $CH_4$ Emission Factors for American Bison, Llamas, Alpacas, and Deer**

| Animal | Enteric Fermentation Emission Factor (kg $CH_4$/Head/Year)[a] |
|---|---|
| American bison | 64[b] |
| Llamas and alpacas | 8 |
| Deer | 20 |

[a] IPCC (2019) Tier 1 estimates.

[b] The IPCC emission factor for buffalo (0.15 kg CH4/head/day or about 55 kg CH4/head/year), adjusted for American bison based on the ratio of live weights of American bison (513 kg) to buffalo (300 kg) to the 0.75 power: $55 \times \left(\frac{513}{300}\right)^{0.75}$

## 4.2.5.3 Limitations and Uncertainty

See appendix 4-B.5 through appendix 4-B.7 for current available default values and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

## 4.3 Housing Estimation Methods

Animal housing emissions include animal manure in housing areas, stored temporarily or for longer periods before moving to an external manure management system. Housing emissions occur from stockpiled or composted manure in lots and barns and from manure solids, slurries, or waters in pits below the housing area or in manure deposited on pasture/range.

Included below are the most up-to-date methods for estimating GHG emissions from barn floors and manure stored in housing areas. Review considerations for total animal production emissions in box 4-1.

Figure 4-4 provides an overview of the emissions calculations for housing and manure management. Equation use is entity-dependent, depending on animal types and management practices, as described in this section and section 4.4.

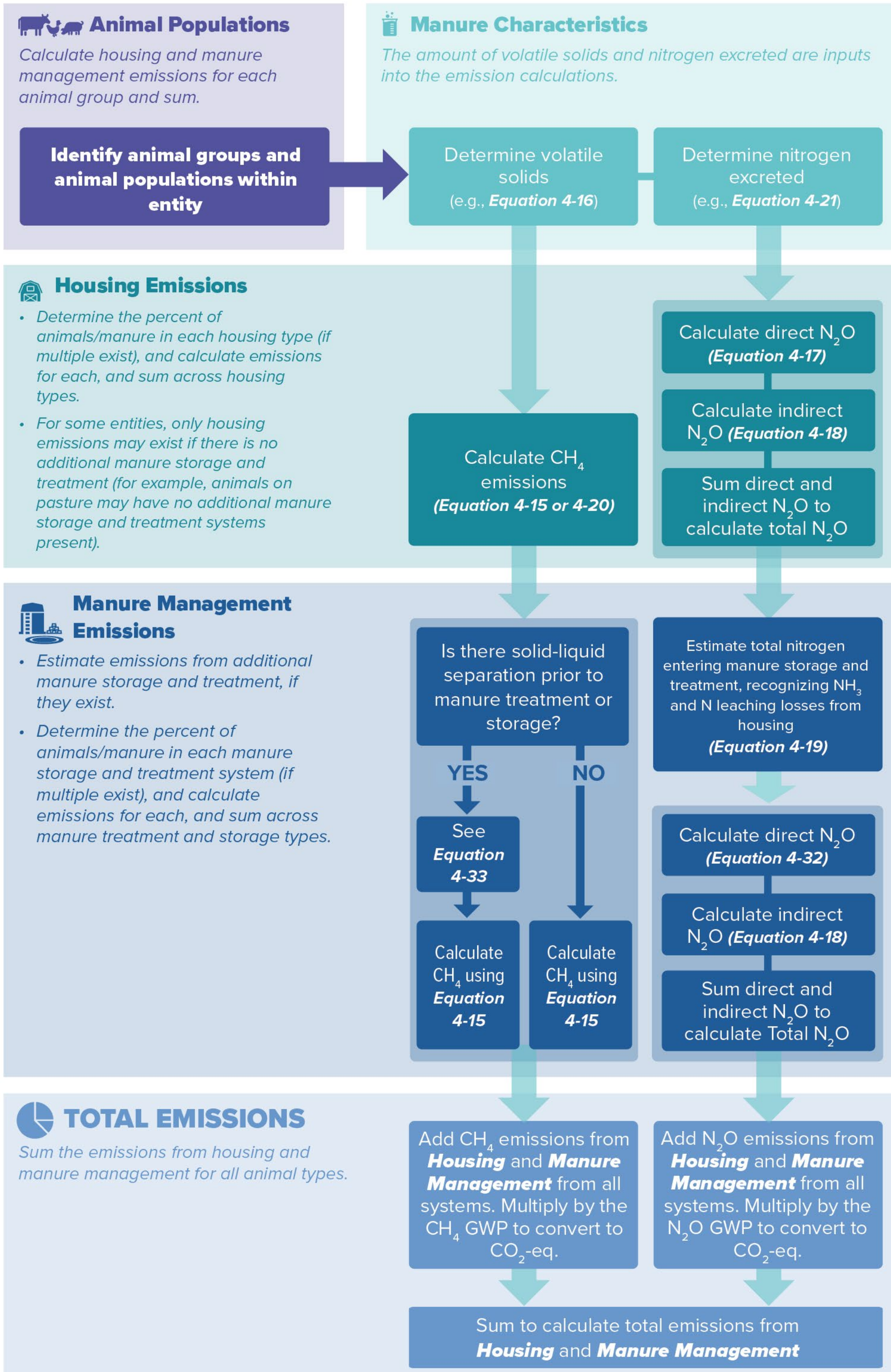



**Figure 4-4. Roadmap for Housing and Manure Storage and Treatment Emissions Estimates**

### *Methane*

Equation 4-15 and equation 4-16 are common equations in subsequent sections for calculating $CH_4$ emissions and are presented here to avoid redundancy. These equations are used for each system type. For multiple systems, sum all calculations to determine the total daily emissions. Review considerations for total animal production emissions in box 4-1.

When manure is allowed to accumulate as a stockpile on a dry lot, in a pit below the animal confinement, as a bedded pack, in a composting barn, or on pasture/range, use the IPCC (2019) Tier 2 method to estimate $CH_4$ emissions, as shown in equation 4-15. This equation uses MCFs and $B_0$ which are determined based on animal or system type or even average temperature and discussed in subsequent sections. Volatile solids (VS) are also required and calculated in equation 4-16, (IPCC, 2019).

**Equation 4-15: IPCC Tier 2 Approach for Estimating $CH_4$ Emissions From Manure**

$$CH_4 = VS \times B_0 \times 0.67 \times \frac{MCF}{100}$$

Where:

| | | |
|---|---|---|
| $CH_4$ | = | $CH_4$ emissions (kg $CH_4$/day) |
| $VS$ | = | volatile solids (kg/day), use equation 4-16 |
| $B_0$ | = | maximum $CH_4$ producing capacity for manure ($m^3$ $CH_4$/kg VS) |
| $MCF$ | = | methane conversion factor for the housing or manure management system (%) |
| 0.67 | = | conversion factor of $m^3$ $CH_4$ to kg $CH_4$ |

**Equation 4-16: Daily VS Excretion Rates**

$$VS = VS_{rate} \times \frac{TAM}{1{,}000} \times Pop \times \frac{\%MMS}{100}$$

Where:

| | | |
|---|---|---|
| $VS$ | = | volatile solids excretion (kg/day) |
| $VS_{rate}$ | = | VS excretion rate (kg VS/1,000 kg animal mass/day) |
| $TAM$ | = | typical animal mass (kg/head) |
| $Pop$ | = | number of animals (head) |
| $\%MMS$ | = | percent or proportion of manure managed in the housing and/or manure storage, if more than one facility or system. Otherwise, assume 100%. |

### *Nitrous Oxide*

Equation 4-17 through equation 4-19 are common equations in subsequent sections calculating $N_2O$ emissions and therefore are presented here to avoid redundancy. Review considerations for total animal production emissions in box 4-1.

Equation 4-17 provides the quantitative method for estimating direct $N_2O$ emissions from animal housing (and manure storage); equation 4-18 from indirect sources. Leaching losses are typical for housing on earthen lots and roofed facilities with bedded packs or composting barns. Where leaching losses are not provided, assume zero percent lost due to leaching. See appendix 4-C.3 for discussion on the uncertainty surrounding the indirect $N_2O$ emissions estimates.

**Equation 4-17: IPCC Tier 2 Approach for Estimating Direct $N_2O$ Emissions From Housing**

$$N_2O_{direct} = Pop \times N_{ex} \times EF_{N2O} \times \frac{44}{28} \times \frac{\%MMS}{100}$$

Where:

| | | |
|---|---|---|
| $N_2O_{direct}$ | = | direct nitrous oxide emissions per day (kg $N_2O$/day) |
| $Pop$ | = | number of animals (head) |
| $N_{ex}$ | = | total nitrogen excretion (kg N/head/day) |
| $EF_{N2O}$ | = | direct $N_2O$ emission factor (kg $N_2O$-N/kg N) |
| $\frac{44}{28}$ | = | conversion of $N_2O$-N emissions to $N_2O$ emissions |
| $\%MMS$ | = | percent or proportion of manure managed in the housing and/or manure storage, if more than one facility or system. Otherwise, assume 100%. |

**Equation 4-18: IPCC Tier 2 Approach for Estimating Indirect $N_2O$ Emissions**

If calculating $N_2O_{indirect}$ for **housing**, use the following equation:

$$N_2O_{indirect} = Pop \times N_{ex} \times [\left(\frac{\%NH_3}{100}\right) + \left(\frac{\%Nleach}{100}\right)] \times 0.01 \times \frac{44}{28} \times \frac{\%MMS}{100}$$

If calculating $N_2O_{indirect}$ for **manure management**, use the following equation:

$$N_2O_{indirect} = TN_{storage} \times [\left(\frac{\%NH_3}{100}\right) + \left(\frac{\%Nleach}{100}\right)] \times 0.01 \times \frac{44}{28} \times \frac{\%MMS}{100}$$

Where:

| | | |
|---|---|---|
| $N_2O_{indirect}$ | = | indirect nitrous oxide emissions (kg $N_2O$/day) |
| $Pop$ | = | number of animals (head) |
| $N_{ex}$ | = | total nitrogen excretion (kg N/head/day) |
| $\%NH_3$ | = | percentage of $N_{ex}$ lost as $NH_3$-N in animal housing |
| $\%Nleach$ | = | percentage of $N_{ex}$ lost as N leaching in animal housing. If no data available, assume 0%. |
| 0.01 | = | indirect $N_2O$ emission factor (kg $N_2O$-N/kg N) |
| $\frac{44}{28}$ | = | conversion of $N_2O$-N emissions to $N_2O$ emissions |
| $\%MMS$ | = | percent or proportion of manure managed in the housing and/or manure storage, if more than one facility or system. Otherwise, assume 100%. |
| $TN_{storage}$ | = | total nitrogen entering manure storage (kg N/day) (from equation 4-19) |

The remaining nitrogen excreted ($N_{ex}$) that is not lost as $N_2O$-N, volatilized as $NH_3$-N, or lost via leaching from housing, then enters manure storage and treatment. The nitrogen entering storage can be estimated as described in equation 4-19. This remaining total nitrogen value is an input into the $N_2O$ and $NH_3$ equations for manure stored or treated. See section 4.4.

**Equation 4-19: Total Nitrogen Entering Manure Storage and Treatment**

$$TN_{storage} = Pop \times N_{ex} \times \left\{1 - \left[\left(\frac{\%NH_3}{100}\right) + \left(\frac{\%Nleach}{100}\right) + EF_{N2O} + \left(EF_{N2O} \times R_{N2(\mathrm{N2O})}\right)\right]\right\}$$

Where:

| | | |
|---|---|---|
| $TN_{storage}$ | = | total nitrogen entering manure storage (kg N/day) |
| $Pop$ | = | number of animals (head) |
| $N_{ex}$ | = | total nitrogen excretion (kg N/head/day) |
| $\%NH_3$ | = | percentage of $N_{ex}$ lost as $NH_3$ in animal housing |
| $\%Nleach$ | = | percentage of $N_{ex}$ lost as N leaching from animal housing. If no data available, assume 0%. |
| $EF_{N2O}$ | = | direct $N_2O$ emission factor (kg $N_2O$-N/kg N) |
| $R_{N2(N2O)}$ | = | ratio of $N_2$:$N_2O$ emissions, the default value is 3 (kg $N_2$-N/kg $N_2O$-N) |

### *Uncertainty*

For all housing estimation methods, much of the published uncertainty information in inventory guidance—e.g., in IPCC *Good Practice Guidance* (IPCC, 2000) and in the U.S. National GHG Inventory (U.S. EPA, 2020)—focuses on uncertainties present in calculating inventories at the regional or national scale, many of which do not translate to the entity level. Consistent improvement in reporting practices can help remove some of this uncertainty. For this reason, uncertainty estimates are not currently included for these methods. See appendix 4-B.8 for current available default values and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

## 4.3.2 $CH_4$ and $N_2O$ Emissions From Dairy Cow Housing

**Method for Estimating Dairy Cows' GHG Emissions From Housing**

**Methane**

- Use the equation developed by Chianese et al. (2009) to calculate $CH_4$ emissions from barn floors.
- Use the IPCC (2019) Tier 2 approach for $CH_4$ emissions from manure in housing.

**Nitrous Oxide**

- Estimate $N_{ex}$ using equations by Bougouin et al. (2022), Johnson et al. (2016), and Reed et al. (2015).
- Use the IPCC (2019) Tier 2 approach for direct $N_2O$ emissions from dairy manure in housing.
- Estimate $NH_3$-N volatilized and N lost in leaching to determine indirect $N_2O$ emissions.

#### 4.3.2.1 Description of Method

***Methane***

To estimate $CH_4$ emissions from barn floors (flushed, scraped, or vacuumed), use the empirical model developed from three freestall barns (Chianese et al., 2009) in equation 4-20.

**Equation 4-20: Calculating $CH_4$ Emissions From Freestall Dairy Barn Floors**

$$CH_4 = 0.13 \times T \times \frac{A_{barn}}{1{,}000}$$

Where:

| | | |
|---|---|---|
| $CH_4$ | = | $CH_4$ emissions (kg $CH_4$/day) |
| $T$ | = | average daily barn temperature (°C) (above 0°C; otherwise, emissions are assumed to be 0 kg $CH_4$/day) |
| $A_{barn}$ | = | area of the barn floor covered with manure ($m^2$) |

When manure is allowed to accumulate as a stockpile on a dry lot, in a pit below the animal confinement, as a bedded pack, or in a composting barn, use the IPCC (2019) Tier 2 method to estimate $CH_4$ emissions (equation 4-15). The data for maximum $CH_4$ producing capacity ($B_0$) and MCFs are listed in table 4-8 and table 4-9.

VS excretion is calculated using equation 4-16 (IPCC, 2019), where parameters are based on individual animal category and productivity system. Typical VS excretion in different animal manures is presented in table 4-26.

***Nitrous Oxide***

The quantitative method for estimating direct $N_2O$ emissions from animal housing is the IPCC Tier 2 approach (equation 4-17). $N_2O$ emission factors for manure stored in housing are listed in table 4-10. Table 4-10 provides estimates of the typical $NH_3$ loss from different housing facilities and animal species as a fraction of $N_{ex}$. For manure in deep pits, on dry lots, mixed with bedding, or composted in place, the emission factors are provided in table 4-10. Estimate the amount of $N_{ex}$ by each animal category using equation 4-21 and equation 4-22 (Bougouin et al., 2022; Johnson et al., 2016; Reed et al., 2015). The $NH_3$-N volatilized or N leached from manure in housing is estimated as a fraction of $N_{ex}$ and is used to calculate the indirect $N_2O$ emissions using equation 4-18.

**Equation 4-21: Estimating $N_{ex}$ From Lactating Cows**

$$N_{ex} = \frac{\{[DMI \times (CP \div 6.25)] \times 0.66\} + 3.03}{1{,}000}$$

Where:

| | | |
|---|---|---|
| $N_{ex}$ | = | total nitrogen excretion (kg N/head/day) |
| $DMI$ | = | dry matter intake (kg/head/day) |
| $CP$ | = | dietary crude protein concentration (g/kg of DM) |
| 6.25 | = | conversion from g of dietary crude protein to g of dietary nitrogen |
| $\frac{1}{1{,}000}$ | = | conversion of grams to kilograms |

**Equation 4-22: Estimating $N_{ex}$ From Nonlactating Cows and Heifers**

$$N_{ex} = \frac{\{[DMI \times (CP \div 6.25)] \times 0.828\} + 15.1}{1{,}000}$$

Where:

| | | |
|---|---|---|
| $N_{ex}$ | = | total nitrogen excretion (kg N/head/day) |
| $DMI$ | = | dry matter intake (kg/head/day) |
| $CP$ | = | dietary crude protein concentration (g/kg of DM) |
| 6.25 | = | conversion from g of dietary crude protein to g of dietary nitrogen |
| $\frac{1}{1{,}000}$ | = | conversion of grams to kilograms |

The remaining nitrogen excreted ($N_{ex}$) that is not lost as $N_2O$-N, volatilized as $NH_3$-N in housing or leached, enters manure storage and treatment. The nitrogen can be estimated as described in equation 4-19. This remaining total nitrogen value is an input into the $N_2O$ equations for manure stored or treated. See section 4.4.

The $NH_3$-N and N loss and $EF_{N2O}$ are dependent on the type of housing.

### 4.3.2.2 Activity Data

Animal population is needed to estimate the daily $CH_4$ and $N_2O$ emissions, as well as $B_0$, VS, MCFs, $NH_3$-N loss, and $EF_{N2O}$ (provided in tables below).

**Table 4-8. Maximum $CH_4$ Producing Capacities and VS Excretion Rates From Dairy Manure**

| Animal | Maximum $CH_4$ Producing Capacity ($B_0$) ($m^3$ $CH_4$/kg VS)[a] | VS Rate (kg/1,000 kg Animal Mass/Day)[a] |
|---|---|---|
| Dairy replacement heifers | 0.17[b] | 7.3 |
| Dairy cow | 0.24 | 11 (5.6[c]) |

[a] Source: USDA Ag Waste Management Field Handbook

[b] Source: U.S. EPA, 2020.

[c] Value in parentheses is for nonlactating mature cow.

**Table 4-9. MCFs for Pit Storage Below Animal Confinement, Deep Bedded Systems, Dry Lots, Compost Barns, and Pasture/Range**

| Housing Type | Storage Time | MCFs (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Cool Temperate Moist (4.6°C)[a] | Cool Temperate Dry (5.8°C)[a] | Warm Temperate Moist (13.9°C)[a] | Warm Temperate Dry (14.0°C)[a] | Tropical Moist (25.2°C)[a] | Tropical Dry (25.5°C)[a] |
| **Liquid/slurry and pit storage below animal confinement** | 1 month | 6 | 8 | 13 | 15 | 36 | 42 |
| | 3 months | 12 | 16 | 24 | 28 | 57 | 62 |
| | 4 months | 15 | 19 | 29 | 32 | 64 | 68 |
| | 6 months | 21 | 26 | 37 | 41 | 73 | 74 |
| | 12 months | 31 | 55 | 64 | 41 | 80 | 80 |

| Housing Type | Storage Time | MCFs (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Cool Temperate Moist (4.6°C)[a] | Cool Temperate Dry (5.8°C)[a] | Warm Temperate Moist (13.9°C)[a] | Warm Temperate Dry (14.0°C)[a] | Tropical Moist (25.2°C)[a] | Tropical Dry (25.5°C)[a] |
| **Deep bedding** | > 1 month | 21 | 26 | 37 | 41 | 73 | 74 |
| **Deep bedding** | < 1 month | 2.75 | 2.75 | 6.5 | 6.5 | 18 | 18 |
| **Dry lot** | 12 months | 1 | 1 | 1.5 | 1.5 | 2 | 2 |
| **Compost barn** | 12 months | 0.50 | 0.50 | 1 | 1 | 1.5 | 1.5 |
| **Pasture/range** | N/A | 0.47 | | | | | |

[a] Values represent average annual temperature.

**Table 4-10. Typical $NH_3$-N Losses and Direct $N_2O$ Emission Factors From Dairy Housing Facilities**

| Facility Description | $NH_3$ Loss (% of $N_{ex}$)[a] | N Loss Leaching (% of $N_{ex}$)[b] | $EF_{N2O}$ (kg $N_2O$ N/kg $N_{ex}$)[b] |
|---|---|---|---|
| Dry lot including housing, including barn and lot combination | 36 | 3.5 | 0.02 |
| Barn (natural or mechanical ventilation) | 15.5 | 0 | 0 |
| Roofed facility—bedded pack (no mix) | 25 | 3.5 | 0.01 |
| Roofed facility—bedded pack (active mix) including compost barns | 50 | 3.5 | 0.07 |
| Pasture/range | 7 | 0 | See section 4.5 and chapter 3 |

[a] Sources for dry lot and barn: Bougouin et al. 2016, Hristov et al., 2011, Liu et al., 2017. Source for bedded pack from IPCC, 2019. Sources for pasture: Voglmeier et al., 2018; Sommer et al., 2019; Adhikari et al., 2020; Fischer et al., 2015.

[b] Source: IPCC, 2019.

### 4.3.2.3 Ancillary Data

Besides the required data noted above, the following entity data are also needed to estimate daily $CH_4$ and $N_2O$ emissions from dairy cattle housing:

- Animal population
- Animal characteristics (e.g., body weight and stage of production)
- Temperatures (local ambient temperature and manure temperature)
- Dry matter intake and dietary crude protein

### 4.3.2.4 Limitations and Uncertainty

See appendix 4-B.8.2 for current available default values and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

### 4.3.3 $CH_4$ and $N_2O$ Emissions From Beef Production Housing

**Method for Estimating Beef Cattle GHG Emissions From Housing**

**Methane**

- Use the IPCC (2019) Tier 2 method to estimate $CH_4$ emissions when manure accumulates on feedlot pen surfaces, on pasture/range, or in bedded or compost barns as described below.

**Nitrous Oxide**

- Estimate $N_{ex}$ for feedlot cattle using the equation of Dong et al. (2014).
- Use the IPCC (2019) Tier 2 approach for direct $N_2O$ emissions from beef cattle manure in housing.
- Estimate $NH_3$-N volatilized and N lost in leaching to determine indirect $N_2O$ emissions.

#### 4.3.3.1 Description of Method

***Methane***

When beef manure is allowed to accumulate as a stockpile on a dry lot, in pasture/range, as a bedded pack, or in a composting barn, use the IPCC (2019) Tier 2 method to estimate $CH_4$ emissions (equation 4-15). The maximum $CH_4$ producing capacity ($B_0$) for manure varies by animal category and is provided in table 4-11. The MCFs for manure deposited on a dry lot, pasture/range, from deep bedding, or in compost barns can be found in table 4-12. Calculate VS using equation 4-16 (IPCC, 2019), where parameters are based on individual animal category and productivity system. Typical VS contents in different cattle manures are presented in table 4-26.

***Nitrous Oxide***

The quantitative method for estimating direct $N_2O$ emissions from animal housing is the IPCC Tier 2 approach (equation 4-17). $N_2O$ emission factors for manure stored in housing are listed in table 4-13. Estimate the quantity of total $N_{ex}$ from feedlot beef cattle using an equation from Dong et al. (2014) (equation 4-23). For a beef feedlot, a default value of 0.069 kg N/kg dry manure can be used if $N_{ex}$ is not calculated. The $NH_3$-N volatilized, or N leached from manure in housing is estimated as a fraction of $N_{ex}$ and is used to calculate the indirect $N_2O$ emissions using equation 4-18.

The remaining nitrogen excreted that is not lost as $N_2O$-N, volatilized as $NH_3$-N or lost via N leaching from housing enters manure storage and treatment, calculated using equation 4-19. Table 4-13 provides estimates on the typical $NH_3$-N loss from different housing facilities as a fraction of $N_{ex}$.

**Equation 4-23: Estimating $N_{ex}$ of Feedlot Cattle**

$$N_{ex} = \frac{(0.51 \times N_{intake} - 14.12) + (0.20 \times N_{intake} + 15.82)}{1{,}000}$$

Where:

| | | |
|---|---|---|
| $N_{ex}$ | = | total nitrogen excretion (g/head/day) |
| $N_{intake}$ | = | nitrogen intake per finished animal (g/head/day) |
| $\frac{1}{1{,}000}$ | = | conversion g to kg |

$$N_{intake} = DMI \times \frac{\frac{CP}{100}}{6.25}$$

Where:

| | | |
|---|---|---|
| $N_{intake}$ | = | nitrogen intake per finished animal (g/head/day) |
| $DMI$ | = | dry matter intake (% body weight) |
| $CP$ | = | dietary crude protein (% DM) |

An alternative approach to calculate $NH_3$ loss, for use in equation 4-17 or equation 4-19, for feedlot cattle is to use the equation of Todd et al. (2013), which calculates feedlot $NH_3$ emissions as a function of dietary crude protein and average monthly temperature.

**Equation 4-24: Beef Feedlot $NH_3$ Emissions and N Estimation**

$$NH_3 = e^{8.82 - 1627 \times \frac{1}{T} + 0.108 \times CP}$$

Where:

| | | |
|---|---|---|
| $NH_3$ | = | $NH_3$ emission from housing (g $NH_3$/head/day) |
| $T$ | = | average monthly temperature (K) |
| $CP$ | = | dietary crude protein (% DM) |

For most feedlot situations, the feed intake of a pen of cattle is well documented. When feed intake is unknown, it can be estimated using a variety of equations. Anele et al. (2014) and subsequently NASEM (2016) suggested DMI as a percent of body weight was best estimated from dietary $NE_m$ contents using equation 4-25.

**Equation 4-25: Estimating DMI of Feedlot Cattle as a Percent of Body Weight**

$$DMI = 1.2425 + 1.9218 \times NE_m - 0.7259 \times NE_m{}^2$$

Where:

| | | |
|---|---|---|
| $DMI$ | = | dry matter intake (% body weight) |
| $NE_m$ | = | net energy required by the animal for maintenance, estimated Mcal/kg of the diet (Mcal/kg of DM) |

### 4.3.3.2 Activity Data

**Table 4-11. Maximum $CH_4$ Producing Capacities and VS Excretion Rates From Beef Cattle Manure**

| Animal | Maximum $CH_4$ Producing Capacity ($B_0$) ($m^3$/kg VS)[a] | VS Rate (kg/1,000 kg Animal Mass/Day)[b] |
|---|---|---|
| Beef cows | 0.33 | 7.6 |
| Steers (> 500 lbs) | 0.33 | 7.6 |
| Stockers (all) | 0.17 | 7.6 |
| Cattle on feed | 0.33 | 7.6 |

[a] Source: U.S. EPA, 2020.

[b] Source: IPCC, 2019.

**Table 4-12. MCFs for Deep Bedded Systems, Dry Lots, Compost Barns, and Pasture/Range**

| Housing Type | Storage Time | MCFs (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Cool Temperate Moist (4.6°C)[a] | Cool Temperate Dry (5.8°C)[a] | Warm Temperate Moist (13.9°C)[a] | Warm Temperate Dry (14.0°C)[a] | Tropical Moist (25.2°C)[a] | Tropical Dry (25.5°C)[a] |
| Deep bedding | >1 month | 21 | 26 | 37 | 41 | 73 | 74 |
| Deep bedding | <1 month | 2.75 | 2.75 | 6.5 | 6.5 | 18 | 18 |
| Dry lot | 12 months | 1 | 1 | 1.5 | 1.5 | 2 | 2 |
| Compost barn | 12 months | 0.50 | 0.50 | 1 | 1 | 1.5 | 1.5 |
| Pasture/range | N/A | 0.47 | | | | | |

[a] Values represent average annual temperature.

**Table 4-13. Typical $NH_3$ Losses and Direct $N_2O$ Emission Factors From Beef Cattle Housing Facilities**

| Facility Description | $NH_3$ Loss (% of $N_{ex}$)[a] | N Loss Leaching (% of $N_{ex}$) | $EF_{N2O}$ (kg $N_2O$ N/kg $N_{ex}$) |
|---|---|---|---|
| Feedlot/dry lot | 65[a] | 3.5 | 0.02 |
| Roofed facility—bedded pack (no mix) | 25 | 3.5 | 0.01 |
| Roofed facility—bedded pack (active mix) including compost barns | 60 | 3.5 | 0.07 |
| Pasture/range | 7[b] | | See section 4.5 and chapter 3 |

Source: Unless otherwise specified IPCC, 2019.

[a] Source for feedlot $NH_3$ losses: Hristov et al., 2011; Liu et al., 2017.

[b] Sources for pasture: Voglmeier et al., 2018; Sommer et al., 2019; Adhikari et al., 2020; Fischer et al., 2015.

#### 4.3.3.3 Ancillary Data

Besides the required data noted above, the following entity data are also needed to estimate daily $CH_4$ and $N_2O$ emissions from beef cattle housing:

- Animal population
- Animal characteristics (e.g., body weight and stage of production) and dietary information
- Temperatures (local ambient temperature and manure temperature)
- Feed information

#### 4.3.3.4 Limitations and Uncertainty

See appendix 4-B.8.2 for current available default values and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

## 4.3.4 $CH_4$ and $N_2O$ Emissions From Swine Production Housing

**Method for Estimating Swine GHG Emissions From Housing**

**Methane**

- Use the IPCC (2019) Tier 2 method to estimate $CH_4$ emissions when manure is allowed to accumulate below the animal confinement, in bedded barns, or on pasture as described below.

**Nitrous Oxide**

- Use the IPCC (2019) Tier 2 approach for nitrogen intake, retention, and excretion.
- Use the IPCC (2019) Tier 2 approach for $N_2O$ from manure in housing.

### 4.3.4.1 Description of Method

#### *Methane*

Use the IPCC (2019) Tier 2 method (equation 4-15) to estimate $CH_4$ emissions from swine housing, regardless of where swine are housed (e.g., pasture, bedded pack in a barn, pit below the animal confinement). The maximum $CH_4$ producing capacity ($B_0$) for manure varies by animal category and is provided in table 4-14. The MCFs for manure stored in a deep pit, from bedding, or in pasture can be found in table 4-15. VS are calculated using equation 4-16 (IPCC, 2019), where parameters are based on individual animal category. Typical VS contents in different manures are presented in table 4-26.

#### *Nitrous Oxide*

The quantitative method for estimating $N_2O$ emissions from animal housing is the IPCC Tier 2 approach (equation 4-17). $N_2O$ emission factors for manure stored in housing are listed in table 4-17. Estimate the amount of $N_{ex}$ for each swine category based on total nitrogen intake ($N_{intake}$) and nitrogen retained by animals ($N_{retention}$) (equation 4-26). Equation 4-27 and equation 4-28 provide the methods for estimating the nitrogen intake and retention for the different swine classes as recommended by IPCC.

**Equation 4-26: Estimating $N_{ex}$ From Swine**

$$N_{ex} = N_{intake} - N_{retention}$$

Where:

| | | |
|---|---|---|
| $N_{ex}$ | = | total nitrogen excretion (kg/head/day) |
| $N_{intake}$ | = | nitrogen intake per finished animal (kg/head/day) |
| $N_{retention}$ | = | nitrogen retained per finished animal (kg/head/day) |

**Equation 4-27: Estimating $N_{intake}$ and $N_{retention}$ From Growing Pigs**

$$N_{intake} = DMI \times [(C_{CP} \div 100) \div 6.25]$$

$$N_{retention} = \left[\left(BW_f - BW_i\right) \times N_{gain}\right] \div GS$$

Where:

| | | |
|---|---|---|
| $N_{intake}$ | = | nitrogen intake per finished animal (kg/head/day) |
| $N_{retention}$ | = | nitrogen retained per finished animal (kg/head/day) |
| $N_{gain}$ | = | fraction of nitrogen retained at a given BW (calculate for the final BW of the phase: for example, for a finishing hog that weighed 109 kg at slaughter, use a value of 0.021 kg N/kg BW gain) |
| $DMI$ | = | dry matter intake (kg/head/day) |
| $C_{CP}$ | = | percentage of crude protein in DM (%) |
| $BW_f$ | = | final body weight at the end of the growth stage (kg) |
| $BW_i$ | = | initial body weight (kg) |
| $GS$ | = | number of days in the growth stage (default value is between 154 and 168 days) |

**Equation 4-28: Estimating $N_{intake}$ and $N_{retention}$ From Breeding Sows**

$$N_{intake} = DMI \times [(C_{CP} \div 100) \div 6.25]$$

$$N_{retention} = \frac{\left[\left(0.025 \times FR \times S_{wtgain}\right) + \left(0.025 \times LTSZ \times FR \times \frac{Pig_{weanwt} - Pig_{birthwt}}{0.98}\right)\right]}{FR \times RC}$$

Where:

| | | |
|---|---|---|
| $N_{intake}$ | = | nitrogen intake per finished animal (kg N/head/day) |
| $N_{retention}$ | = | nitrogen retained per finished animal (kg N/head/day) |
| $DMI$ | = | dry matter intake (kg N/head/day) |
| $C_{CP}$ | = | percentage of crude protein in DM (%) |
| 6.25 | = | conversion from kg of dietary protein to kg of dietary N |
| $FR$ | = | fertility rate of sows (parturitions/year) |
| $S_{wtgain}$ | = | live weight change of sows during gestation (kg) |
| $LTSZ$ | = | litter size (head) |
| $Pig_{weanwt}$ | = | live weight of piglets at weaning (kg/head) |
| $Pig_{birthwt}$ | = | live weight of piglets at birth (kg/head) |
| $RC$ | = | days in the reproductive cycle (default value is 146 days) |

Some of the nitrogen excreted is volatilized as $NH_3$, so the estimation of $NH_3$ losses is necessary to estimate $N_2O$ emissions using a nitrogen balance approach. The $NH_3$ lost via volatilization and N leached from swine housing is estimated as a fraction of $N_{ex}$ according to table 4-17.

### 4.3.4.2 Activity Data

**Table 4-14. Maximum $CH_4$ Producing Capacities and VS Rates From Swine Manure**

| Animal | Maximum $CH_4$ Producing Capacity ($B_0$) ($m^3$/kg VS) | VS Rate (kg/1,000 kg Animal Mass/Day) |
|---|---|---|
| Growing swine | 0.48 | 3.9 |
| Breeding swine | 0.48 | 1.8 |

Source: IPCC, 2019.

**Table 4-15. MCFs for Pit Storage Below Animal Confinement, Deep Bedded Systems, and Pasture**

| Housing Type | Storage Time | MCF (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Cool Temperate Moist (4.6)[a] | Cool Temperate Dry (5.8)[a] | Warm Temperate Moist (13.9)[a] | Warm Temperate Dry (14.0)[a] | Tropical Moist (25.2)[a] | Tropical Dry (25.5)[a] |
| Liquid/slurry and pit storage below animal confinement | 1 month | 6 | 8 | 13 | 15 | 36 | 42 |
| | 3 months | 12 | 16 | 24 | 28 | 57 | 62 |
| | 4 months | 15 | 19 | 29 | 32 | 64 | 68 |
| | 6 months | 21 | 26 | 37 | 41 | 73 | 74 |
| | 12 months | 31 | 55 | 64 | 41 | 80 | 80 |
| Deep bedding | > 1 month | 21 | 26 | 37 | 41 | 73 | 74 |
| Deep bedding | < 1 month | 2.75 | 2.75 | 6.5 | 6.5 | 18 | 18 |
| Pasture | N/A | 0.47 | | | | | |

[a] Values represent average annual temperature (°C).

**Table 4-16. Nitrogen Gain by Growth Stage**

| Facility Description | $N_{gain}$ (kg N/kg BW) |
|---|---|
| Nursery (4–7 kg) | 0.031 |
| Nursery (7–20 kg) | 0.028 |
| Grower (20–40 kg) | 0.025 |
| Grower (40–80 kg) | 0.024 |
| Finisher (80–120 kg) | 0.021 |

Source: IPCC, 2019.

**Table 4-17. Typical $NH_3$ Losses and Direct $N_2O$ Emission Factors From Swine Housing Facilities**

| Facility Description | $NH_3$ Loss (% of $N_{ex}$)[a] | N loss Leaching (% of $N_{ex}$) | $EF_{N2O}$ (kg $N_2O$ N/kg $N_{ex}$)[b] |
|---|---|---|---|
| Roofed facility—bedded pack (no mix) | 40 | 3.5 | 0.01 |
| Roofed facility—bedded pack (active mix) including compost barns | 65 | 3.5 | 0.07 |

| Facility Description | $NH_3$ Loss (% of $N_{ex}$)[a] | N loss Leaching (% of $N_{ex}$) | $EF_{N2O}$ (kg $N_2O$ N/kg $N_{ex}$)[b] |
|---|---|---|---|
| Roofed facility—pit storage below animal confinement | 25 | 0 | 0.002 |
| Pasture | 19 | | See section 4.5 and chapter 3 |

a Source for everything except pasture: IPCC (2019). Source for pasture: Sommer et al., 2019.

b Source: IPCC, 2019.

#### 4.3.4.3 Ancillary Data

Besides the required data noted above, the following entity data are also needed to estimate daily $CH_4$ and $N_2O$ emissions from swine housing:

- Animal population
- Animal characteristics (e.g., body weight and growth stage) and dietary information
- Bedding characteristics
- Temperatures (local ambient temperature and manure temperature)
- Feed information

#### 4.3.4.4 Limitations and Uncertainty

See appendix 4-B.8.2 for current available default values and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

### 4.3.5 $CH_4$ and $N_2O$ Emissions From Poultry Housing

**Method for Estimating Emissions From Poultry Housing**

**Methane**

- Use the IPCC (2019) Tier 2 approach with barn capacity and manure CH4 emission factors per poultry type.
- The IPCC emission factor for poultry enteric CH4 production is 0. Emissions from hindgut fermentation are small and generally considered part of housing emissions.

**Nitrous Oxide**

- Use the IPCC (2019) Tier 2 approach for $N_{ex}$.
- Use the IPCC (2019) Tier 2 approach for $N_2O$ from manure in housing.

#### 4.3.5.1 Description of Method

***Methane***

Use the IPCC (2019) Tier 2 method (equation 4-15) to estimate $CH_4$ emissions from poultry production systems. The maximum $CH_4$ producing capacity ($B_0$) is provided in table 4-18. The MCFs for manure deposited in poultry houses can be found in table 4-19.

Calculate VS using equation 4-16 (IPCC, 2019), where parameters are based on individual animal category and productivity system. Typical VS contents in different poultry manures are presented in table 4-26.

### *Nitrous Oxide*

The quantitative method for estimating $N_2O$ emissions from poultry housing is the IPCC Tier 2 approach (equation 4-17). $N_2O$ emission factors and $NH_3$ lost from manure for meat and egg-producing birds as a fraction of $N_{ex}$ for manure stored in housing are listed in table 4-20.

The remaining nitrogen excreted that is not lost as $N_2O$ or volatilized as $NH_3$ in housing enters manure storage and treatment. If data are not available to track the nitrogen that is transferred along with the manure-to-manure storage and treatment, the nitrogen can be estimated as described in equation 4-19. This remaining total nitrogen value is an input into the $N_2O$ equations for manure stored or treated.

Estimate the quantity of total $N_{ex}$ using equations from IPCC (IPCC 2019) and ASABE (2005). Equation 4-29 and equation 4-30 are the equations recommended by IPCC (2019) for estimating $N_{ex}$ from poultry produced for meat (broilers, turkeys, ducks) and egg-laying poultry, respectively.

**Equation 4-29: Estimating $N_{ex}$ From Poultry Produced for Meat**

$$N_{ex} = [DMI \times (CP\% \div 100 \div 6.25)] - \{[(BW_f - BW_i) \times 0.028] \div PP\}$$

Where:

| | | |
|---|---|---|
| $N_{ex}$ | = | total nitrogen excretion (kg N/head/day) |
| $DMI$ | = | dry matter intake (kg DMI/head/day) |
| $CP\%$ | = | percentage of crude protein in the diet (%) |
| $BW_f$ | = | final body weight (kg) |
| $BW_i$ | = | initial body weight (kg) |
| $PP$ | = | production period (length of time from chick to slaughter) (days) |

**Equation 4-30: Estimating $N_{ex}$ From Egg-Laying Poultry**

$$N_{ex} = [DMI \times (CP\% \div 100 \div 6.25)] - \{0.028 \times WG + [(0.0185 \times EP) \div 1{,}000]\}$$

Where:

| | | |
|---|---|---|
| $N_{ex}$ | = | total nitrogen excretion (kg N/head/day) |
| $DMI$ | = | dry matter intake (kg DMI/head/day) |
| $CP\%$ | = | percentage of crude protein in the diet (%) |
| $WG$ | = | average daily weight gain for cohort (kg/head/day) |
| $EP$ | = | egg mass production (g egg/head/day); default egg weight is 60 g for light layer strains and 63 g for heavy layer strains |

#### 4.3.5.2 Activity Data

**Table 4-18. Maximum $CH_4$ Producing Capacities and VS Rates From Poultry Manure**

| Animal | Maximum $CH_4$ Producing Capacity ($B_0$) ($m^3$/kg VS) | VS Rate (kg/1,000 kg Animal Mass/Day) |
|---|---|---|
| Poultry—layer | 0.39 | 9.4 |
| Poultry—meat | 0.36 | 16.8 |

Source: IPCC, 2019.

**Table 4-19. MCFs for Poultry Manure With and Without Litter**

| Housing Type | All Climates (%) |
|---|---|
| Poultry manure with and without litter | 1.5 |

**Table 4-20. Typical $NH_3$ Losses and Direct $N_2O$ Emission Factors From Poultry Housing Facilities**

| Facility Description | $NH_3$ Loss (% of $N_{ex}$) | $EF_{N2O}$ (kg $N_2O$ N/kg $N_{ex}$) |
|---|---|---|
| Roofed facility—with litter | 40 | 0.001 |
| Roofed facility—without litter | 48 | 0.001 |
| Use of alum or another acidifying agent in litter | 20[a] | — |

Source: IPCC, 2019.

[a] Source: Author expert judgment based on Anderson et al. (2020), Eugene et al. (2015), Madrid et al. (2012), and Moore et al. (2008).

#### 4.3.5.3 Ancillary Data

Besides the required data listed in the tables above, the following entity data are also needed to estimate daily $CH_4$ and $N_2O$ emissions from poultry housing:

- Animal population and animal characteristics (e.g., body weight, growth potential, egg production)
- Feed intake
- Temperatures (local ambient temperature and manure temperature)

#### 4.3.5.4 Limitations and Uncertainty

See appendix 4-B.8.2 for current available default values and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

## 4.3.6 $CH_4$ and $N_2O$ Emissions From Other Animals Housing

**Method for Estimating Emissions From Other Animals**

**Methane**

- Use the IPCC (2019) Tier 1 approach, or Tier 2 when data are available.

**Nitrous Oxide**

- Use the IPCC (2019) Tier 1 approach for $N_{ex}$.
- Use the IPCC (2019) Tier 2 approach for $N_2O$ from manure in housing.

### 4.3.6.1 Description of Method

#### *Methane*

To estimate $CH_4$ emissions from other animal housing—sheep, goats, American bison, deer, horses, mules and asses, rabbits, and fur bearing animals—use the IPCC (2019) Tier 2 method (equation 4-15) when activity data are available; otherwise, use the Tier 1 default emission factors provided in table 4-21 and table 4-22, in lieu of using MCF and $B_0$ values.

#### *Nitrous Oxide*

To estimate $N_2O$ emissions from other animals, use the IPCC Tier 2 approach (equation 4-17) when activity data are available; otherwise, use the Tier 1 default values.

### 4.3.6.2 Activity Data

**Table 4-21. Housing (Dry Lot) Methane Emission Factors by Animal Category and Climate Zone**

| Animal | $CH_4$ Emission Factor (g $CH_4$/kg VS) | | |
|---|---|---|---|
| | Cool | Temperate | Warm |
| Sheep | 1.3 | 1.9 | 2.5 |
| Goats | 1.2 | 1.8 | 2.4 |

Source: IPCC, 2019, assuming high-productivity systems.

**Table 4-22. $CH_4$ Emission Factors by Animal Category, MCF for Housing (Pasture/Range), Maximum $CH_4$ Producing Capacity of Manure, and VS Excretion**

| Animal | Methane Emission Factor | | Maximum $CH_4$ Producing Capacity ($B_0$) ($m^3$/kg VS) | VS | |
|---|---|---|---|---|---|
| | MCF % [a] | kg $CH_4$/Head/Year | | kg/Day | kg/1,000 kg Animal Mass/Day |
| American bison[b] | 0.47 | — | 0.10 | — | 7.7 |
| Sheep | 0.47 | — | 0.19 | — | 8.2 |
| Goats | 0.47 | — | 0.18 | — | 9 |
| Deer | — | 0.22 | — | — | — |
| Horses | 0.47 | — | 0.33 | — | 6.1 |

| Animal | Methane Emission Factor | | Maximum $CH_4$ Producing Capacity ($B_0$) ($m^3$/kg VS) | VS | |
|---|---|---|---|---|---|
| | MCF % [a] | kg $CH_4$/Head/Year | | kg/Day | kg/1,000 kg Animal Mass/Day |
| Mules and asses | 0.47 | — | 0.33 | — | 7.2 |
| Rabbits | — | 0.08 | 0.32 | 0.10 | — |
| Fur-bearing animals | — | 0.68 | 0.25 | 0.14 | — |

[a] Assuming animals on pasture/range (IPCC, 2019)

[b] Surrogating values for buffalo from IPCC (2019).

**Table 4-23. $N_{ex}$ Values for Other Animals**

| Category of Animal | Units | $N_{ex}$ |
|---|---|---|
| Sheep | kg N/1,000 kg BW/day | 0.35 |
| Goats | kg N/1,000 kg BW/day | 0.46 |
| American bison | kg N/1,000 kg BW/day | 0.40[a] |
| Horses | kg N/hd/yr | 0.25 |
| Mules and asses | kg N/hd/yr | 0.30 |
| Deer | kg N/hd/yr | 0.67 |
| Rabbits | kg N/hd/yr | 8.10 |
| Mink | kg N/hd/yr | 4.59 |

[a] Average of values for western Europe and eastern Europe.

**Table 4-24. Typical $NH_3$ Losses and Direct $N_2O$ Emission Factors From the Housing of Other Animals**

| Facility Description | $NH_3$ Loss (%) | $EF_{N2O}$ (kg $N_2O$ N/kg $N_{ex}$) |
|---|---|---|
| Pasture/range/paddock | — | See section 4.5 and chapter 3 |
| Dry lot | 30 | 0.02 |

Source: IPCC, 2019. IPCC (2019) does not have guidance for rabbit and mink housing.

### 4.3.6.3 Ancillary Data

Besides the required data listed in the tables above, the following entity data are also needed to estimate daily $CH_4$ and $N_2O$ emissions from housing other animals:

- Animal population and animal body weight
- Temperatures (local ambient temperature and manure temperature)

### 4.3.6.4 Limitations and Uncertainty

See appendix 4-B.8.2 for current available default values and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

## 4.4 Manure Management Estimation Methods

Manure can be handled as a solid or liquid. It can be applied directly to land, stored, or treated before storage or land application. In some practices, solids are separated from the liquid manure stream and treated using a solid handling system.[3] Individual practices may be combined to treat manure based on the need at the entity level. Each manure management practice is described as an individual unit practice in this document. The references for estimation of GHG emission for individual practices are listed in table 4-3. Review considerations for total animal production emissions in box 4-1.

Note for all manure management estimation methods, much of the published uncertainty information in inventory guidance—e.g., in IPCC *Good Practice Guidance* (IPCC, 2000) and in the U.S. National GHG Inventory (U.S. EPA, 2020)—focuses on uncertainties present in calculating inventories at the regional or national scale, many of which do not translate to the entity level. Consistent improvement in reporting practices can help remove some of this uncertainty. For this reason, uncertainty estimates are not currently included for these methods. See appendix 4-B.8.2 for current available default values and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

## 4.4.1 $CH_4$ and $N_2O$ From Solid Manure Storage (Stockpiles)

**Method for Estimating Emissions From Manure Storage and Treatment— Solid Manure Storage (Stockpiles)**

**Methane**

- Use the IPCC Tier 2 approach with IPCC and U.S. EPA Inventory emission factors and VS of animal manure.
- Solid-liquid separation is addressed in section 4.4.4 but should be considered here too if separated solids are stored as stockpiles.

**Nitrous Oxide**

- Use the IPCC Tier 2 approach with U.S.-based emission factors and total nitrogen.
- The $NH_3$-N lost from stockpiled manure is used to calculate the indirect $N_2O$ emissions.

### 4.4.1.1 Description of Method

#### *Methane*

Use the IPCC Tier 2 approach to estimate $CH_4$ emissions and is described in equation 4-15 (IPCC, 2019). The data for maximum $CH_4$ production capacity ($B_0$) and MCF are listed in table 4-25, table 4-26, and table 4-27. VS are calculated using equation 4-16 (IPCC, 2019), where parameters are based on individual animal categories and productivity systems. Typical VS excretion in different animal manures is presented in table 4-26. Review box 4-1 for considerations for total animal production emissions.

#### *Nitrous Oxide*

The only quantitative method for estimating $N_2O$ emissions from solid manure is the IPCC Tier 2 approach, which is also used for the U.S. Inventory. This approach uses emission factors from IPCC (2019) guidelines, and total nitrogen values are estimated according to equation 4-19. Equation

[3] No method is provided for solid-liquid separation as GHG emissions are negligible. While no method is provided, solids separation impacts the potential emissions from other systems (e.g., anaerobic lagoons) as its use would remove total solids (and therefore VS or total nitrogen) from those systems.

4-31 and equation 4-18 present the equations to estimate the direct and indirect $N_2O$ emissions for solid manure, respectively. $N_2O$ emission factors for solid manure storage are listed in table 4-28.

**Equation 4-31: IPCC Tier 2 Approach for Estimating Direct $N_2O$ Emissions**

$$E_{N2O} = EF_{N2O} \times TN_{storage} \times \frac{44}{28}$$

Where:

| | | |
|---|---|---|
| $E_{N2O}$ | = | nitrous oxide emissions (g $N_2O$/day) |
| $EF_{N2O}$ | = | direct nitrous oxide emission factor (kg $N_2O$-N/kg N) |
| $TN_{storage}$ | = | total nitrogen entering manure storage at a given day (kg/day), use equation 4-19 |
| $\frac{44}{28}$ | = | conversion of $N_2O$-N emissions to $N_2O$ emissions |

### 4.4.1.2 Activity Data

**Table 4-25. Maximum $CH_4$ Producing Capacities ($B_0$) From Different Animal Manures**

| Animal | Maximum $CH_4$ Producing Capacity ($B_0$) ($m^3$/kg VS)[a] | Animal | Maximum $CH_4$ Producing Capacity ($B_0$) ($m^3$/kg VS)[a] |
|---|---|---|---|
| Beef replacement heifers | 0.17[b] | Layer (dry) | 0.39 |
| Dairy replacement heifers | 0.17[b] | Layer (wet) | 0.39 |
| Mature beef cows | 0.17[b] | Broiler | 0.36 |
| Steers (> 500 lbs) | 0.17[b] | Turkey | 0.36 |
| Stockers (all) | 0.17[b] | Duck | 0.36 |
| Cattle on feed | 0.33[b] | Sheep | 0.19[b] |
| Dairy cow | 0.24[b] | Feedlot sheep | 0.36[b] |
| American bison | 0.1[c] | Goat | 0.18[b] |
| Market swine | 0.48 | Horse | 0.3 |
| Breeding swine | 0.48 | Mule/ass | 0.33 |
| Rabbits | 0.32 | Fur-bearing animals | 0.25 |

[a] Source: IPCC, 2019, unless otherwise noted.

[b] Source: U.S. EPA, 2020.

[c] There are no data for North America; the data from western Europe are used to calculate the estimate. Data for buffalo used as a surrogate for American bison.

**Table 4-26. Typical VS Excretion in Different Animal Manures**

| Animal | VS Rate (kg/1,000 kg Animal Mass/Day) | Animal | VS Rate (kg/1,000 kg Animal Mass/Day) |
|---|---|---|---|
| Beef replacement heifers | 7.6 | Layer (dry) | 14.5 |
| Dairy replacement heifers | 9.3 | Layer (wet) | 14.5 |
| Mature beef cows | 7.6 | Broiler | 16.8 |

| Animal | VS Rate (kg/1,000 kg Animal Mass/Day) |
|---|---|
| Steers (> 500 lbs) | 7.6 |
| Stockers (all) | 7.6 |
| Cattle on feed | 7.6 |
| Dairy cow | 9.3 |
| American bison[a] | 7.7[a] |
| Market swine | 3.9 |
| Breeding swine | 1.8 |
| Rabbits | 0.10[b] |

| Animal | VS Rate (kg/1,000 kg Animal Mass/Day) |
|---|---|
| Turkey | 10.3 |
| Duck | 7.4 |
| Sheep | 8.2 |
| Feedlot sheep | 8.2 |
| Goat | 9 |
| Horse | 5.65 |
| Mule/ass | 7.2 |
| Fur-bearing animals | 0.14[b] |

Source: IPCC, 2019.

[a] There are no data for North America; the data from western Europe are used to calculate the estimate.

[b] Units are kg VS/day.

### Table 4-27. MCFs for Storage of Solid Manure From Different Animals and Practices

| Animal | MCF (%) | | |
|---|---|---|---|
| | 10 14°C | 15 25°C | 26 28°C |
| Dairy cattle | 2 | 4 | 5 |
| Beef cattle | 2 | 4 | 5 |
| American bison[a] | 2 | 4 | 5 |
| Market swine | 2 | 4 | 5 |
| Breeding swine | 2 | 4 | 5 |
| Layer (dry) | 1.5 | 1.5 | 1.5 |
| Broiler | 1.5 | 1.5 | 1.5 |
| Turkey | 1.5 | 1.5 | 1.5 |
| Duck | 1 | 1.5 | 2 |
| Sheep | 1 | 1.5 | 2 |
| Goat | 1 | 1.5 | 2 |
| Horse | 1 | 1.5 | 2 |
| Mule/ass | 1 | 1.5 | 2 |
| Covered/compacted | 2 | 4 | 5 |
| Bulking agent addition | 0.5 | 1.0 | 1.5 |
| Additives | 1 | 2 | 2.5 |

Source: IPCC, 2019.

[a] There are no data for North America; the data from western Europe are used to calculate the estimate.

**Table 4-28. Direct $N_2O$ Emission Factors for Solid Manure Storage**

| Type of Storage | Direct $N_2O$ Emission Factor (kg $N_2O$ N/kg $N_{ex}$) |
|---|---|
| Storage of solid manure | 0.01 |
| Solid storage covered/compacted | 0.01 |
| Solid storage bulking agent addition | 0.005 |
| Solid storage additives | 0.005 |

Sources: IPCC, 2019; U.S. EPA, 2020.

**Table 4-29. Nitrogen Loss Fractions for Volatilization and Leaching for Solid Manure Storage**

| | Swine | | Dairy Cow | | Poultry | | Other Cattle | | Other Animals | |
|---|---|---|---|---|---|---|---|---|---|---|
| | %$NH_3$ N | %$N_{leach}$ | %$NH_3$ N | %$N_{leach}$ | %$NH_3$ N | %$N_{leach}$ | %$NH_3$ N | %$N_{leach}$ | %$NH_3$ N | %$N_{leach}$ |
| Storage of solid manure | 45 | 2 | 30 | 2 | 40 | 2 | 45 | 2 | 12 | 2 |
| Solid storage covered/ compacted | 22 | 0 | 14 | 0 | 20 | 0 | 22 | 0 | 5 | 0 |
| Solid storage bulking agent addition | 58 | 2 | 38 | 2 | 54 | 2 | 58 | 2 | 15 | 2 |
| Solid storage additives | 17 | 2 | 11 | 2 | 16 | 2 | 17 | 2 | 4 | 2 |

Source: IPCC, 2019.

#### 4.4.1.3 Ancillary Data

To estimate the daily emissions from solid manure storage, the following information is needed:

- Animal type
- Animal population
- Temperatures (local ambient temperature and manure temperature)
- Total nitrogen content of the manure

Although daily estimates for the activity data are optimal, tracking this level of detail would be burdensome. Annual estimates do not allow for seasonal variation in diets and climate. Consequently, disaggregation of the data by season or by periods of major shifts in animal population is suggested.

#### 4.4.1.4 Limitations and Uncertainty

See appendix 4-B.8.2 for current available default values and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

## 4.4.2 $CH_4$ and $N_2O$ From Composting

**Method for Estimating Emissions From Manure Storage and Treatment—Composting**

**Methane**

- Use the IPCC Tier 2 approach with data on VS of animal manure.
- Solid-liquid separation is addressed in section 4.4.4 but should be considered here too if separated solids are composted.

**Nitrous Oxide**

- Use the IPCC Tier 2 approach with data on a $N_2O$ emission factor.
- The method depends on whether the system is in a vessel, a static pile, an intensive windrow, or a passive windrow.
- The $NH_3$-N lost from composting manure is used to calculate the indirect $N_2O$ emissions.

### 4.4.2.1 Description of Method

The IPCC Tier 2 methodology is provided for estimating $CH_4$ and $N_2O$ emissions from composting (IPCC, 2019). This methodology uses country-specific emission factors from the U.S. National GHG Inventory (U.S. EPA, 2020). The amount of manure, VS content, and temperature are entity-specific. Review considerations for total animal production emissions in box 4-1.

#### *Methane*

Use the IPCC Tier 2 approach to estimate $CH_4$ emissions, as described in equation 4-15 (IPCC, 2019). The data for $B_0$ and MCF are listed in table 4-11 and table 4-30. Calculate VS using equation 4-16 (IPCC, 2019), with parameters based on individual animal categories and productivity systems. Table 4-26 lists typical VS excretion in different animal manures.

#### *Nitrous Oxide*

Use the IPCC Tier 2 method to estimate direct and indirect $N_2O$ emissions from composting, as shown in equation 4-31 and equation 4-18 above. $N_2O$ emission factors for composting are listed in table 4-31.

### 4.4.2.2 Activity Data

**Table 4-30. MCFs for Composting Solid Manure**

| Composting Method | MCF (%) | | |
|---|---|---|---|
| | Cool Climate | Temperate Climate | Warm Climate |
| Manure composting—in-vessel | 0.5 | 0.5 | 0.5 |
| Manure composting—static pile | 1 | 2 | 2.5 |
| Manure composting—intensive windrow | 0.5 | 1 | 1.5 |
| Manure composting—passive windrow | 1 | 2 | 2.5 |

Source: IPCC, 2019.

**Table 4-31. Direct $N_2O$ Emission Factors for Composting Solid Manure**

| Composting Method | Direct $N_2O$ Emission Factor (kg $N_2O$ N/kg $N_{ex}$) |
|---|---|
| Composting—in-vessel | 0.006 |
| Composting—static pile (forced aeration) | 0.010 |
| Composting—intensive windrow | 0.005 |
| Composting—passive windrow | 0.005 |

Source: IPCC, 2019.

**Table 4-32. Nitrogen Loss Fractions for Volatilization and Leaching for Composting Solid Manure**

| Type of Storage | Swine | | Dairy Cow | | Poultry | | Other Cattle | | Other Animals | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\%NH_3$ N | $\%N_{leach}$ | $\%NH_3$ N | $\%N_{leach}$ | $\%NH_3$ N | $\%N_{leach}$ | $\%NH_3$ N | $\%N_{leach}$ | $\%NH_3$ N | $\%N_{leach}$ |
| Composting—in-vessel | 60 | 0 | 45 | 0 | 60 | 0 | 60 | 0 | 18 | 0 |
| Composting—static pile (forced aeration) | 65 | 6 | 50 | 6 | 65 | 6 | 65 | 6 | 20 | 6 |
| Composting—intensive windrow | 65 | 6 | 50 | 6 | 65 | 6 | 65 | 6 | 20 | 6 |
| Composting—passive windrow | 60 | 4 | 45 | 4 | 60 | 4 | 60 | 4 | 18 | 4 |

Source: IPCC, 2019.

#### 4.4.2.3 Ancillary Data

To estimate the daily $CH_4$ emissions from composting, the following information is needed:

- Animal type
- Animal population
- Temperatures (local ambient temperature and manure temperature)
- Total nitrogen in manure

#### 4.4.2.4 Limitations and Uncertainty

A limitation of the GHG estimation method for manure composting is that it does not consider other organic carbon sources that might be added into manure composting. See appendix 4-B.8.2 for current available default values and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

## 4.4.3 $CH_4$ and $N_2O$ From Aerobic Lagoons

**Method for Estimating Emissions From Manure Storage and Treatment—Aerobic Lagoons**

**Methane**

- The MCF for aerobic treatment is negligible and is designated as zero percent in accordance with the IPCC guidance.

**Nitrous Oxide**

- The IPCC Tier 2 method is used with IPCC emission factors.
- The method considers the volume of the lagoon and the total nitrogen content of the manure.
- The $NH_3$-N lost from aerobic lagoons is used to calculate the indirect $N_2O$ emissions.

### 4.4.3.1 Description of Method

The IPCC Tier 2 methodology is provided for estimating $CH_4$ and $N_2O$ emissions from aerobic lagoons. This methodology uses a combination of IPCC and country-specific emission factors from the U.S. EPA GHG Inventory. Aerobic conditions result in the oxidation of carbon to $CO_2$, not the reduction of carbon to $CH_4$, so $CH_4$ emissions from aerobic lagoons are considered negligible. The method for calculating $N_2O$ emissions accounts for the volume of the lagoon as well as the total nitrogen content of the manure. Review considerations for total animal production emissions in box 4-1.

#### *Methane*

The MCF for aerobic treatment is negligible and was designated as zero percent in accordance with the IPCC (2019).

#### *Nitrous Oxide*

The IPCC Tier 2 approach is adapted to estimate $N_2O$ emissions from aerobic lagoons (equation 4-31). The $N_2O$ conversion factors for different aeration systems are listed in table 4-33. Use equation 4-18 to calculate indirect $N_2O$ emissions.

**Table 4-33. Direct $N_2O$ Emission Factors ($EF_{N2O}$) for Aerobic Lagoons**

| Aeration Type | Direct $N_2O$ Emission Factor (kg $N_2O$-N/kg $N_{ex}$) |
|---|---|
| Natural aeration | 0.01 |
| Forced aeration | 0.005 |

Source: IPCC, 2019.

**Table 4-34. Nitrogen Loss Fractions for Volatilization and Leaching for Aerobic Lagoons**

| Type of storage | Swine | | Dairy Cow | | Poultry | | Other Cattle | | Other Animals | |
|---|---|---|---|---|---|---|---|---|---|---|
| | %$NH_3$-N | %$N_{leach}$ | %$NH_3$-N | %$N_{leach}$ | %$NH_3$-N | %$N_{leach}$ | %$NH_3$-N | %$N_{leach}$ | %$NH_3$-N | %$N_{leach}$ |
| Natural aeration | — | — | — | — | — | — | — | — | — | — |
| Forced aeration | 85 | 0 | 85 | 0 | — | 0 | 85 | 0 | 27 | 0 |

Source: IPCC, 2019. There are no data available for natural aeration or forced aeration for poultry.

#### 4.4.3.2 Activity Data

No activity data are needed for the estimation of $CH_4$ emissions from aerobic lagoons (MCF = 0). To estimate daily $N_2O$ emissions, the following information is needed:

- Total nitrogen content of the manure (TNstorage)

#### 4.4.3.3 Limitations and Uncertainty

See appendix 4-B.8.2 for current available default values and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

### 4.4.4 $CH_4$ and $N_2O$ From Anaerobic Lagoons, Runoff Holding Ponds, and Storage Tanks

**Method for Estimating Emissions From Manure Storage and Treatment—Anaerobic Lagoons, Runoff Holding Ponds, Storage Tanks**

**Methane**

- The IPCC Tier 2 method is used to estimate $CH_4$ emissions.

Solid-liquid separation impacts the potential emissions from other systems (e.g., anaerobic lagoons) as its use would remove total solids (and therefore VS) from those systems. Use a modified IPCC Tier 2 approach if solid-liquid separation units are used and ensure emissions are captured from solid systems, as described in section 4.4.1 or 4.4.2. See appendix 4-C.3 for gaps concerning nitrogen removal due to solid-liquid separation.

**Nitrous Oxide**

- Emissions are a function of the exposed surface area and U.S.-based emission factors.
- The $NH_3$-N lost from anaerobic lagoons, runoff holding ponds, and storage tanks is used to calculate the indirect $N_2O$ emissions.

#### 4.4.4.1 Description of Method

***Methane***

The IPCC Tier 2 approach is recommended to estimate $CH_4$ emissions and is described in equation 4-15 (IPCC, 2019). The data for maximum $CH_4$ producing capacity ($B_0$) and MCF are listed in table 4-11 and table 4-35. Alternatively, MCFs can be calculated using the “MCF Calculations Example Spreadsheet” from IPCC (2019). Calculate VS using equation 4-16 (IPCC, 2019), where parameters are based on individual animal categories and productivity systems. Typical VS excretion in different animal manures is presented in table 4-26. Review considerations for total animal production emissions in box 4-1.

If there is a manure solid-liquid separation system in place prior to final manure storage, estimate the amount of solids (VS) removed from the manure stream and use equation 4-32 to estimate $CH_4$ emissions. Table 4-36 presents average values (or ranges) for different animal classes and separation technology. However, separation efficiency is highly dependent on the characteristics of the manure, screen size, total solid concentrations of the manure stream and the loading rate. If on-farm separation efficiencies are known, those values should be used. Alternatively, more detailed information can be found in the USDA National Resources Conservation Service (NRCS) Part 637 *Environmental Engineering National Engineering Handbook*. Nitrogen removal via solid-liquid separation is currently not addressed in these methods; see appendix 4-C.3 for gaps concerning nitrogen removal.

**Equation 4-32: Modified IPCC Tier 2 Approach for Estimating $CH_4$ Emissions From Manure in Anaerobic Lagoon, Runoff Holding Ponds, and Storage Tanks With Solid-Liquid Separation**

$$CH_4 = VS \times \left(\frac{100\% - \%VS}{100}\right) \times B_0 \times 0.67 \times \frac{MCF}{100}$$

Where:

| | | |
|---|---|---|
| $CH_4$ | = | daily $CH_4$ emissions (kg $CH_4$/day) |
| $VS$ | = | volatile solids (kg/day), use equation 4-16 |
| $\%VS$ | = | percent of VS removed via solid-liquid separation. Use table 4-36, or if not used, assume 0%. |
| $B_0$ | = | maximum $CH_4$ producing capacity for manure ($m^3$ $CH_4$/kg VS) |
| $MCF$ | = | methane conversion factor for the manure management system (%) |
| 0.67 | = | conversion factor of $m^3$ $CH_4$ to kg $CH_4$ |

### *Nitrous Oxide*

$N_2O$ emissions from liquid manure storage typically represent a relatively small portion of the $N_2O$ emissions from farms. Most studies indicate the criticality of the crust for the formation and emission of $N_2O$ (Petersen and Sommer, 2011). The crust allows air to be retained on the surface which, as ammonia diffuses through the crust, increases the potential for nitrification and denitrification due to microbial activity (Hansen et al., 2009; Nielsen et al., 2010). When a crust does not form, oxygen is not retained on the liquid surface with nitrogenous compounds, and therefore no $N_2O$ is formed and emitted. Therefore, $N_2O$ emissions from liquid manure storage are estimated as a function of the exposed surface area of the manure storage and the presence of a crust on the surface (equation 4-33), and the emission factor for $N_2O$ depends on crust formation on the liquid storage. Use equation 4-18 for indirect $N_2O$ emissions. The emission factors of $N_2O$ for different liquid storage methods are listed in table 4-37. Review considerations for total animal production emissions in box 4-1.

**Equation 4-33: IPCC Tier 2 Approach for Estimating $N_2O$ Emissions From Anaerobic Lagoon, Runoff Holding Ponds, and Storage Tanks**

$$E_{N2O} = EF_{N2O} \times \frac{A_{surface}}{1{,}000}$$

Where:

| | | |
|---|---|---|
| $E_{N2O}$ | = | daily nitrous oxide emissions (kg $N_2O$/day) |
| $EF_{N2O}$ | = | $N_2O$ emission factor (g $N_2O$-N/$m^2$/day) |
| $A_{surface}$ | = | exposed surface area of the lagoon/pond/tank ($m^2$) |
| 1,000 | = | conversion factor for grams to kilograms (1 kg/1,000 g) |

### 4.4.4.2 Activity Data

**Table 4-35. MCFs for Liquid Storage**

| Housing Type | Storage Time | MCFs (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Cool Temperate Moist (4.6°C)[a] | Cool Temperate Dry (5.8°C)[a] | Warm Temperate Moist (13.9°C)[a] | Warm Temperate Dry (14.0°C)[a] | Tropical Montane (21.5°C)[a] | Tropical Wet (25.9°C)[a] | Tropical Moist (25.2°C)[a] | Tropical Dry (25.5°C)[a] |
| Holding pond/storage tank | 1 month | 6 | 8 | 13 | 15 | 25 | 38 | 36 | 42 |
| | 3 months | 12 | 16 | 24 | 28 | 43 | 61 | 57 | 62 |
| | 4 months | 15 | 19 | 29 | 32 | 50 | 67 | 64 | 68 |
| | 6 months | 21 | 26 | 37 | 41 | 59 | 76 | 73 | 74 |
| | 12 months | 31 | 55 | 64 | 41 | 73 | 80 | 80 | 80 |
| Uncovered anaerobic lagoon | N/A | 60 | 67 | 73 | 76 | 76 | 80 | 80 | 80 |
| Anaerobic digester, low leakage,[b] high quality gastight storage, best complete industrial technology | N/A | 1 | | | | | | | |
| Anaerobic digester, low leakage, high quality industrial technology, low quality gastight storage technology | N/A | 1.41 | | | | | | | |
| Anaerobic digester, low leakage, high quality industrial technology, open storage | N/A | 3.55 | | 4.38 | | 4.59 | | | |
| Anaerobic digester, high leakage, low quality technology, high quality gastight storage technology | N/A | 9.59 | | | | | | | |
| Anaerobic digester, high leakage, low quality technology, low quality gastight storage technology | N/A | 10.00 | | | | | | | |
| Anaerobic digester, high leakage, low quality technology, open storage | N/A | 12.14 | | 12.97 | | | 13.17 | | |

[a] Values represent average annual temperature.

[b] Leakage rate of the gastight storage (with $0 \leq L_{sto,gt} \leq 1$ $m^3$ $m^{-3}$). For high quality gastight storage of the digestate $L_{sto,gt}$ is assumed to be 0.01 $m^3$ $m^{-3}$. For low quality gastight storage of the digestate, $L_{sto,gt}$ is assumed to be 0.1 $m^3$ $m^{-3}$. For open storage of the digestate, $L_{sto,gt}$ is assumed to be 1.0 $m^3$ $m^{-3}$.

Source: IPCC, 2019.

### Table 4-36. Total Solids Removal Efficiency of Select Manure Separation Systems

| | Separation Efficiency (%VS) by Livestock Class (%) | | | |
|---|---|---|---|---|
| | **Dairy** | **Beef** | **Swine** | **Poultry** |
| Sloped screen, static | 30–60 | 30–50 | 10–60 | 24–60 |
| Slope screen, vibrating | 50–70 | — | 30–60 | — |
| Rotary drum | 25 | — | — | — |
| Screw press | 25–50 | | 16 | — |
| Belt press | 50 | 16 | 20–60 | — |
| Roller press | 24 | — | — | — |
| Centrifuge | 50 | 50 | 30–60 | — |

Sources: Williams et al., 2020; USDA NRCS, 2019.

### Table 4-37. Direct $N_2O$ Emission Factors for Liquid Storage With Different Crust Formation

| Type of Liquid Storage | Units | $EF_{N2O}$ | Associated Equation |
|---|---|---|---|
| Uncovered liquid manure without crust | g $N_2O/m^2/day$ | 0 | Equation 4-33 and equation 4-18 |
| Uncovered liquid manure with crust | g $N_2O/m^2/day$ | 0.8 | Equation 4-33 and equation 4-18 |
| Covered liquid manure | g $N_2O/m^2/day$ | 0 | Equation 4-33 and equation 4-18 |
| Anaerobic digester | kg $N_2O$/kg $N_{ex}$ | 0.0006 | Equation 4-17 and equation 4-18 |

Source: Rotz et al., 2011; Olesen et al., 2006; Külling et al., 2003; Sneath et al., 2006; IPCC, 2019.

### Table 4-38. Nitrogen Loss Fractions for Volatilization and Leaching for Liquid Storage

| Type of Storage | | Swine | | Dairy Cow | | Poultry | | Other Cattle | | Other Animals | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\%NH_3$ N | $\%N_{leach}$ | $\%NH_3$ N | $\%N_{leach}$ | $\%NH_3$ N | $\%N_{leach}$ | $\%NH_3$ N | $\%N_{leach}$ | $\%NH_3$ N | $\%N_{leach}$ |
| Uncovered Anaerobic lagoon | | 40 | 0 | 35 | 0 | 40 | 0 | 35 | 0 | 35 | 0 |
| Anaerobic digester[a] | | 5–50 | 0 | 5–50 | 0 | 5–50 | 0 | 5–50 | 0 | 5–50 | 0 |
| Liquid/slurry | Uncovered liquid manure without crust | 48 | 0 | 48 | 0 | 40 | 0 | 48 | 0 | 15 | 0 |
| | Uncovered liquid manure with crust | 30 | 0 | 30 | 0 | - | 0 | 30 | 0 | 9 | 0 |
| | Covered liquid manure | 10 | 0 | 10 | 0 | 8 | 0 | 10 | 0 | 3 | 0 |

Source: IPCC, 2019.

[a] IPCC (2019) notes "Nitrogen losses from digestate storage strongly depend on the digestate composition and on the storage cover. Digestate with a low dry matter content and no cover can [lose] up to [50%] of nitrogen. The lower range of [5%] losses is valid for digestate with a high dry matter content and a cover. The ranges indicated also apply to co-digestates. It is advised to use, the liquid slurry without cover for uncovered digestate."

#### 4.4.4.3 Ancillary Data

To estimate daily $CH_4$ and $N_2O$ emissions from liquid manure storage, the following information is needed:

- Animal type
- Animal population
- Temperatures (local ambient temperature or manure temperature)
- The exposed surface area of the manure storage

#### 4.4.4.4 Limitations and Uncertainty

See appendix 4-B.8.2 for current available default uncertainty bounds and appendix 4-C.4 for a brief discussion of uncertainty data gaps/limitations.

### 4.4.5 $CH_4$ From Anaerobic Digesters With Biogas Utilization

**Method for Estimating Emissions From Manure Storage and Treatment—Anaerobic Digesters With Biogas Utilization**

**Methane**

- Use the IPCC Tier 2 method, with Clean Development Mechanism emission factors for digester types, to estimate $CH_4$ leakage from digesters.
- Anaerobic digester systems convert organic matter in manure into $CH_4$ and subsequently combust $CH_4$ into $CO_2$.
- Gas leakage from digesters is the main source of GHG emissions.
- Leakage of $CH_4$ from the anaerobic digester system is estimated.

**Nitrous Oxide**

- $N_2O$ leakage from digesters is negligible.

#### 4.4.5.1 Description of Method

Since an anaerobic digestion system converts organic carbon in manure into $CH_4$ and subsequently combusts $CH_4$ into $CO_2$, the GHG emissions from manure anaerobic digestion operation are mainly from the leakage of digesters. The leakage of $CH_4$ can be estimated based on the IPCC Tier 2 approach in combination with technology-specific emission factors. Review considerations for total animal production emissions in box 4-1.

***Methane***

Equation 4-34 describes the IPCC Tier 2 approach for estimating $CH_4$ emissions for anaerobic digesters. The $CH_4$ generated from digesters is assumed to be flared or used as the biogas for electricity generation; the only emissions from digesters are from system leakage. The $B_0$ values are obtained from IPCC (2019) and are listed in table 4-25. The emission factors for the fraction of $CH_4$ leaked from the digestion are listed in table 4-39. Estimate the VS data using equation 4-16.

**Equation 4-34: IPCC Tier 2 Approach for Estimating $CH_4$ Emissions From Anaerobic Digesters**

$$E_{CH4} = VS \times B_0 \times 0.67 \times \frac{EF_{CH4\ leakage}}{100}$$

Where:

| | | |
|---|---|---|
| $E_{CH4}$ | = | daily $CH_4$ emissions (kg $CH_4$/day) |
| $VS$ | = | volatile solids (kg VS/day) |
| $B_0$ | = | maximum $CH_4$ producing capacity for manure ($m^3$ $CH_4$/kg VS) |
| $EF_{CH4\ leakage}$ | = | emission factor for the fraction of $CH_4$ leaked from the digestion (%) |
| 0.67 | = | conversion factor of $m^3$ $CH_4$ to kg $CH_4$ |

#### 4.4.5.2 Activity Data

**Table 4-39. Emission Factors for the Fraction of $CH_4$ Leaking From Digesters**

| Digester Configurations | $EF_{CH4\ leakage}$ (%) |
|---|---|
| Digesters with steel or lined concrete or fiberglass digesters with a gas holding system (egg-shaped digesters) and monolithic construction | 2.8 |
| UASB-type digesters with floating gas holders and no external water seal | 5 |
| Digesters with unlined concrete/ferrocement/brick masonry arched-type gas holding section; monolithic fixed-dome digesters | 10 |
| Other digester configurations | 10 |

Source: CDM, 2012.

#### 4.4.5.3 Ancillary Data

To estimate daily $CH_4$ leakage from anaerobic digestion, the following information is needed:

- Animal type
- Animal population
- Digester configurations

#### 4.4.5.4 Limitations and Uncertainty

See appendix 4-B.8.2 for current available default values and appendix 4-C.4 for a brief discussion of uncertainty data gaps.

## 4.5 Available Nitrogen for Land Application

In the case where manure is land applied, whether directly on pasture or removed from housing or manure storage and treatment and subsequently applied, use the following equations to determine the nitrogen available for land application and then consult chapter 3 to determine subsequent emissions. The calculation is based on IPCC (2019), and considers nitrogen lost to emissions, nitrogen added (from organic forms of bedding such as straw, sawdust, wood chippings) and nitrogen removed (e.g., to be used for feed, fuel, or construction). The nitrogen removed should be estimated by the entity based on other uses of manure or litter.

**Equation 4-35: Available N for Land Application**

$$N_{available} = [(N_{ex} \times 365) \times (1 - N_{lost})] + BeddingN - ([N_{ex} \times 365 + (BeddingN)] \times N_{removed})$$

Where:

| | | |
|---|---|---|
| $N_{available}$ | = | managed manure N available for land application, by system (kg N/year) |
| $N_{ex}$ | = | total nitrogen excretion (kg N/head/day) |
| 365 | = | days in year (days/year) |
| $N_{lost}$ | = | N lost via direct emissions, $NH_3$ volatilization, and leaching, see equation below (fraction) |
| *BeddingN* | = | additional nitrogen from bedding material for all animals managed on the system (kg N/year) |
| $N_{removed}$ | = | N removed from the system prior to land application (fraction) |

$$N_{lost} = EF_{N2O} + (EF_{N2O} \times R_{N2(\mathrm{N2O})}) + \frac{\%NH_3}{100} + \frac{\%Nleach}{100}$$

Where:

| | | |
|---|---|---|
| $N_{lost}$ | = | N lost via direct emissions, $NH_3$ volatilization, and leaching (fraction) |
| $EF_{N2O}$ | = | direct $N_2O$ emission factor (kg $N_2O$-N/kg N) |
| $R_{N2(N2O)}$ | = | Ratio of $N_2$:$N_2O$ emissions, the default value is 3 (kg $N_2$-N/kg $N_2O$-N) |
| $\%NH_3$ | = | percentage of $N_{ex}$ lost as $NH_3$-N in animal housing |
| *%Nleach* | = | percentage of $N_{ex}$ lost as N leaching in animal housing. If no data are available, assume 0. |

$$BeddingN = Bedding\ Factor \times Pop$$

Where:

| | | |
|---|---|---|
| *BeddingN* | = | additional nitrogen from bedding material for all animals managed on the system (kg N/year) |
| *Bedding Factor* | = | additional nitrogen from organic forms of bedding material, (kg N/head/year), see table 4-40. |
| *Pop* | = | number of animals (head) |

**Table 4-40. Bedding and Feed Loss Factors**

| Animal Type | Housing or Manure Storage and Treatment | Bedding (kg N/Head/Year) |
|---|---|---|
| All | Pasture | 0 |
| Poultry | Anaerobic lagoon | 0 |
| Poultry | With and without litter, and solid storage | 0 |
| Market swine | Liquid systems, solid storage | 0.8 |
| Breeding swine | Liquid systems, solid storage | 5.5 |
| Dairy cow | Liquid systems, solid storage, dry lot | 7 |
| Dairy heifer | Dry lot | 7 |
| Horses, mules & ass, goats, sheep, On feed cattle | Dry lot | 4 |

Source: IPCC, 2019.

## 4.6 Chapter 4 References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# Appendix 4-A: Animal Production Systems

This section discusses the production systems for beef and dairy cattle, sheep, swine, and poultry, and provides the background necessary for understanding sections 4-A.2 through 4-A.3, which cover GHG emissions from these systems.

## 4-A.1 Dairy Production Systems

### 4-A.1.1 Overview of Dairy Production Systems

The U.S. dairy production system features several key processes for dairy cattle, their manure, and their end products (meat, milk), as shown in figure 4A-1. This conceptual model provides an overview of the typical dairy system, following cattle from birth to slaughter and following manure from the animal through a management system. Manure is produced during each stage and is managed differently depending on location. Its management has implications for the quantity of GHG emissions and sinks. The estimation methods include emissions estimates from enteric fermentation, housing, and manure management; however, they do not constitute a full LCA.

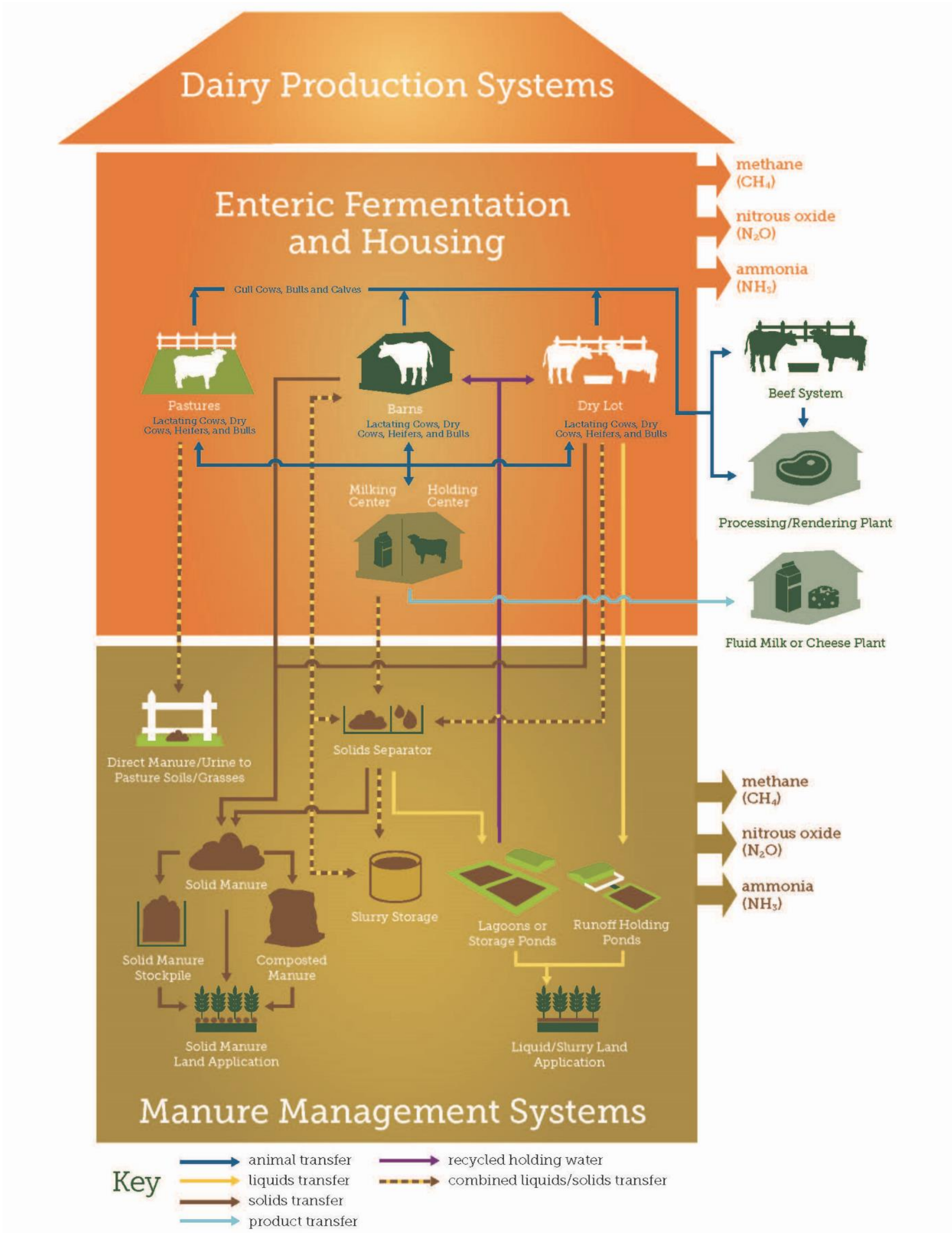


**Figure 4A-1. Conceptual Model of Dairy Systems in the United States**

### 4-A.1.2 Dairy Diets, Housing, and Manure Handling

Two general dairy farm types can be distinguished in the United States: confinement feeding systems (including barns and dry lots) and pasture-based systems (USDA, 2004). Typical housing systems for confinement feeding operations include tie stall barns, compost barns, freestall barns, freestall barns with dry lot access, and dry lots. Dry lot systems house animals in pens similar to beef cattle feedlots, but at a lower stocking density. In pasture-based systems, cattle graze pasture for periods of time based on feed availability and environmental conditions, but are housed in barns/dry lots and fed stored feed when pasture is not available. The dairy cattle life cycle production phase is generally divided into three segments: growing animals (calves and replacement heifers), lactating mature cows, and dry mature cows. Nutrient needs, and therefore diets, and intake are very different between the different life cycle phases. Housing and manure management systems vary considerably throughout the country and can differ within a region and by the size of the herd. In cases where housing and manure management varies by animal group (e.g., heifers, nonlactating cows, and lactating cows), estimates of GHG emissions from one group are not applicable to other groups. When housing and manure management are similar between groups (e.g., all cattle on dry lots), diet and intake adjustment factors can be used to compare GHG emissions for the different groups.

Manure and soiled bedding from barns can be handled in a number of ways. Manure can be removed from the barns mechanically and directly loaded into manure spreaders, although this is not common on medium and large farms. Manure and bedding may be managed as a compost within the barn via regular mechanical turning, while deep-bedded systems with no composting may be cleaned out and their manure stored as solid stacks or composted before land application. Manure with a lower solids content may be stored in a tank or pit as a slurry or transported to a solid–liquid separation system with the liquid fraction conveyed (pumped or by gravity) to a long-term wastewater storage pond, while the solids can be dewatered naturally and reused as bedding, composted, land-applied, and/or sold.

Liquid manure can also be processed in an anaerobic digester, where bacteria break it down to produce biogas that can be flared or captured for energy purposes before storage of digester effluent. In dry lot systems, the manure is typically stacked within or near the lots, then either land-applied or composted. Lot runoff and milking parlor wash water is typically pumped to a wastewater storage pond. Some dry lot dairies use flush systems to clean manure from alleyways behind the feed bunks; this washwater is eventually stored in a wastewater storage pond. Open freestall dairies have a combination of barns with exercise yards between the barns, so they handle manure similarly to traditional freestall barns and dry lot production systems. Wastewater from milking centers (manure, clean-in-place water, and floor washdown water) is typically combined with barn manure and stored in wastewater storage ponds or lagoons; in many cases this liquid goes through a solid–liquid separation process first. In pasture-based systems, manure is deposited directly onto the pasture and therefore not intensively managed, but may accumulate in areas where animals tend to congregate (e.g., watering areas, shade).

## 4-A.2 Beef Production Systems

### 4-A.2.1 Overview of Beef Production Systems

The U.S. beef production system has several key components for cattle, their waste, and their end products, as depicted in figure 4A-2. This conceptual model provides an overview of the typical beef processing systems, following the segments of the beef cattle industry (i.e., cow-calf, stocker, feeder/finisher, and packer) from birth to slaughter and following waste from the animal through a management system. Waste is produced during each stage of activity in the system and is managed differently depending on location.

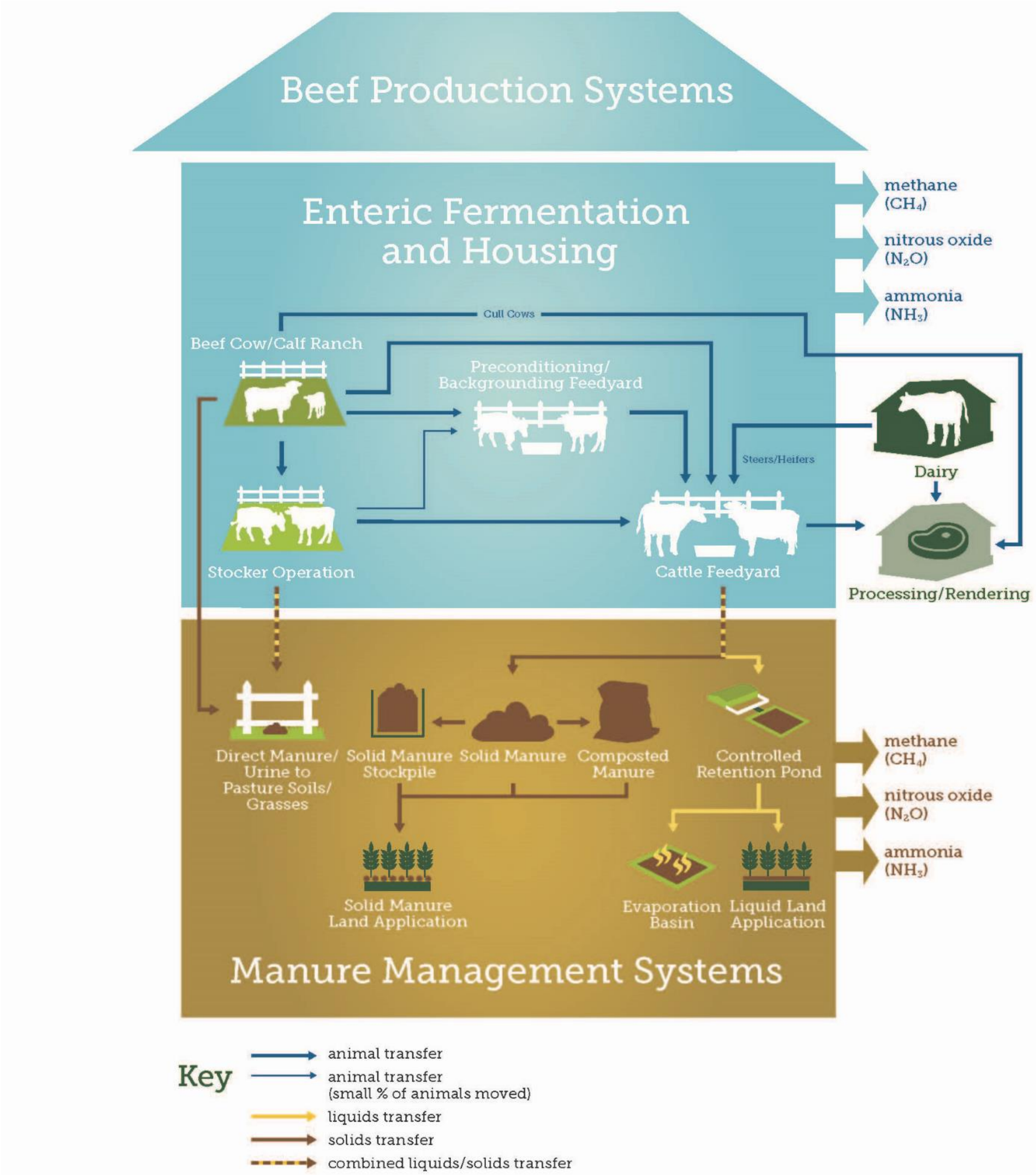


**Figure 4A-2. Conceptual Model of Beef Production Systems in the United States**

### 4-A.2.2 Beef Cattle Diets, Housing, and Manure Handling

#### *Cow-Calf Operations and Bulls*

Cow herds and replacement heifers are most often housed on pasture. They deposit feces and urine on pastures and rangeland, which may be concentrated in areas in which feeding or watering takes place. A methodology for estimating $CH_4$ emissions from pasture and rangeland is included in chapter 4, but the $N_2O$ emission methodology is included as part of the croplands system because of the manure's influence on carbon stock changes in a process-based model (see chapter 3). Under severe drought conditions, beef cows may be moved to confinement operations and fed diets based primarily on byproducts. However, only a small percentage of the U.S. beef cow herd undergoes this confined feeding.

#### *Stockers*

Stocker cattle are usually housed on pasture. A methodology for estimating $CH_4$ emissions from pasture and rangeland is included in chapter 4, but the $N_2O$ emission methodology is included as part of the croplands system because of the manure's influence on carbon stock changes in a process-based model (see chapter 3). Weaned calves from the cow-calf segment are used as stocker cattle and can be housed for short periods of time in dry lots before being moved to grazing pasture.

#### *Feedlot Cattle*

Housing and manure management at most beef cattle feeding operations differ greatly from those used in other animal species, with the vast majority being finished in dry lot pens with soil surfaces. Manure is normally deposited on the pen surface and scraped from the pens after each lot of cattle goes to market. Part of the manure may be stacked in the pen to provide mounds that improve pen drainage and ensure that cattle have a dry place to lie after rains. Manure removed from the pen may be immediately applied to fields near the feedlot, stockpiled for later use, or composted in windrows. Manure scraped from the pens normally has a moisture content of 30 to 50 percent and may contain some soil from the pen. Runoff from pens is normally collected in retention ponds. Settling basins may be used to limit the quantity of manure solids and soil particles that reach the retention pond.

In the northern United States, and in areas with high rainfall, cattle may be fed in naturally ventilated barns with slotted floors for collection of urine and feces or in deep-bedded barns with concrete floors in which the manure and bedding (normally straw or stalks) accumulates during the feeding period (Spiehs et al., 2011). Adding bedding will increase the quantity of carbon (and possibly nitrogen) available to be metabolized by microbes possibly enhancing emissions. These confined facilities are characterized by the absence of runoff control systems.

## 4-A.3 Sheep Production Systems

### 4-A.3.1 Overview of Sheep Production Systems

There are 102,000 sheep and lamb operations in the United States, with an inventory of 5.27 million sheep and lambs as of January 1, 2017 (USDA NASS, 2021). Most breeding flocks are small and consist of less than 100 head of ewes. The lamb feeding industry is also diverse in size, with small feedlots located throughout the farm flock areas and large feeding operations located in close proximity to local grain production capacity (Shiflett, 2011).

### 4-A.3.2 Sheep Diets, Housing, and Manure Handling

Lambing season may occur at various times of the year, depending on production objectives, feed resources, environmental conditions, and market targets. When lambing occurs, in January through March, ewes are generally housed in bedded barns. Bedding is removed and spread after animals are turned out on pasture. Ewes are generally bred on pasture in September through November and, depending on weather, will be moved into barns before lambing—or earlier as forage availability and weather dictate.

Pasture lambing is another farm flock production system that is used to maximize nutrients provided by grazed forages. In this case the ewe is bred in November or December to lamb on pasture in April or May. Lambs are weaned at about 120 days and 32 kilograms and may be sent to the feedlot or finished on grass. Ewes are not fed grain, and harvested forage is provided only when growing seasons and weather dictate. These flocks will be housed in bedded barns only when they need protection from winter weather.

Sheep feedlots are primarily dry lots, and manure is scraped from the pens as in beef cattle feedlots.

## 4-A.4 Swine Production Systems

### 4-A.4.1 Overview of Swine Production Systems

The conceptual model of the U.S. swine production system (figure 4A-3) provides an overview of typical production systems, following animals from birth to harvest and following manure from the animal through a management system. Manure is produced during each stage of production in the system and is managed differently depending on location, which has implications for the quantity of GHG emissions.

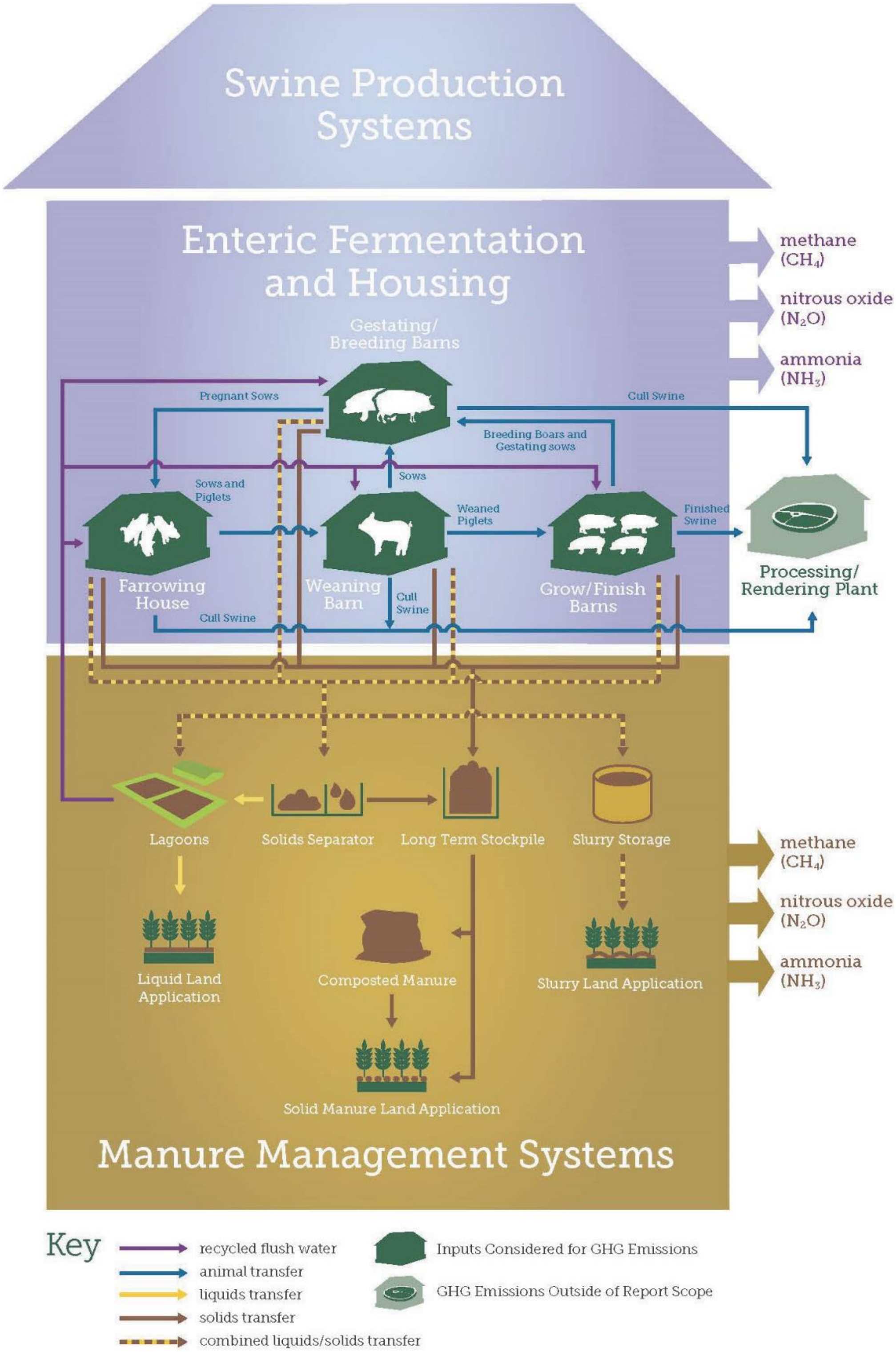


**Figure 4A-3. Conceptual Model of Swine Production Systems in the United States**

### 4-A.4.2 Swine Housing and Manure Handling

The manure management systems associated with production operations all have the basic elements of collection, storage, treatment, transport, and utilization. Most swine facilities handle manure as a slurry either within the building (deep pit finishing barns or shallow pit nurseries, gestation or finishing barns) or in outside storage (pull-plug systems for nurseries, sows, or finishing pigs). The manure is generally stored under the facility, discharged to a separate storage tank, or flushed to an anaerobic lagoon. In the case of in-house manure storage, little water is added to the storage structure, and anaerobic conditions prevail with little biological processing of manure taking place. Outside storage structures that contain slurry with little dilution water offer minimal biological treatment as well. However, lagoon systems where manure is flushed from housing and additional dilution water is added offer more treatment. Dry systems or deep-bedded systems are much less common. They are mainly used for sow or finishing production, in which case bedding material, often straw, is provided and manure plus bedding is handled as solid material, sometimes composted.

## 4-A.5 Poultry Production Systems

### 4-A.5.1 Overview of Poultry Production Systems

The U.S. poultry production system features several key processes for poultry, their manure/litter, and their end products (meat, eggs), as shown in figure 4A-4. The figure provides an overview of the typical production systems, following both the layer and broiler phases. It follows birds from birth to slaughter and follows manure from the animal through a management system. Manure is produced during each stage of activities in the system and is managed differently depending on location.

The U.S. poultry industry is the world's largest producer and second largest exporter of poultry meat. The United States is also a major egg producer. The poultry and egg industry are a major feed grain user, accounting for about 45.4 billion kilograms (100 billion pounds) of feed yearly.

The egg incubation period for a chicken is 21 days. Following hatch, broiler chickens are reared for 42 to 49 days (six to seven flocks per year), depending upon the market intent (e.g., roasters). U.S. egg operations produce more than 90 billion eggs annually. More than 75 percent of egg production is for human consumption (the table-egg market). The remainder of production is for the hatching market. These eggs are hatched to provide replacement birds for the egg-laying flocks and to produce broiler chicks for grow-out operations. Following a 16- to 22-week growth period, hens start laying eggs.

The U.S. turkey industry produces more than one-quarter of a billion birds annually, with the live weight of each bird averaging more than 25 pounds. The egg incubation period for a turkey is 28 days. Following hatch, turkey poults are reared for 15 to 22 weeks (one to three flocks per year) depending on the market intent (e.g., roasters).

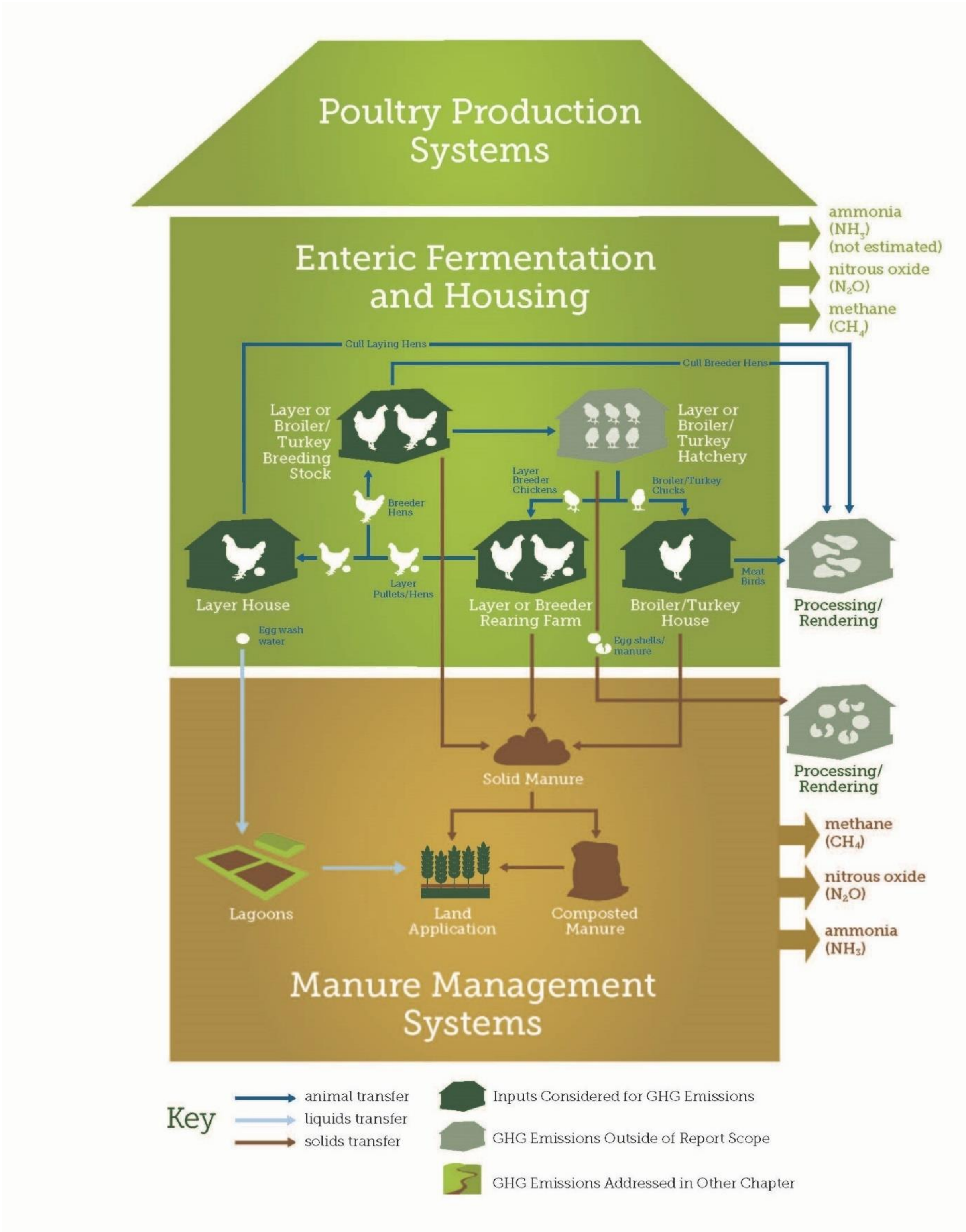


**Figure 4A-4. Conceptual Model of Poultry Production Systems in the United States**

### 4-A.5.2 Poultry Housing and Manure Handling

The vast majority of the industry raises birds on litter in mechanically ventilated or naturally ventilated houses. Reuse of litter and number of flocks grown on the same litter is variable across the country and can range from as low as a single flock to as many as 18 flocks on the same litter source. Litter dry matter content can vary from 40 to 80 percent, depending on management.

Laying hen and pullet housing types range from high-rise houses, where hens are in cages and manure accumulates in a basement under the cages and is removed annually, to a manure-belt house where hens are in cages and manure is removed daily or more frequently from the basement to an external shed and stacked before periodic removal for land application (once or twice per year), to aviaries where hens are raised on litter (in large rooms as opposed to cages) that is removed from the aviary annually or more frequently. When manure is removed from the house it may be immediately applied to fields, stockpiled, or composted. Moisture content may vary from 80 percent moisture down to 20 percent moisture (aviaries).

## 4-A.6 Background on Enteric Fermentation $CH_4$ Emissions

$CH_4$ is a normal byproduct of anaerobic fermentation of carbohydrates and proteins in the foregut of ruminants and the hindgut of ruminants and nonruminants. The microbiology, physiology, and biochemistry of enteric fermentation $CH_4$ production have been reviewed (Beauchemin et al., 2020; NASEM, 2016; Thompson and Rowntree, 2020) and summaries are available in those articles and will not be covered in this overview. Factors affecting enteric $CH_4$ emissions, and potential mitigation strategies to decrease enteric $CH_4$ (Beauchemin et al., 2020; Hristov et al., 2013a, 2013b; Hunerberg et al., 2015; Ouatahar et al., 2021) emissions are reviewed below in section 4-A.6.4. Hammond et al. (2016) reviewed methods to measure enteric $CH_4$ emissions from individual animals or groups of ruminants; their findings are briefly summarized below.

### 4-A.6.1 Methods for Measuring Enteric $CH_4$

#### *Individual Animals*

The standard method of measuring $CH_4$ emissions from ruminants is by respiration calorimetry (oxygen($O_2$), $CO_2$, and $CH_4$ sensors) or environmental chambers ($CO_2$ and $CH_4$ sensors only). Other techniques, including head boxes, internal tracers, micrometeorology, isotope dilution, and polyethylene tunnels, have also been used (Cole et al., 2018; Harper et al., 2011; Kebreab et al., 2006). More recently, several new technologies have been developed to measure individual animal emissions. To address the difficulty in measuring enteric $CH_4$ emissions while cattle graze pasture, alternate methods are being sought and developed. As one example, Goopy et al. (2011) has proposed a portable static chamber method to measure daily $CH_4$ production. Until validated, results using alternate methods should be viewed with caution.

A variety of respiration chambers have been developed to measure enteric $CH_4$ losses, total energy metabolized, or both, by the animal. In general, air is pulled from the chamber at a known rate and replaced with outside air. Flow of air and concentrations of $CH_4$, $CO_2$, and $O_2$ are measured in the air entering and leaving the chamber to determine total $CO_2$ and $CH_4$ production and $O_2$ consumption by difference. When properly calibrated and used, respiration chambers give highly accurate, precise measurements. However, they are expensive to build and operate and require significant knowledge, skill, and labor.

Feed intake and production is usually decreased while animals are in chambers and the measurements do not necessarily reflect intake and production from typical commercial systems.

This limitation can be partially overcome by feeding animals at different levels of intake and measuring the effects. Head boxes use the same principles as respiration chambers and have many of the same limitations. In-barn chambers using drop-down curtains have been used to measure $NH_3$, $CH_4$, and other gases emitted from groups of dairy cows at relatively lower cost than chambers (Aguerre et al., 2011; Powell et al., 2007, 2008).

Internal tracer techniques such as the sulfur hexafluoride ($SF_6$) tracer method (Johnson et al., 1994) were developed to allow measurements of $CH_4$ emissions by free-ranging animals, such as those grazing pasture, or when real-world levels of feed intake are needed that occur with large pens. The limitations to this method are the need for trained animals, the need for larger sample sizes (compared with chambers) to detect the influence of mitigation techniques, and concerns about inconsistent releases of tracer gas from $SF_6$ permeation. Additionally, the $SF_6$ technique generally results in emissions estimates that are lower than chamber measurements, possibly because the $SF_6$ method does not measure all lower gut $CH_4$ production (McGinn et al., 2006). The advantages and shortcomings of the $SF_6$ method have been reviewed (Lassey et al., 2011).

To overcome the feed intake limitations of respiration chambers and to measure $CH_4$ emissions of grazing cattle, automated head chamber systems have been developed (i.e., GreenFeed by C-Lock™, Rapid City, South Dakota). These commercially available systems appear to give mean values similar to respiration chambers, although there is greater variability in individual animals because $CH_4$ is primarily emitted during eructation and emissions are measured for short time periods (5 minutes or less) several times daily and thus may not collect a representative sample of eructations (Cole et al., 2020a; Gunter and Bradford, 2017; Hammond et al., 2015). These systems have also been successfully employed to measure enteric $CH_4$ from confined dairy cattle (Hristov and Melgar, 2020). Proper calibration and maintenance (Gunter et al., 2017; Gunter and Beck, 2018) and adequate numbers of animals and readings (Arthur, 2017; Hammond et al., 2015; Hristov and Melgar, 2020; Jonker et al., 2016) are needed to obtain reliable results.

### *Group of Animals*

Micrometeorology methods have been used extensively to measure $CH_4$ and $NH_3$ emissions from grazing land, whole feed yards, or portions of feed yards (pens, retention ponds, manure stockpiles, etc.). These methods have been reviewed (Flesch et al., 2005; Fowler et al., 2001; Harper et al., 2011). Laubach et al. (2008) compared the $SF_6$ method with three micrometeorological methods (integrated horizontal flux, flux gradient, and backward Lagrangian stochastic (bLS)) using steer grazing paddocks. In general, the micrometeorological methods yielded higher $CH_4$ emissions estimates than the $SF_6$ method, with a greater difference when animals were within 22 meters of the $CH_4$ sampler. This effect was especially true for the flux gradient method. The lower values for the $SF_6$ method could be due in part to the fact that the $SF_6$ method does not measure emissions from the lower gut or from fermentation of feces on the paddock surface.

Tomkins et al. (2011) compared enteric $CH_4$ emissions for steers grazing pasture using the bLS method and respiration chambers. Emissions estimated using the bLS model were slightly greater than with respiration chambers (136.1 vs. 114.3 g/head daily). However, emissions per gram of DMI were not different (29.7 vs. 30.1 g $CH_4$/kg DMI), suggesting that the bLS model may be suitable for estimating enteric $CH_4$ emissions for groups of cattle.

Most dispersion models and micrometeorological methods assume that emissions are uniformly distributed over the source area. In some cases, such as for individual cattle in a pen or field, this is untrue. Therefore, McGinn et al. (2011) developed a method that used a point-source dispersion model and measured atmospheric $CH_4$ concentrations using multiple open-path lasers to measure

$CH_4$ emissions from a paddock containing 18 cattle. Enteric $CH_4$ emissions did not differ from values measured using other techniques. However, recoveries of known $CH_4$ releases averaged only 77 percent using this method, and this method gave more reliable measurements during the daytime when atmospheric conditions were unstable, than at night when atmospheric conditions were stable.

Todd et al. (2019) measured enteric $CH_4$ emissions from beef cows on Oklahoma tall-grass prairie during three seasons using the McGinn (2011) point source dispersion model, the automated head chamber system, and eddy covariance. They concluded in their study that the point source dispersion model tended to overestimate enteric $CH_4$ emissions, whereas the automated head chamber system tended to underestimate emissions. Their study demonstrated the challenges in quantifying $CH_4$ emissions by grazing animals because of their mobility and dispersed behavior while grazing, and the dynamic interactions of forage quality, selective grazing, and diurnal variations in DMI.

In California, Frank Mitloehner (see Cooprider et al., 2011, and Stackhouse-Lawson et al., 2013) developed cattle pen enclosures that allowed for collection of GHG and other emissions from pens of beef or dairy cattle and estimations did not differ from respiration chambers. The emissions measured included both enteric and pen surface manure $CH_4$ emissions.

### 4-A.6.2 Background on Enteric Methane Emissions From Dairy Cattle

Enteric $CH_4$ production varies primarily with feed intake and is associated with production stage in dairy cattle, with the highest rates of feed intake and $CH_4$ emissions being produced by lactating cows (table 4A-1). This table illustrates, conceptually, the observed variation in dairy cattle at different stages of maturity and activity, but it is not intended to show absolute differences. Many factors affect enteric $CH_4$ production, and therefore altering dairy cattle diets could have an impact on enteric $CH_4$ production. However, the results in table 4A-1 clearly illustrate the difference in enteric $CH_4$ emissions; in particular, emissions from lactating dairy cattle are relatively higher than those from growing (i.e., heifers) and dry cattle. While there have been overall improvements in milk production with breeding programs, there is no evidence that any breed of dairy cow produces less enteric $CH_4$. Münger and Kreuzer (2008) measured enteric $CH_4$ production from Holstein, Simmental, and Jersey cows and found no persistent differences in $CH_4$ yields, with average enteric $CH_4$ being about 25 g $CH_4$/kg DMI.

Although the dairy industry is primarily composed of three animal types—growing (i.e., calves, replacement heifers), lactating cows, and nonlactating cows—most of the limited emissions research conducted to date has been targeted at lactating cows, which typically produce at least 50 percent more enteric $CH_4$ per head than other dairy cattle types. Few emissions data exist for calves, heifers, and nonlactating cows. Therefore, most of the information presented in this appendix focuses on lactating cows.

**Table 4A-1. Examples of $CH_4$ Emissions Measured in Dairy Cattle**

| Animal Type | $CH_4$ Emissions | Method Used to Measure Emissions | Reference |
|---|---|---|---|
| Dairy cattle | 260 g/animal/day | Calculated Blaxter and Clapperton (1965) | Crutzen et al. (1986) |
| Heifer, 6–24 months | 140 g/LU/day | | |
| Dairy cattle, dry period | 139 g/LU/day | Respiration calorimetry | Holter and Young (1992) |
| Dairy cattle, lactating | 268 g/LU/day | | |

| Animal Type | $CH_4$ Emissions | Method Used to Measure Emissions | Reference |
|---|---|---|---|
| Dairy cattle | 257 g/LU/day | Respiration calorimetry | Kirchgessner et al. (1991) |
| Dairy cattle, lactating | 429 g/animal/day | Wind tunnel | Sun et al. (2008) |
| Dairy cattle, dry period | 290 g/animal/day | | |
| Dairy cattle, lactating | 538–648 g/animal/day | Respiration calorimetry | Aguerre et al. (2011) |

LU = livestock unit (500 kg)

### 4-A.6.3 Background on Enteric Methane Emissions From Beef Cattle

Because of differences in the diets, animal physiological state and age, and manure handling, the proportions and sources of GHG emissions differ among the cow-calf, stocker, and finishing segments of the beef cattle industry. The primary source of GHG emissions from the beef cattle industry is enteric $CH_4$, produced primarily in the rumen, although some $CH_4$ is also produced in the lower gut.

Beauchemin et al. (2010) used the Holos model (Little et al., 2008) to conduct an LCA of beef production in western Canada:

- Of total $CO_2$-eq, 63 percent was from enteric $CH_4$ (5 percent of emissions were from manure $CH_4$, 23 percent from manure $N_2O$, 4 percent from soil $N_2O$, and 5 percent from energy $CO_2$).
- 61 percent of $CO_2$-eq emissions were from the cow-calf herd, 19 percent were from replacement heifers, 8 percent were from backgrounding operations, and 12 percent were from feedlots.
- 79 percent of enteric $CH_4$ losses were from the cow herd, 3 percent from bulls, 2 percent from calves, 7 percent from backgrounders, and 9 percent from feedlots.
- $N_2O$ contributions ($CO_2$-eq) as a percent of total GHG emissions were as follows: 2 percent for feedlot manure, 2 percent for feedlot soil, 2 percent for cow-calf herd soil, and 20 percent for cow-calf herd manure.

#### *Cow-Calf Operations and Bulls*

There is no evidence that any breed of beef cow produces less enteric $CH_4$ than another. A few reports suggest that efficient cattle (those selected for feed efficiency or residual feed intake) may produce less enteric $CH_4$ (Basarab et al., 2013; de Haas et al., 2017; Dini et al., 2019; Hegarty et al., 2007; Nkrumah et al., 2006; Pickering et al., 2015). However, Freetly et al. (2015) reported that cattle with greater feed efficiency actually produced more $CH_4$, thus raising some questions about the genetic factors associated with feed efficiency and $CH_4$ emissions. It is unclear whether the changes observed are a result of altered feed intake, ruminal microbial population, or rate of passage of feed through the digestive tract (Hammond et al., 2014; Johnson and Johnson, 1995). Additionally, recent information indicates that diet quality and feed efficiency interact to affect enteric $CH_4$ emissions: efficient cows produce less $CH_4$ when grazing high-quality pasture but not when grazing poor-quality forage (Jones et al., 2011). Residual feed intake is moderately heritable (0.28 to 0.58; Moore et al., 2009), so it might be possible to genetically select for animals with lower enteric $CH_4$ production. However, Donoghue et al. (2016) and Herd et al. (2014) suggested that selection for lower enteric $CH_4$ emissions might have negative effects on animal productivity. Simulations using published data indicate that without accurate feed intake information and a method by which many animals can be screened for $CH_4$ emissions, selection for lower enteric $CH_4$ emissions is not likely to be economically viable (Cottle et al., 2011).

Measurement of enteric $CH_4$ emissions from grazing cattle has been conducted primarily with animals grazing improved pastures using micrometeorological methods, tracer techniques, and automated head chamber systems (i.e., GreenFeed). Lassey (2007) summarized much of the $CH_4$ emissions data that had been collected using the $SF_6$ tracer technique and external markers to estimate forage intake. Estimated forage digestibility (in vitro) ranged from 49 to 83 percent, which resulted in estimated $Y_m$ (i.e., enteric $CH_4$ as a percentage of GEI) ranging from 3.7 to 9.5 percent. The mean $Y_m$ from all the studies was 6.25 percent, which agrees with the $Y_m$ IPCC (2006, 2019) used for cattle on pasture. $CH_4$ emissions from cows grazing improved pasture, Kentucky fescue, and bermuda grass in the southern United States were reported by Pavao-Zuckerman et al. (1999) and DeRamus et al. (2003). In both studies, significant reductions in enteric $CH_4$ emissions per unit of animal BW gain resulted from the implementation of best management practices designed to improve pasture quality. Pavao-Zuckerman at al. (1999) did not specify these pasture practices, but DeRamus et al. (2003) evaluated intensive grazing.

Enteric $CH_4$ emissions can be estimated using micrometeorological methods and tracer techniques. Todd et al. (2019) measured $CH_4$ emissions from beef cows grazing native Oklahoma range in October and May and reported a large variation in enteric emissions. In October, when cows were losing BW, they produced 87 g $CH_4$/head daily, and on the same pasture in May they produced 252 g $CH_4$/head daily (Olson et al., 2000). Westberg et al. (2001) measured $CH_4$ emissions from cows grazing the same pasture across seasons and found similar results, with higher $CH_4$ emissions from cows grazing lush spring growth and the lowest emissions from grazing stockpiled fall pasture. These differences are attributable to differences in both DMI and forage quality.

### *Stockers*

Enteric $CH_4$ emissions of stocker cattle, while grazing, have been measured by Laubach et al. (2008), Tomkins et al. (2011), McGinn et al. (2011), Boadi et al. (2002), Gunter and Bradford (2017), and Gunter et al. (2017) using a variety of techniques including the $SF_6$ tracer, micrometeorological, and automated head chamber approaches. The same factors that affect $CH_4$ emissions from grazing beef cows are important in stocker cattle. Those factors are level of forage intake, digestibility of forage consumed, supplementation, and chemical composition of the plants consumed. Critical variables include estimations of feed intake and feed quality (chemical composition). However, many of the equations currently available may not accurately predict measured enteric $CH_4$ emissions from grazing cattle (Tomkins et al., 2011) or cattle fed harvested forages (Cole et al., 2020a).

### *Feedlot Cattle*

Most estimates of enteric $CH_4$ emissions from finishing beef cattle are based on work using animals confined to respiration chambers, although a few studies have used micrometeorological methods in open feedlots or automated head chambers. Enteric $CH_4$ losses from finishing beef cattle normally range from 50 to 200 L/head/day (Beauchemin et al., 2008; Hales et al., 2012, 2013, 2014, 2015a, 2015b, 2017a, 2017b; Johnson and Johnson, 1995; Loh et al., 2008; McGinn et al., 2004; Todd et al., 2014a, 2014b). In most studies in the United States, diets have been based on dry-rolled or steamed-flaked corn, whereas in most studies in Canada the diets are based on barley. The IPCC Tier 2 (2006, 2019) enteric $CH_4$ conversion factor ($Y_m$) is 3 ± 1 percent of GEI for feedlot cattle fed steam-flaked corn-based diets and 3.9 percent of GEI for cattle fed barley diets. The primary factors that control enteric $CH_4$ emissions in feedlot cattle are feed intake, grain type, grain processing method, dietary roughage concentration and characteristics, feeding of an ionophore, and dietary fat concentration.

### 4-A.6.4 Factors Affecting Enteric Methane Emissions of Ruminants

Several factors may influence enteric fermentation and resulting $CH_4$ emissions. A thorough review of such factors is outside the scope of this document, but key factors have been reviewed by others (Beauchemin et al., 2008, 2020; Eckard et al., 2010; Hristov et al., 2013a, 2013b; Martin et al. 2010; Monteny et al., 2006; NASEM, 2016; Thompson and Rowntree, 2020) and are discussed briefly below or in other sections of this appendix. Many factors affect enteric $CH_4$ emissions, but the most critical factors are the:

- Level of dry matter intake
- Composition of the diet
- Digestibility of the organic matter

Benchaar et al. (2001) used the rumen digestion model of Dijkstra et al. (1992), as modified by Benchaar et al. (1998), and the $CH_4$ prediction system of Baldwin (1995) to estimate the effects of dietary modifications on the enteric $CH_4$ production of a 500-kilogram dairy cow. The model predicted enteric $CH_4$ production based on a ruminal hydrogen balance. Inputs into the model included daily DMI; chemical composition of the diet; solubility and degradability of protein and starch; degradation rates of protein, starch, and NDF; ruminal volume; and fractional passage rates of solids and liquid fractions from the rumen. Values modified in the simulations were DMI, dietary forage, concentrate ratio, starch availability (barley vs. corn), stage of maturity of forage, form of forage (hay or silage), particle size of alfalfa, and ammonization of cereal straw. The modeled effects of dietary changes on enteric $CH_4$ emissions in diets fed to dairy cows are presented in table 4A-2.

**Table 4A-2. Summary of Effects of Various Dietary Strategies on Enteric $CH_4$ Production in Dairy Cows using Modeled Simulations**

| Strategy | $CH_4$ Variation (per Unit of GEI) | $CH_4$ Variation (per Unit of DE) |
|---|---|---|
| Increasing DMI | -9 to -23% | -7 to -17% |
| Increasing concentrate proportion in the diet | -31% | -40% |
| Switching from fibrous concentrate to starchy concentrate | -24% | -22% |
| Increased forage maturity | +15% | -15% |
| Alfalfa vs. timothy hay | +28% | -21% |
| Method of forage preservation (ensiled vs. dried) | -32% | -28% |
| Increased forage processing (smaller particle size) | -21% | -13% |
| Ammoniated treatment of poor-quality forage (straw)[a] | × 5 | × 2 |
| Protein supplementation of poor-quality forage (straw) | × 3 | × 1.5 |

Source: Benchaar et al., 2001, table 12.

[a] Effects are due to significant increase in hay digestibility with no change in DMI.

### 4-A.6.5 Dietary Management Practices

#### *Mitigating Enteric Methane in Dairy Cattle*

Practices for mitigating enteric $CH_4$ production (g/day/cow) from lactating dairy cows in the United States include the incorporation of dietary management practices. These may include 3-nitrooxypropanol (3-NOP), nitrate, lipid supplementation, oilseeds, and tanniferous forages, and red algae (Arndt et al., 2020).

### 3-NOP

The inhibitor 3-NOP is an analog of methyl-coenzyme M that reacts with the nickel ion in the active site of methyl-coenzyme M reductase, thus competitively inhibiting the last step of the methanogenesis pathway in the rumen (Duin et al., 2016). The molecule is highly specific to methanogenesis and exhibits a positive dose-response behavior (Dijkstra et al., 2018; Melgar et al., 2020). The lowest effective dose recommended for dairy cows fed total mixed rations is 60 mg per kg of feed dry matter, without adverse effects on productivity. Dietary NDF content reduces the response in both dairy and beef cattle (Dijkstra et al., 2018). Higher 3-NOP doses may be needed for beef than for dairy cattle to achieve a similar reduction in $CH_4$ emissions (Dijkstra et al., 2018). The inhibitor 3-NOP is not yet registered for use in cattle in the United States but is expected to be registered in other countries soon. As of June 2023, Bovaer® (Elanco Animal Health Inc. and DSM-Firmenich) is available in 45+ countries, including the EU/EEA, Australia, Brazil, Chile, Pakistan, Switzerland, and Turkey, and has been the subject of multiple on-farm trials in 15+ countries and over 60 peer-reviewed studies (DSM, 2023).

### Nitrate

Nitrate is a competitive hydrogen sink in the rumen, replacing carbon dioxide as the electron acceptor. Nitrate is reduced sequentially to nitrite and $NH_3$ following stoichiometric relationships (Honan et al., 2021). Nitrate supplementation reduces $CH_4$ production in a dose-dependent manner and elevated DMI decreases the effect of nitrate supplementation on $CH_4$ mitigation (Feng et al., 2020). Nitrate supplementation mitigates $CH_4$ production to a greater extent in dairy than in beef cattle. The greater mitigation efficacy in dairy cattle may be related to the use of slow-release nitrate only in beef cattle diets and to the generally greater feed intake in dairy. Nitrite is a toxic intermediate of nitrate reduction to $NH_3$ that can cause methemoglobinemia (Honan et al., 2021). Because of this, nitrates are recommended with caution and under supervisions of a trained or certified nutritionist. Nitrite toxicity in cattle can be prevented by controlling nitrate intake and gradual acclimation to higher doses but represents a health risk to the animals and can lead to death. Other toxicity prevention options such as encapsulation (slow release) and feeding denitrifying probiotics need more evidence for wide application.

### Lipid Supplementation and Oilseeds

Dietary supplementation with lipids (oils and fats) modifies the rumen environment in several ways reducing enteric $CH_4$ production (Honan et al., 2021).

- Supplemental lipids replace fermentable carbohydrates, reduce the abundance and activity of protozoa and methanogens, provide an alternative hydrogen sink, and reduces fiber digestion shifting the ruminal metabolism to propionate production.
- Supplemental lipids also reduce DMI without affecting milk production and composition in some instances but reducing them in others (Hristov et al., 2013a). The general recommendation to prevent undesirable suppression of DMI is for total lipids, measured as ether extract, not to exceed 6–7 percent of diet dry matter. This maximum inclusion level limits the practical application of supplemental oils and fats to reduce $CH_4$ emissions in diets that contain ether extract below 6 percent of dry matter.
- Supplemental lipids reduce $CH_4$ in a dose-response manner. However, the response varies over a wide range depending on the fatty acid profile of the supplement and diet composition. Medium-chain and polyunsaturated fatty acids reduce $CH_4$ production most effectively (Honan et al., 2021) but feeding unsaturated fatty acids also increases the likelihood of milk fat depression mediated by the biohydrogenation intermediate trans-10, cis-12 conjugated linoleic acid (Palmquist and Jenkins, 2017).

- Feeding intact or extruded oilseeds is another practical way to increase the dietary lipid content to reduce $CH_4$ emissions.

### Tanniferous Forages

Many browse and warm climate forages accumulate tannins. Tannins mitigate enteric $CH_4$ through mechanisms that are not well understood (Honan et al., 2021). Some evidence points to tannins reducing fiber digestion and hydrogen formation, and directly inhibiting methanogens. Tannins also have antiparasitic properties and antinutritional effects. The latter are more pronounced when dietary protein is limited because tannins reduce amino acid absorption (Hristov et al., 2013a), and high tannin doses can lead to intoxication. Tannins reduce $CH_4$ emissions in a linear dose-response manner, but the response is variable and reliable effects are only expected with tannin inclusion above 20 g/kg of diet DM (Jayanegara et al., 2011). Tanniferous forages, especially direct grazing of Lesdepeza species, can mitigate enteric $CH_4$ production (g/day) by 11.6 percent on average (Arndt et al., 2020). The recommendation to feed tanniferous forages only when grazing and exclude dietary tanning supplementation is based on the lack of a clearly understood mode of action, poor characterization of supplemental tannins, high variable response, and narrow dose range between $CH_4$ mitigation and risk for detrimental effects on animal nutrition and health.

### Red Algae

The interest in macroalgae for mitigation of enteric $CH_4$ emissions in ruminants has dramatically increased in recent years, since Li et al. (2018) documented a strong anti-methanogenic effect of the red alga *Asparagopsis taxiformis* in sheep. Research groups around the globe have screened red, brown, and green macroalgae for anti-methanogenic effect (Dubois et al., 2013; Machado et al., 2014; Maia et al., 2016; Wasson et al., 2021) and while some species have shown promising results, *Asparagopsis* spp. (*taxiformis* and *armata*) appear to be the only ones with confirmed mitigating effect in in vivo experiments with dairy and beef cattle (Li et al., 2018; Roque et al., 2019; Kinley et al., 2020; Stefenoni et al., 2021).

The current understanding is that the anti-methanogenic activity of *Asparagopsis* spp. is based on its content of low molecular weight halogenated compounds, of which the brominated halomethane bromoform is dominant (Genovese et al., 2012). *Asparagopsis* spp. cause dramatic decrease in $CH_4$ emissions in vivo, but DMI may also decrease (Stefenoni et al., 2021) and there are concerns with the environmental impact of bromoform (ozone layer depletion) and effects on animal health and milk quality (Stefenoni et al., 2021; Muizelaar et al., 2021; Hegarty et al., 2021). Bromoforms are volatile and activity may decrease over prolonged storage, or if exposed to sunlight or heat (Stefenoni et al., 2021). Decreasing bromoform concentration and its intake will linearly diminish the mitigation potential of *A. taxiformis*. Based on data from Stefenoni et al. (2021) and unpublished data from Hristov et al. (n.d.), $CH_4$ yield will decrease by 1.5 to 2.0 g/kg DMI for every 100 mg/d increase in bromoform intake.

Long-term effects on animal productivity, health, reproduction, and milk quality need to be studied and the economics of mass application in the global dairy and beef industries are unclear. As a result of these uncertainties, Hegarty et al. (2021) rated the confidence in *Asparagopsis* spp. efficacy as "Low Agreement and Limited Evidence". Research in this novel field will certainly continue in the near future, but its long-term impact on livestock GHG emissions is difficult to predict.

## *Mitigating Enteric Methane in Beef Cattle*

### Dietary Fat

Many studies have shown that supplemental fat can decrease enteric $CH_4$ emissions in ruminants. In a review of studies, Beauchemin et al. (2007) and Martin et al. (2010) noted that enteric $CH_4$

emissions (g/kg DMI) decreased by approximately 3.8 to 5.6 percent for each 1 percent increase in fat added to the diet. Similar decreases have been noted in sheep (Wang et al., 2018). Although added fat may reduce enteric $CH_4$ emissions, ruminants have a low tolerance for added dietary fat because it interferes with fiber digestion (Beck et al., 2019; NASEM, 2016). Thus, total fat level in the diet must usually be kept below 6–8 percent of dietary dry matter.

### Grain Source, Grain Processing, Starch Availability

Grain source and grain processing method can also affect enteric $CH_4$ losses. In general, the greater the ruminal starch digestibility, the lower the enteric $CH_4$ emissions. At constant energy intake (two times maintenance), Hales et al. (2012) reported approximately 20 percent lower (2.5 vs. 3.0 percent of GEI) enteric $CH_4$ emissions in cattle fed typical high-concentrate (75 percent corn) steam-flaked-corn based finishing diets than in steers fed dry-rolled-corn-based diets. Similar responses were noted with the feeding of high-moisture corn compared with dry-rolled corn (Archibeque et al., 2006). Beauchemin and McGinn (2005) reported that enteric $CH_4$ emissions were 38 percent (barley) to 65 percent (corn) lower on high-concentrate (9 percent silage) finishing diets than on grower (70 percent silage) diets.

### Feeding Coproduct Ingredients

Distillers grains with solubles (DGS) and other coproducts of the milling and ethanol industries are widely used as animal feeds. The effects of feeding 30 to 35 percent DGS (dry matter basis) in beef cattle feedlot diets on enteric $CH_4$ emissions have been variable, ranging from a significant decrease of 25 to 30 percent (McGinn et al., 2009) to no effect (Hales et al., 2012), and an increase (Hales et al., 2013). These differing results were probably due to differences in forage sources and processing and dietary fat characteristics. Researchers have reported conflicting results on the effect of DGS on nitrogen excretion, with some reporting a linear increase in N excretion with an increase of DGS inclusion in the diet (Hales et al., 2013). Some researchers note that the effect of DGS on nitrogen excretion are not known (Hünerberg, et al., 2013a; Hünerberg, et al., 2013b; Hünerberg, et al., 2014). Increased nitrogen excretion could lead to increased overall GHG emissions, even if $CH_4$ emissions may be reduced. Other research indicates the otherwise fate of coproducts not fed to animals should be considered, as the avoided emissions from landfills or composting could be considerable (de Ondarza and Tricarico, 2021). More research may be needed to fully understand the potential for emissions reductions.

### Roughage Concentration and Form

The concentration and form of roughage in the diet will affect both enteric and manure $CH_4$ production (Beauchemin and McGinn, 2005; Hales et al., 2014). In general, as the concentration of forage in the diet increases, enteric $CH_4$ production increases and the quantity of volatile solids excreted increases. Using a ruminal volatile fatty acids stoichiometry model, Dijkstra et al. (2007) suggested that $CH_4$ losses from carbohydrate substrates (g/kg substrate) in a concentrate diet with a ruminal pH of 6.5 were 2.11, 3.18, 3.38, and 3.10 for starch, soluble sugars, hemicellulose, and cellulose, respectively. Similarly, with dairy cows, Moe and Tyrrell (1979) reported that enteric $CH_4$ production per unit carbohydrate digested was three times greater for cellulose than for hemicellulose. Aguerre et al. (2011) found that lactating dairy cattle emitted more $CH_4$ when the forage:concentrate ratio was changed from 47:53 to 68:32—0.54 kg $CH_4$/day vs. 0.65 kg $CH_4$/day, respectively. Blaxter and Wainman (1964) compared the effects of feeding diets with six hay to flaked corn ratios (100:0, 80:20, 60:40, 40:60, 20:80, 5:95) on enteric $CH_4$ emissions when fed at twice the maintenance level of intake. $CH_4$ emissions as a percentage of GEI increased slightly between the 100:0 diet (7.44 percent) and the 60:40 diet (8.17 percent), then decreased with the 5:95 diet (3.4 percent). In Ireland, Lovett et al. (2003) reported total daily enteric $CH_4$ emissions of 0.15, 0.19, and 0.12 kg/head (reported as 207, 270, and 170 L/head) for heifers fed diets containing

65, 40, and 10 percent forage (the remainder as concentrate), respectively. As a percentage of GEI, losses were 6.1, 6.6, and 4.4 percent, respectively.

### Roughage Quality

Using steers fed all-forage diets, Ominski et al. (2006) reported that, within the range of forage qualities tested (alfalfa-grass silage containing 61, 53, 51, or 46 percent NDF, dry matter basis), enteric $CH_4$ emissions of steers, as a percentage of GEI, were not significantly affected by NDF content (5.1 to 5.9 percent), although daily $CH_4$ production tended to be highest for the 53 percent NDF diet (0.12, 0.15, 0.13, and 0.14 kg/head/day, respectively). Similarly, using grazing sheep, Milano and Clark (2008) reported no effect of forage quality (perennial rye grass—52 or 47 percent NDF, 77 or 67 percent organic matter digestibility) on enteric $CH_4$ emissions. Cole et al. (2020a) noted that daily enteric $CH_4$ emissions were not affected by forage quality in steers fed a low-quality grass hay in combination with alfalfa hay. However, $CH_4$ emissions per unit of organic matter digested decreased linearly as forage quality increased. Protein supplementation of the low-quality forage did not affect total $CH_4$ emissions but decreased $CH_4$ per kg digestible organic matter.

Although, in some instances, there may be limited effect of forage quality on enteric $CH_4$ emissions, forage quality will affect digestibility and excretions of VS in feces, thus affecting $CH_4$ emissions from manure. Therefore, feeding more easily digestible forages or concentrates may decrease VS excretion thereby decreasing $CH_4$ emissions from manure (Boadi et al., 2004; Ominski et al., 2006; Cole et al., 2020a).

### Level of Feed Intake

Blaxter and Wainman (1964) noted that enteric $CH_4$ emissions, as a percent of GEI, were 23 percent greater in steers fed at maintenance than in steers fed at twice maintenance (8.1 vs. 6.6 percent of GEI, respectively). However, in a study evaluating emissions from cattle fed ryegrass diets, Milano and Clark (2008) reported that as DMI increased from 0.75 percent of maintenance to two times maintenance, enteric $CH_4$ emissions (g/day) increased linearly ($r^2 = 0.80$ to 0.84). Emissions as a percentage of GEI were not affected by DMI and ranged from 4.9 to 9.5 percent of GEI (15.9 to 30.4 g/kg DMI).

Using a high-forage (70 percent barley silage) or medium-forage (30 percent silage) diet fed at levels from maintenance to about 1.8 times maintenance, Beauchemin and McGinn (2006b) noted that enteric $CH_4$ emissions, as a percent of GEI, decreased by approximately 0.77 percentage units[1] for each unit increase in feed intake (expressed as level of feed intake above maintenance). This was less than the estimate using the Blaxter and Clapperton (1965) equation (0.93 to 1.28 percentage units) or the 1.6 percentage units suggested by Johnson and Johnson (1995).

### Feed Additives and Growth Promoters

Cooprider et al. (2011) noted that the daily $CH_4$ and manure $N_2O$ emissions by beef cattle fed through a "natural" program with no use of antibiotics, ionophores, or growth promoters were similar to those from beef cattle fed in more traditional systems that used anabolic implants and diets that contained ionophores and beta-agonists. However, typical beef cattle had greater average daily BW gains (1.85 vs. 1.35 kg/day) and thus took 42 fewer days to reach the same end point (596 kg BW). Hence, beef cattle fed using modern growth technologies had 31 percent lower GHG

[1] This appendix uses the term "percentage units" to refer to changes in diets or emissions that are *not* proportional to their baselines. For example, a reduction in emissions from 3 percent to 1 percent is a two "percentage unit" reduction, or a *67-percent reduction*.

emissions per head. $CH_4$ emissions per kilogram of BW gain was 1.1 kilogram greater for the "natural" cattle (5.02 vs. 3.92 $CO_2$-eq/kg BW gain) than the traditional beef cattle.

Odongo et al. (2007) reported that monensin (24 ppm) in dairy diets decreased enteric $CH_4$ by 7 to 9 percent for up to 6 months, while Waghorn et al. (2008) reported no effect of monensin delivered by controlled-release capsules in dairy cows grazing pasture, and Hamilton et al. (2010) also found no change in enteric $CH_4$ production from monensin when fed to dairy cows offered a total mixed ration.

A number of studies have shown that a variety of halogenated analogues have the potential to dramatically decrease ruminal $CH_4$ production (Cole and McCroskey, 1975; Johnson, 1972, 1974; Tomkins and Hunter, 2004; Tomkins et al., 2009; Trei et al., 1972). In general, the effect was greater in cattle fed high-forage diets than in cattle fed high-concentrate diets. When $CH_4$ emissions were dramatically reduced, a significant quantity of hydrogen could be lost (1 to 2 percent of GEI) via eructation, suggesting an alternative electron sink is also needed. In general, the compounds did not improve production efficiency significantly. In addition, the potential toxicity of these compounds made them impractical for routine use where formulation errors in the field are possible.

A number of studies have demonstrated that feeding nitrates in place of urea in cattle diets can significantly decrease enteric $CH_4$ production (Dijkstra et al., 2018; Feng et al., 2020; Honan et al., 2021; Lee et al., 2015, 2017a, 2017b; Velazco et al., 2014). However, the risk of nitrate toxicity may limit the use of this technology in real practice.

Several studies have suggested that feeding of condensed tannins can decrease enteric $CH_4$ production by 13 to 16 percent, either through a direct toxic effect on ruminal methanogens or indirectly via a decrease in feed intake and diet digestibility (Arndt et al., 2020; Eckard et al., 2010; Min et al., 2020; Moraes et al., 2014, 2018; Niu et al., 2018). Tannins may also shift nitrogen excretion away from urine to feces and inhibit urease activity in feces, which could decrease $NH_3$ and $N_2O$ emissions from manure (Powell et al., 2009, 2011). In arid environments, nearly all urinary nitrogen is volatized (Russelle, 1992), so if dietary tannin supplementation could shift nitrogen excretion from urine to feces less may be volatized into the atmosphere.

Feeding yeast cultures, enzymes, dicarboxylic acids (fumarate, malate, acrylate), and plant secondary compounds, such as saponins, may decrease enteric $CH_4$ emissions under some feeding conditions (Beauchemin et al., 2008; Beauchemin and McGinn, 2006a; Eckard et al., 2010; Martin et al., 2010; McGinn et al., 2004; Ungerfeld et al., 2007).

### Novel Microorganisms and Their Products

Klieve and Hegarty (1999) noted that enteric $CH_4$ emissions may be biocontrolled directly by use of viruses and bacteriocins. Lee et al. (2002) reported that a bacteriocin (Bovicin HC5) from *Streptococcus bovis* reduced in vitro $CH_4$ production by up to 50 percent. It appeared, that in contrast to results with monensin, the ruminal microorganisms did not adapt to the bacteriocin. Further, Australian researchers have suggested that vaccinating against methanogens can decrease $CH_4$ emissions. However, the results have not been consistent (Eckard et al., 2010; Wright et al., 2004) because efficacy is dependent on the specific methanogen population and that is dependent on diet, location, and other factors.

### Genetics

Potential genetic effects are discussed in section 4-A.5.2.

## 4-A.7 Background on Housing Emissions

Emissions from animal housing are highly dependent upon the type of housing (pasture, open lot, confinement, etc.), bedding used, and animal species. For example, $CH_4$ emissions from beef or dairy dry lot operations seems to be low, whereas emissions of $N_2O$ can be significant. Examples of reported emissions from varying dairy cattle housing systems are presented in Ttble 4A-3.

**Table 4A-3. Examples of Reported On-Farm Emissions Estimates for $CH_4$, $N_2O$, and $NH_3$ From a Variety of Dairy Cattle Housing Systems**

| Housing | Country | Emissions (g/Cow/Day) | | | Reference |
|---|---|---|---|---|---|
| | | $CH_4$ | $N_2O$ | *$NH_3$* | |
| Barn | Germany | 402 | | *64.8* | Saha et al. (2014) |
| Tie stall barn | Austria | 170–232[a] | 0.14–1.2[a] | *4–7.4*[a] | Amon et al. (2001) |
| Barn | Germany | 256 | 1.8 | *14.4* | Jungbluth et al. (2001) |
| Dry lot | United States | | | *41–140* | Cassel et al. (2005) |
| Hardstanding | United Kingdom | 0.03[b] | 0.01 | *11* | Ellis et al. (2001) |
| Open-freestall | United States | 410 | 22 | *80* | Leytem et al. (2013) |
| Tie stall barn | Canada | 390 | | | Kinsman et al. (1995) |
| Pasture | New Zealand | 300–427 | | | Laubach and Kelliher (2005) |
| Dry lot | United States | 490 | 10 | *130* | Leytem et al. (2011) |
| Standoff pad | New Zealand | 1.66[b] | 0.03 | | Luo and Saggar (2008) |
| Barn | Denmark | 256 | 1.2 | *16* | Zhang et al. (2005) |
| Dry lot | China | 397 | 37 | | Zhu et al. (2014) |
| Barn | Sweden | 216–312[a] | | *21–27*[a] | Ngwabie et al. (2009) |
| Barn | Germany | 464 | 45 | *92.4* | Samer et al. (2011) |
| Pasture | Uruguay | 372 | | | Dini et al. (2012) |

[a] Measured in g/LU/day, where an LU (livestock unit) = 500 kg.

[b] Measurements do not include enteric $CH_4$ production.

Variations in emissions from housing are due to factors such as temperature, diet composition, water consumption, ventilation flow rates, type of manure handling systems, manure removal frequency, feces and urine characteristics (i.e., pH, VS and total ammoniacal nitrogen), and type of bedding used. Although differences can be great between emission rates, there are some emission characteristics that are consistent across most studies.

Many studies have reported strong diel trends in emissions of $CH_4$ and $NH_3$, with emissions tending to be lower in the late evening and early morning and then higher throughout the day until early evening (Aguerre et al., 2011; Amon et al., 2001; Bjorneberg et al., 2009; Cassel et al., 2005; Flesch et al., 2009; Hales and Cole, 2017; Leytem et al., 2011; Ngwabie et al., 2009; Powell et al., 2008; Sun et al., 2008; Todd et al., 2011a, 2014a, 2015). This strong diel trend in emissions can be associated with wind speed and temperature, as winds tend to be light in the late evening and early morning and then, in most instances, steadily increase throughout the day to reach a peak in the late afternoon. Temperature also increases from early morning to late afternoon, and then decreases again. Additionally, animal activity tends to increase from morning to late afternoon as animals wake and begin to eat, drink, ruminate, defecate, and urinate. As these activities increase, one would expect an increase in $CH_4$ (and $NH_3$) emissions.

There are also seasonal trends in emissions, the most prominent being in $NH_3$ emissions, with the lowest rates in winter compared with the other seasons (Aguerre et al., 2011; Amon et al., 2001; Bjorneberg et al., 2009; Flesch et al., 2009; Leytem et al., 2011; Powell et al., 2008; Todd et al., 2011a). Powell et al. (2008), Flesch et al. (2009), and Aguerre et al. (2011) reported that dairy barn emissions of $NH_3$ in Wisconsin were lowest in winter, with winter rates about one-half to one-third lower than those in the spring and summer, which was attributed to cold winter temperatures. In general, $N_2O$ emissions from housing were found to be low and showed no discernible diel or seasonal trends (Adviento-Borbe et al., 2010; Bjorneberg et al., 2009; Leytem et al., 2011; Ngwabie et al., 2009). There are consistent reports of both diel and seasonal variations in both $CH_4$ and $NH_3$ emissions, so it is imperative that these factors be captured in any estimation of emissions for a given production system.

Amon et al. (2001) examined $CH_4$ emissions from a tie-stall dairy barn in Austria using either a slurry-based system or a straw-based system. In both systems, about 80 percent of the net $CH_4$ emissions were due to enteric fermentation, with the remaining amount coming from the manure. Sun et al. (2008) measured $CH_4$ emissions from dairy cows and fresh manure in chambers and reported that fresh manure alone did not produce noticeable $CH_4$ fluxes. In some dairy production systems, manure is removed from the animal housing area often; therefore, $CH_4$ emissions from animal housing areas of a dairy can be largely attributed to enteric emissions. When manure is stored mainly as a liquid, however, manure $CH_4$ emissions may exceed enteric emissions (Arndt et al., 2018 Todd et al., 2011b). $N_2O$ emissions tend to be negligible from both animals and fresh manure. The majority of $N_2O$ emissions result from manure storage, pasture, and land application of manures. Therefore, the main sources of $N_2O$ emissions from animal housing would be dry lots, feedlots, and stand-off pads, because there is potential for deposited nitrogen to be nitrified and denitrified under wet conditions and lost as $N_2O$. Luo and Saggar (2008) measured $N_2O$ and $CH_4$ emissions from a dairy farm stand-off pad in New Zealand and reported $N_2O$ fluxes from 0 to 3 g $N_2O$-N/day, which they attributed to the concentrations of water and nitrate in the pad materials. Overall, only 54 g of $N_2O$-N was emitted from the pad over the time of use, representing ~0.01 percent of the excreta nitrogen deposited on the pad.

In nonruminant systems, GHG emissions are dominated by housing and manure handling, as there is very little enteric $CH_4$ and $N_2O$ production. Liu et al. (2013) conducted a meta-analysis to identify factors that contribute to GHG emissions from swine production. Findings, shown in table 4A-4, illustrate that type of emission source (swine buildings or manure storage facilities) was not significant for $CH_4$ and $N_2O$ emissions. Liu et al. (2013) found that:

- Swine buildings with straw-flow systems generated the lowest $CH_4$ and $N_2O$ emissions of systems compared, while pit systems generated the highest $CH_4$ emissions and bedding systems generated the highest $N_2O$ emissions.
- Emissions from lagoons and slurry storage basin/tanks were compared; lagoons generated significantly higher $N_2O$ emissions than slurry storage basin/tanks, while $CH_4$ emissions were not different.
- Straw-based bedding resulted in numerically higher $CH_4$ but lower $N_2O$ emissions when compared with sawdust or corn stalk bedding systems.
- There is an increasing trend for $CH_4$ emissions as manure removal frequency decreased ($P = 0.13$).

- Deep pits and pits flushed using lagoon effluent also generated relatively high $CH_4$ emissions.
- Results for $N_2O$ emissions showed very high uncertainties (P = 0.49).
- Deep pits and pits with manure removed every 3 or 4 months had relatively higher $N_2O$ emissions.
- $CH_4$ emissions from slurry storage facilities without covers were significantly higher than from those with covers.
- When evaluating stage of production, the highest $CH_4$ emissions were from farrowing swine and were significantly higher than those from finishing and nursery swine. Compared with farrowing swine, the gestating swine had significantly lower $CH_4$ emissions.

The highest $N_2O$ emissions were from gestating swine and were significantly higher than those from finishing swine.

**Table 4A-4. P Values of Main Effects on GHG Emissions From Swine Operations**

| Cause of Variation | $CH_4$ (n=76) | $N_2O$ (n=53) |
|---|---|---|
| Emission source | 0.94 | 0.93 |
| Swine category | 0.05 | <0.01 |
| Geographic region | 0.04 | 0.02 |
| Temperature | 0.20 | 0.95 |
| Size of operation | 0.89 | 0.24 |

Source: Liu et al. (2013).

Greenhouse gas emissions from broiler chicken production will originate almost exclusively from the animal housing, which also serves as the storage location for manure. Liu et al. (2011) reported that for a 20-week grow-out of turkeys on litter, average daily $N_2O$ emissions were 0.045 g/kg bodyweight and daily $CH_4$ emissions were 0.08 g/kg bodyweight. If a house is cleaned or decaked (removal of the top, crusted portion of the litter) and stored on the farm, GHG and $NH_3$ production and emissions could occur. Practices to decake and the timing of land application of cake and litter vary from site to site and may or may not include further composting.

Greenhouse gas emissions from egg production will originate from the housing or the manure storage location. Laying hen housing systems without litter would likely exhibit greater emissions than litter systems, but comparisons of estimates are sparse. Laying hen houses typically store excreta in a basement or may move excreta out of the house frequently (daily or more often); this would relocate emissions to a storage shed rather than change the cumulative emissions unless some form of processing (drying) took place prior to storage. Li et al. (2010) reported daily $CH_4$ emissions of 39.3 to 45.4 mg/hen and $N_2O$ emissions of 58.6 mg/hen (hen bodyweight average = 1.9 kg) in a basement-type system. This compares to a litter system for a 20-week grow-out of turkeys where average daily $N_2O$ emissions were 0.045 g/kg bodyweight and daily $CH_4$ emissions were 0.08 g/kg bodyweight (Liu et al., 2011). Based on the comparison of these two studies, differences in GHG emissions from dry litter systems and wetter, stacked laying hen systems would be expected.

## 4-A.8 Background on Manure Management Emissions

Manure storage and treatment, as a component of manure management systems, plays a critical role in GHG emissions and their mitigation. At the entity level, various manure storage and treatment approaches will lead to different amounts of GHG emissions. Animal manure can be classified into two categories based on their physical properties: solid (more than 15 percent dry matter) and liquid (less than 15 percent dry matter, including liquid manure with less than 10 percent dry matter and slurry manure with 10–15 percent dry matter).

At the farm entity level, several practices are often strategically combined to treat manure. Activity data (i.e., mass flow data and chemical and physical characteristics of influent and effluent, environmental temperature, pH, and total nitrogen) from individual practices can be used to link practices in the combined system for individual farm entities.

In general, $CH_4$ emissions from manure management will vary depending on the amount of volatile solids stored, the maximum $CH_4$ generation potential of those solids, moisture content (aerobic vs. anaerobic environment), temperature, and length of storage. $N_2O$ emissions from manure management will be affected by the total nitrogen content of the manure, use of bedding, loss of nitrogen as $NH_3$, moisture content (aerobic vs. anaerobic environment), temperature and length of storage. Therefore, both the animal category and manure handling and storage system will have large impacts on the total GHG emissions.

### 4-A.8.1 Temporary Stack and Long-Term Stockpile

Management methods for stored manure are differentiated by the length of time they are stockpiled:

- Temporary stack is a short-term manure storage method that is used to temporarily hold solid manure when bad weather prohibits land application, and/or when there is limited availability of cropland for manure application. With temporary stack, the manure is removed and applied to land within a few weeks of piling. Temporary storage is not a preferred method to store manure because it requires the manure to be handled twice.
- Long-term storage is a method in which solid manure is piled on a confined area or stored in a deep pit for longer than 6 months. In low-rainfall areas, the stockpile can be piled on the field with the installation of nutrient runoff control. In higher rainfall areas, a concrete pad and wall are constructed to store solid manure and prevent nutrient runoff from heavy rain.

Carbon and nitrogen compounds in manure are broken down by microbes to $CH_4$, and $N_2O$. The main factors influencing GHG emissions from storage are temperature and storage time. Due to the longer storage time, long-term stockpile solid manure storage generates a significant amount of GHGs. Temporary stack, as a short-term manure storage method, generates less GHGs than the long-term stockpile solid storage. However, it is still necessary to quantitatively delineate the emissions to help animal farms evaluate their manure management operations.

### 4-A.8.2 Composting

Composting is the controlled aerobic decomposition of organic material into a stable, humus-like product (USDA, 2007). Animal manure may be composted in a variety of different systems, including in-vessel systems, windrows, or static piles. In-vessel systems are closed—for example, a rotary drum or box that uses regular movement to ensure proper aeration. The largest composting operations divide up the compost into long heaps for windrow composting or into one large pile for aerated static pile composting. In the former method, proper oxygen flow can be maintained via manual turning or pipe systems; in the latter method, it is maintained through pipe systems. Composting has become a popular method in some regions to decrease the volume and weight of animal manure and to produce a product that is often more acceptable to farmers as a fertilizer. Furthermore, the heat generated through the composting process can kill parasites, pathogens, and weed seeds found in animal waste, creating a safer product for crop application.

The quantity of GHG emissions is affected by the composting method employed and manure characteristics (carbon, nitrogen, and carbon:nitrogen). To the extent that the rate of GHG formation depends on oxygen saturation in the pore space, aeration method (i.e., forced-air vs. passive/convective) and rate (or turning frequency) will affect the magnitude of GHG emissions during the composting process.

### 4-A.8.3 Aerobic Lagoons

Aerobic lagoons are artificial outdoor basins that hold animal wastes. The aerobic treatment of manure involves the biological oxidation of manure as a liquid, with either forced or natural aeration. Natural aeration is limited to aerobic lagoons with photosynthesis and is consequently shallow to allow for oxygen transfer and light penetration. These systems become anoxic during low-sunlight periods. Due to the depth limitation, naturally aerated aerobic lagoons have large surface area requirements and are impractical for large operations and subsequently there are few truly aerobic lagoons used for manure treatment.

### 4-A.8.4 Anaerobic Lagoons, Storage Basins, Runoff Holding Ponds, and Storage Tanks

The most frequently used liquid manure storage systems are anaerobic lagoons (in the southern United States), earthen or earth-lined storage basin (in the northern part of the country), runoff holding ponds, and above-grade storage tanks. Anaerobic lagoons are earthen basins that provide an environment for anaerobic digestion and storage of animal waste. Both the American Society of Agricultural and Biological Engineers and USDA's Natural Resources Conservation Service have engineering design standards for construction and operation of anaerobic lagoons. Storage basins collect liquid manure from flush systems, milking parlors, holding areas, etc. with most being earthen basins not specifically designed for manure treatment as are anaerobic lagoons. In most feedlots, a holding pond is constructed to collect runoff for short-term storage. Storage tanks range from lower cost earthen basins to higher cost, glass-lined steel tanks. The manure that enters these systems is usually diluted with flush water, water wasted at stalls, and rainwater.

All of these storage systems (without aeration) are biologically anaerobic lagoons, which means that they have similar potential to produce $CH_4$ and $N_2O$. Due to the large quantity of liquid manure produced in the United States, liquid manure storage can be a major source of GHG emissions from animal operations. In terms of estimation of GHG emissions from anaerobic lagoon/runoff holding pond/storage tanks, these storage systems are classified into four categories:

- Covered storage with a crust formed on the surface
- Covered storage without a crust formed on the surface
- Uncovered storage with a crust formed on the surface
- Uncovered storage without a crust formed on the surface

### 4-A.8.5 Anaerobic Digester With Biogas Utilization

One of the most commonly discussed manure management alternatives for GHG reduction and energy generation is anaerobic digestion. Anaerobic digestion is a natural, biological conversion process that has been proven effective at converting wet organic materials into biogas (approximately 60 percent $CH_4$ and 40 percent $CO_2$). Biogas can be used as a fuel source for engine-generator sets, producing relatively clean electricity while also reducing some of the environmental concerns associated with manure. The digester can be as simple as a covered anaerobic lagoon (Gould-Wells and Williams, 2004) or as sophisticated as a thermophilic or media matrix (attached growth) digester (Cantrell et al., 2008). There are a wide variety of anaerobic digestion configurations, such as continuous stirred tank reactor (CSTR), covered lagoon, plug-flow, temperature phased, upflow anaerobic sludge blanket (UASB), packed-bed, and fixed film. The digestion is also categorized based on culture temperature: thermophilic digestion in which manure is fermented at a temperature of around 55 °C, or mesophilic digestion at a temperature of around 35 °C. Among these technologies, CSTR, plug-flow, and covered lagoon, all under mesophilic conditions, are the most often used methods.

During anaerobic digestion, a group of microbes work together to convert organic matter into $CH_4$, $CO_2$, and other simple molecules. The main advantages of applying anaerobic digestion to animal manures are odor reduction, electricity generation, and the reduction of GHG emissions and manure-borne pathogens. Anaerobic digestion is also an excellent pretreatment process for subsequent manure treatment to remove organic matter and concentrate phosphorus. Considering the small amount of $N_2O$ existing in biogas, $N_2O$ emissions are not estimated for the anaerobic digestion of liquid manure.

The challenges associated with anaerobic digestion relate to initial capital cost, operation, and maintenance and other gases that may be generated (e.g., nitric oxides). The economics relate to access to the electrical grid and sufficient green-electricity offsets to make the operation profitable. Profitable conditions are relatively scarce. Finally, the digester sludge must be managed. Another conversion alternative with energy creation potential is thermochemical conversion (Cantrell et al., 2008). Systems that use thermochemical conversions to syngases, bio-oil, and biochar for electricity and fuel are emerging, but are not yet established.

### 4-A.8.6 Solid–Liquid Separation

Solid–liquid manure separation has been used widely by dairy farms. One purpose of solid–liquid separation is to physically separate and remove the larger solids from liquid manure in order to store and treat them separately. The available commercial methods include gravity sedimentation and mechanical separation (with or without coagulation flocculation). Sedimentation and mechanical separation without coagulation flocculation are the most popular methods used by animal farms. GHG emissions from the operation are minimal; however, separation has an impact on nutrient distribution in separated solid and liquid manure, which will influence GHG emissions from the next stage of manure storage and treatment for solid and liquid manure. The separated liquid manure is treated as the influent for the next step of storage and treatment operations.

# Appendix 4-B: Method Documentation

The following provides the rationale for the chosen method as well as any additional technical documentation not provided in the chapter. For the following documentation sections, uncertainty guidance may include a range. To assign an appropriate uncertainty to a given parameter consider that uncertainty depends on the availability of "reliable and representative survey data that differentiates animal populations by system usage" (IPCC, 2006). IPCC (2006) notes that "[a]ccurate and well-designed emission measurements from well [characterized] types of manure and manure management systems can help reduce these uncertainties further." Volume I, chapter 3 of IPCC (2006) describes how to elicit expert judgement on uncertainty.

## 4-B.1 Enteric Methane Emissions From Dairy Cattle

### 4-B.1.1 Rationale for Methods

There are many equations available in the scientific literature to estimate enteric $CH_4$ emissions from lactating dairy cows and nonlactating dairy cows and heifers. The methods selected here represent the most accurate empirical equations derived from recent meta-analyses of individual animal records (lactating cows) or published treatment means (nonlactating cows, heifers) in the United States. The most accurate equations for lactating cows, nonlactating (dry) cows, and heifers in these publications were selected by evaluating the root mean square prediction error (RMSPE) to assess prediction accuracy and other available model performance indicators to assess bias. The use of the empirical equations by Niu et al. (2018) and Moraes et al. (2014) is recommended over the IPCC Tier 2 equation (IPCC, 2019) to estimate enteric $CH_4$ emissions because they were derived with individual animal records from studies conducted in the United States.

### 4-B.1.2 Technical Documentation

Additional technical documentation and discussion of uncertainty for dairy cattle is provided below.

Uncertainties in the parameters for the lactating cows are given in equation 4B-1. USDA hopes to prioritize filling this gap in the next version of the report. Uncertainties in parameters for the nonlactating cows are given in equation 4B-2, and for dairy heifers in equation 4B-3. The available information does not quantify all uncertainty associated with GEI used in the calculation for the nonlactating cows and dairy heifers.

Use the explicit model-based method to estimate uncertainty for dairy cattle enteric fermentation (see chapter 8). Uncertainty is assumed to be minor for the management activity data provided by the entity, and therefore the values are assumed to be certain. Uncertainties in parameters are propagated through the calculations using a Monte Carlo simulation. See chapter 8 for more information about the explicit model-based method.

***Estimating Enteric Methane Emissions From Lactating Cows***

Niu et al. (2018) developed various equations to estimate $CH_4$ emissions from enteric fermentation in lactating dairy cows using 1,084 individual dairy cow records from 45 studies conducted in the United States with primarily Holsteins (91 percent) and Jerseys (9 percent). The $CH_4$ emissions equation for lactating cows (Niu et al., 2018) contained the most prediction variables and had the highest prediction accuracy, as indicated by the lowest RMSPE.

**Equation 4B-1: Quantifying Uncertainty for Enteric Fermentation $CH_4$ Emissions From Lactating Cows**

$$CH_4 = -126 + 11.3 \times DMI + 2.30 \times NDF + 28.8 \times MF + 0.148 \times BW$$

Where:

| | | |
|---|---|---|
| Intercept | = | 126 |
| Parameter for *DMI* | = | 11.3 |
| Parameter for *NDF* | = | 2.30 |
| Parameter for *MF* | = | 28.8 |
| Parameter for BW | = | 0.148 |

The explicit model-based method requires a covariance matrix for joint probability draws from the model parameters and intercept, along with the random effects for the Monte Carlo simulation. Use expert judgement or elicit expert judgement for uncertainties.

### *Estimating Enteric Methane Emissions From Nonlactating (Dry) Cows and Dairy Heifers*

Moraes et al. (2014) developed $CH_4$ emissions prediction equations from individual animal records from 62 studies conducted in the United States as follows: 591 Holstein and Jersey nonlactating cow records, and 414 Holstein, Angus, Hereford, and Angus-Hereford cross heifers. The $CH_4$ emissions equations for nonlactating cows and heifers that had the lowest RMSPE and highest prediction accuracy were the simple models based on GEI.

**Equation 4B-2: Quantifying Uncertainty for Enteric Fermentation $CH_4$ Emissions From Nonlactating Cows**

$$CH_{4,MJ} = 2.381 + 0.053 \times GEI$$

Where:

| | | |
|---|---|---|
| Intercept | = | 2.381 |
| Parameter for *GEI* | = | 0.053 |

The explicit model-based method requires the following standard deviations associated with the model parameter and intercept for the Monte Carlo simulation:

| | Intercept |
|---|---|
| **Intercept** | 0.153 |
| ***GEI*** | 0.001 |

### *Estimating Enteric Methane Mitigation by Feeding 3-NOP, Nitrate, and Lipid Supplementation in Dairy Cattle*

The strategies for mitigating enteric $CH_4$ emissions from dairy cattle and the methods to calculate the magnitude of the reduction were selected based on the availability of meta-analyses that quantitatively evaluated explanatory variables that explain the heterogeneity quantitative effects and their variation in the $CH_4$ mitigation response for each mitigant (Dijkstra et al., 2018; Feng et al., 2020). Only the mitigants that reduced enteric $CH_4$ emissions significantly (more than a 10 percent reduction) without decreasing animal productivity are recommended.

**Equation 4B-3: Quantifying Uncertainty for Enteric Fermentation $CH_4$ Emissions From Dairy Heifers**

$$CH_{4,MJ} = 1.289 + 0.051 \times GEI$$

Where:

Intercept = 1.289

Parameter for *GEI* = 0.051

The explicit model-based method requires the following standard deviations associated with the model parameter and intercept for the Monte Carlo simulation:

| | Intercept |
|---|---|
| **Intercept** | 0.185 |
| ***GEI*** | 0.001 |

## 4-B.2 Enteric Methane Emissions From Beef Cattle

### 4-B.2.1 Rationale for Method

There are many equations available in the scientific literature to estimate enteric $CH_4$ emissions from beef cattle. The diets of beef cattle are highly variable, so the most appropriate method depends heavily on diet and cattle type (cows, replacement heifers, stockers, feedlot cattle).

The methods used for cows and stockers are those used by IPCC. This chapter presents a modified IPCC method for feedlot cattle, which is more representative than other available methods such as equations derived from recent meta-analyses of beef cattle studies in the United States and Canada. Most available equations do not have a correction for grain type or grain processing method, both of which have significant effects on enteric $CH_4$ production. Based on our evaluation, the model developed for feedlot cattle had the highest prediction accuracy as indicated by the lowest standard error of the estimate ($S_{yx}$) and greatest Lin's concordance coefficient.

The most recent Nutrient Requirements of Beef Cattle (NASEM, 2016) recommend the use of up to five empirical equations to estimate $CH_4$ emissions of feedlot cattle (IPCC, 2006; Ellis et al., 2007, 2009; Escobar et al., n.d.). Ellis et al. (2009) reported that several equations appeared to be good predictors of enteric $CH_4$ losses by feedlot cattle fed barley-based diets in Canada. However, many of those equations tend to greatly overestimate enteric $CH_4$ losses when compared with data from cattle fed more typical U.S.-style finishing diets based on corn (Hales et al., 2012, 2013; Todd et al., 2014a, 2014b). Kebreab et al. (2008) reported that MOLLY and IPCC Tier 2 (2006) gave predicted values similar to measured values with feedlot cattle, but there was a large variability in individual animals, with errors of 75 percent or greater. Kebreab et al. (2008) noted the average $Y_m$ (MJ enteric $CH_4$/MJ GEI) for feedlot cattle based on experimental data was 3.88 percent (range 3.36 to 4.56), which was higher than the IPCC (2006) value of 3.0 percent and the values with typical Southern Great Plains finishing diets of 2.85 to 3.03 percent (Hales et al., 2012, 2013; Todd et al., 2014a; 2014b). The more recent IPCC guidance (IPCC, 2019) recommends a $Y_m$ of 3.9 for feedlot diets based on dry-rolled corn or barley and 3.0 for diets based on steam-flaked corn. The purpose of the current model/decision tree was not to estimate $CH_4$ inventories, but to estimate the effects that changes in diet and management have on $CH_4$ emissions by cattle.

### *Calculating Gross Energy Requirements*

The equations selected for estimating gross energy requirements and feed intake of grazing and feedlot cattle were chosen from those preferred in the NASEM (2016).

## 4-B.2.2 Technical Documentation

### *Uncertainty Discussion*

The uncertainty of Tier 2 $Y_m$ values for grazing and feedlot beef cattle reported by IPCC (2019) was ±20 percent. The uncertainty for total U.S. enteric fermentation emissions reported by the U.S. EPA (2020) was -11 to +18 percent.

The method presented for feedlot beef cattle enteric $CH_4$ emissions appears to be as accurate or more accurate than the equations proposed by NASEM (2016) or the IPCC (2019) $Y_m$ values of 3.0 and 3.9 percent. If the uncertainty is calculated as the standard error divided by the mean, the uncertainty of these estimates would range from 30 to 45 percent. However, the proposed uncertainty of IPCC (2019) $Y_m$ values is ±20 percent. Because the proposed model appears to be more representative of U.S. values than the IPCC (2019) $Y_m$ values, the uncertainty of ±20 percent is recommended.

### *Model for Adjusted Feedlot $Y_m$*

Currently, the IPCC (2019) Tier 2 model may be the easiest method for estimating $CH_4$ emissions from feedlot beef cattle. Unfortunately, the Tier 2 method does not allow for estimating changes in enteric $CH_4$ emissions related to changes in diet or management. A modified Tier 2 IPCC (2006, 2019) method is recommended to estimate enteric $CH_4$ emissions from beef cattle fed high concentrate finishing diets. The $CH_4$ conversion factor ($Y_m$) is adjusted by factors in the animals' diets as described in section 4.2.2.1. A baseline scenario, based on typical U.S. beef cattle feeding conditions, is established, and the $Y_m$ values are adjusted based on published research. Emission values are modified using correction factors that are based on changes in animal management and feeding conditions from the baseline scenario.

We used a $Y_m$ of 3 percent as the baseline value, as recommended by the IPCC (2006, 2019) estimates and supported by Todd et al. (2014a), who measured $CH_4$ emissions from a feedyard in the Texas Panhandle at which cattle were fed diets similar to the presented "baseline" scenario.

To evaluate the feedlot cattle $Y_m$ adjustment model, a dataset consisting of 33 studies and 99 to 105 treatment means was developed. The authors evaluated the model by comparing the proposed model to models adjusted for baseline $Y_m$ (2, 3, 3.5, or 4 percent of GEI), effect of fat supplementation (2, 4, or 6 percent per 1 percentage unit increase in dietary fat content), effect of steam flaking grain (10, 20, or 30 percent), dietary starch:NDF adjustment (0.30, 0.45, or 0.60 units), and monensin adjustment (0.12 or 0.30 percentage units). Predicted $Y_m$ and daily enteric $CH_4$ production (g/day) were compared to actual values using linear regression with and without a Y intercept and Lin's concordance correlation (Lin, 1989). In general, the adjustments tested had only minor effects on $r^2$ and standard error of the estimate ($S_{yx}$).

The regressions of predicted vs. actual $Y_m$ and predicted vs. actual $CH_4$ (g/day) are as follows:

$$\text{Predicted } Y_m = 3.41(\pm 0.22) + 0.261(\pm 0.049) \times \text{actual } Y_m \; (r^2 = 0.214, S_{yx} = 0.69)$$

$$\text{Predicted } Y_m = 0.972(\pm 0.026) \times \text{actual } Y_m \; (r^2 = 0.928, S_{yx} = 1.24)$$

$$CH_4 \text{ (g/day)} = 18.49(\pm 10.98) + 1.232(\pm 0.097) \times \text{actual } CH_4 \text{ (g/day)} \; (r^2 = 0.631, S_{yx} = 39.3)$$

$CH_4$ (g/day) = 1.385(±0.036) × actual $CH_4$ (g/day) ($r^2$ = 0.940, $S_{yx}$ = 39.71)

These equations compare to the following regression analysis of the enteric $CH_4$ prediction equations recommended by NASEM (2016) for high-concentrate beef cattle diets:

Escobar et al. (n.d.): predicted $CH_4$ (g/day) = -24.63(± 13.32) + 1.798(± 0.133) × actual $CH_4$ (g/day) ($r^2$ = 0.655, $S_{yx}$ = 45.00)

Ellis et al. (2007), equation 9b: predicted MJ/d = -1.978(±1.073) + 3.494(±0.470) × actual MJ/day ($r^2$ = 0.363, $S_{yx}$ = 1.85)

Ellis et al. (2007), equation 10b: predicted MJ/d = 1.514(±0.499) + 0.961(± 0.103) × actual MJ/day ($r^2$ = 0.474, $S_{yx}$ = 1.682)

Ellis et al. (2009), equation G: predicted MJ/d = 2.189(±0.416) + 0.673(±0.069) × actual MJ/day ($r^2$ = 0.493, $S_{yx}$ = 1.651)

The predicted versus actually determined values for the proposed model and the equations proposed by NASEM (2016) are presented in table 4B-1.

**Table 4B-1. Actual vs. Predicted Enteric $CH_4$ Emissions From Feedlot Beef Cattle Using the Proposed Model and Four Equations Proposed by NASEM (2016)**

| Equation | Units | Actual | Predicted |
|---|---|---|---|
| Proposed model | g/d | 137.7±54.8 | 148.0±64.1 |
| Proposed model | % of gross energy | 4.36±1.38 | 4.55±0.78 |
| Escobar et al. (unpublished) | g/d | 137.7±54.8 | 93.66±34.41 |
| Ellis et al. (2007), equation 9b | MJ/d | 7.69±3.07 | 2.246±0.401 |
| Ellis et al. (2007), equation 10 | MJ/d | 7.69±3.07 | 4.534±1.662 |
| Ellis et al. (2009), equation G | MJ/d | 7.69±3.07 | 5.469±2.420 |

The Lin's concordance statistics for the new model and the NASEM (2016) equations are as follows. In some cases, the extant NASEM (2016) equations appeared to be equal to or better than the proposed model. This may be due in part to the fact that some of the data used in the testing dataset were also used in the development dataset for those models.

**Table 4B-2. Lin's Concordance Statistics for the Proposed Feedlot Beef Cattle Model and Four Models Proposed by NASEM (2016)**

| Statistic | This Model ($Y_m$) | This Model ($CH_4$, g/day) | Escobar (g/day) | Ellis Eq. 9b (MJ/day) | Ellis Eq. 10b (MJ/day) | Ellis Eq. G (MJ/day) |
|---|---|---|---|---|---|---|
| r | 0.464 | 0.794 | -0.15 | 0.608 | 0.692 | 0.706 |
| CCC | 0.390 | 0.549 | -0.002 | 0.060 | 0.538 | 0.695 |
| Lower CI | 0.249 | 0.448 | -0.004 | 0.038 | 0.418 | 0.577 |
| Upper CI | 0.515 | 0.637 | 0.005 | 0.083 | 0.639 | 0.785 |
| $r^2$ | 0.215 | 0.631 | 0.024 | 0.370 | 0.479 | 0.498 |
| Location shift | 0.182 | 0.834 | 13.26 | -3.77 | -0.68 | -0.17 |
| Scale shift | 0.562 | 1.552 | 26.15 | 0.175 | 0.72 | 1.05 |
| $C_b$, bias feature | 0.843 | 0.692 | 0.010 | 0.010 | 0.776 | 0.985 |

### *Effect of Ionophores Adjustment*

The published effects of ionophores such as monensin on enteric $CH_4$ emissions have been somewhat inconsistent. Tedeschi et al. (2003), McGinn et al. (2004), Guan et al. (2006), and Hemphill et al. (2018) suggested that monensin decreased $CH_4$ emissions from 5 to 20 percent during the first 4 weeks of feeding, but that the effect was transient and lasted only about 30 days. However, a meta-analysis by Appuhamy et al. (2013) reported that monensin decreased $Y_m$ of beef cattle about 0.3 units (14–19 g $CH_4$/d) and that the effect did not significantly change over the 15- to 180-day feeding periods. Therefore, the authors assumed monensin decreased the $Y_m$ of finishing beef cattle by 0.3 units.

### *Effect of Dietary Fat Concentration Adjustment*

Increased dietary fat concentration tends to decrease enteric $CH_4$ emissions from 3.8 to 5.6 percent for each percentage unit increase in dietary fat concentration (Beauchemin et al., 2008; Martin et al., 2010; Zinn and Shen, 1996). Lovett et al. (2003) reported that total daily $CH_4$ emissions decreased from 0.19 to 0.12 kg/animal daily (reported as 260 vs. 172 L $CH_4$/head daily, or 6.6 vs. 4.8 percent of GEI) from steers fed diets containing 0 or 350 grams of coconut oil, respectively. The effect was consistent across various forage concentrations (65:40 and 10 percent of dry matter). More recently Hales et al. (2017b) noted a linear decrease in enteric $CH_4$ emissions (i.e., $Y_m$) of finishing beef cattle (decreased from 3.39 to 2.23 percent; about 5.7 percent/percent added fat) in cattle fed finishing diets that contained 0, 2, 4, and 6 percent added corn oil. Many byproduct feeds such as distillers grains contain relatively high concentrations of fat (generally as corn oil) and this fat may be partially protected from ruminal biohydrogenation (Corrigan et al., 2009; Vander Pol et al., 2009); however, the fat in distillers grains is assumed to have the same effect on enteric $CH_4$ as added corn oil/fat. This assumption is supported by the studies of Hunerberg et al. (2013, 2014) and McGinn et al. (2009) who reported about a 6.7-percent decrease in enteric $Y_m$ for each percentage unit increase in dietary total fat added by distillers grains. Hunerberg et al. (2014) suggested that the maximum effect of fat on $Y_m$ of beef cattle was limited to a 12-percent decrease. In addition, cattle have a low tolerance for dietary lipids; therefore, dietary concentrations are generally kept below 8 percent total fat. The authors opted to use the conservative estimate of a 4-percent increase in enteric $CH_4$ for each 1-percent decrease in dietary fat below the baseline values of 3 percent added fat and 6 percent total fat and assumed adding fat above the 6 percent total fat baseline did not affect enteric $CH_4$ production any further.

### *Dietary Grain Source and Processing Method Adjustment*

There are few studies comparing the enteric $CH_4$ production of cattle fed high concentrate diets based on different grain sources and different gain processing methods. Based on the rumen stoichiometry of Wolin (1960), Zinn and Barajas (1997) estimated that $CH_4$ emissions per unit of glucose fermented in the rumen would decrease with increasing grain processing intensity. Hales et al. (2012) reported that cattle fed diets based on steam-flaked corn had enteric $CH_4$ production that was 20 percent lower than cattle fed diets based on dry-rolled corn. This relationship was consistent when diets contained 0 and 30 percent wet distillers grains with solubles (WDGS). Archibeque et al. (2006) noted a similar difference between $CH_4$ production of cattle fed dry-rolled corn and high-moisture corn finishing diets. In contrast, Hales et al. (2015b) reported no difference in $CH_4$ production of finishing cattle fed diets based on dry-rolled corn or high-moisture corn. However, the starch digestibility of the high-moisture corn was very low in the study by Hales et al. (2015b), suggesting the high-moisture corn was not representative of high-moisture corn in the industry. Therefore, the authors assumed cattle fed high moisture corn-based diets would have enteric $Y_m$ similar to cattle fed steam-flaked corn-based diets. In addition, because steam flaking has little effect on digestibility of barley (Owens et al., 1997) the authors assumed that steam flaking would not affect enteric $Y_m$ of finishing cattle fed barley-based diets. Because some producers use blends of grain processed in different manners the authors assumed that any steam flaking effects should be based on the proportion (percent of the grain) that is steam flaked.

Enteric $CH_4$ emissions are 20 to 40 percent greater with finishing diets that are based on barley rather than corn, probably because of the differences in fiber content between the grains (Benchaar et al., 2001; Beauchemin and McGinn, 2005). In the USDA-OCE (2014) model, the authors assumed a mean increase of 30 percent in enteric $Y_m$ when barley replaced corn as the grain source in the diet. However, in the revised model the effect of barley replacement is considered in the starch:NDF ratio of the diet, so the effect of barley is not adjusted directly.

***Dietary Starch:NDF Ratio Adjustment***

It is well established that increasing fiber content of ruminant diets tends to increase $Y_m$, whereas increasing the starch content tends to decrease $Y_m$. Little data exists to evaluate the effects of diet forage content on $Y_m$ in high-concentrate finishing diets. The authors of the 2014 model (USDA 2014) developed a correction factor for dietary concentrate content based on equations of Ellis et al. (2007, 2009). In this new model, the authors chose to base the correction factor on the starch:NDF ratio of the diet. In feedlot finishing diets, the fiber (i.e., NDF) and starch content of diets can be modified by replacing corn with barley, replacing grain with forage, or replacing grain with high-fiber grain-based byproducts such as WDGS (Samuelson et al., 2016). Limited data exists to evaluate effects of dietary barley, forage, WDGS, and grain concentrations or their ratios on enteric $CH_4$ production from beef cattle that are fed typical U.S.-based, high-concentrate finishing diets. Therefore, the authors developed a dataset consisting of 4 published studies (Beauchemin and McGinn, 2005; Hales et al., 2012, 2013, 2014) and 14 treatment means. In these studies, the dietary starch:NDF ratio was modified by replacing corn with either barley (Beauchemin and McGinn, 2005) or forage (Hales et al., 2014), by changing the roughage source (barley vs. corn silage: Beauchemin and McGinn, 2005), or by replacing a portion (0 to 45 percent) of the corn with WDGS (Hales et al., 2012, 2013). In all studies dietary fat concentrations were equalized across treatments. Simple linear regression was performed to determine the effects of forage percentage, dietary NDF percent, dietary starch percent, and the starch:NDF ratio on the $Y_m$. The equation for dietary NDF concentration had the greatest $r^2$ (0.72) and lowest $S_{yx}$ (0.432), followed closely by the starch:NDF ratio ($r^2 = 0.66$ and $S_{yx} = 0.47$). Because the dietary NDF concentration is confounded by simultaneous changes in dietary starch content, the authors felt the starch:NDF ratio was more biologically explainable, and thus the starch:NDF ratio was selected. The equation developed was as follows:

$$Y_m = 4.514\ (\pm 0.472) - 0.453\ (\pm 0.148) \times starch{:}\,NDF$$

Therefore, the authors assumed that $Y_m$ changed 0.453 units for each unit change in the starch:NDF ratio.

## 4-B.3 Enteric Methane Emissions From Sheep

### 4-B.3.1 Rationale for Method

The following subsections describe the rationale for the methodologies presented within the chapter for sheep. In terms of uncertainty, IPCC continues to recommend the use of IPCC 2006 Tier 1 uncertainty ranges as defined in IPCC (2019), IPCC section 10.3.4.

#### *Estimating Enteric Methane Emissions From Sheep*

Howden et al. (1994) generated an equation from which to predict $CH_4$ emissions from sheep, included in this chapter as equation 4-13. This equation resulted from a linear extrapolation of DMI to emissions. It has since been evaluated, found to be robust, and selected by the Australian National GHG Inventory. Klein and Wright (2006) measured $CH_4$ from sheep in respiration chambers and compared their results to the Howden equation. Actual $CH_4$ averaged 1.1 g/head (standard error ± 0.05) and predicted $CH_4$ was 1.1 g/head (standard error ± 0.02). A potential concern about the Howden equation is that much of the data included in the analysis was based on tropical forages.

Nonetheless, when intake data are available, the Howden equation presents the best method by which to estimate sheep enteric $CH_4$ emissions.

#### *Estimating Enteric Methane Emissions From Sheep If Intake Is Not Known*

If there is no intake data available, the revised (IPCC, 2019) equations can be used. The revision considers new data submitted from New Zealand and Australia that results from measurements from sheep housed in respiration calorimetry chambers.

## 4-B.4 Enteric Methane Emissions From Swine

Due to the small amount of enteric $CH_4$ emissions generated from swine and a lack of data for estimating Tier 2 emission factors, the authors recommend using the IPCC Tier 1 methodology.

In terms of uncertainty, for swine, the recommended $CH_4$ estimation methods for emissions from enteric fermentation are based on the IPCC Tier 1 approach, which has an uncertainty of ±30 to 50 percent.

## 4-B.5 Enteric Methane Emissions From Goats

The proposed method is the best option for calculating emissions at the entity level. These data came from an analysis of 65 studies in which $CH_4$ emissions were measured or calculated. Many of the studies were from areas of the world that manage goats very differently than in the United States. Nonetheless, the compiled $Y_m$ value, 5.5 ± 1.0 percent is not much different than $Y_m$ values from measurements conducted in the United States.

In terms of uncertainty, for goats, the recommended estimation methods for enteric $CH_4$ emissions are based on the IPCC Tier 1 approach, which has an uncertainty of ±30 to 50 percent.

## 4-B.6 Enteric Methane Emissions From American Bison

The U.S. EPA uses IPCC Tier 1 methodologies to estimate bison emissions (U.S. EPA, 2020), and currently Tier 1 is the best option to estimate enteric $CH_4$ emissions for bison. Galbraith et al. (1998) measured enteric $CH_4$ from growing bison (n=5) fed alfalfa pellets in the winter–spring (February–March) and spring (April–May) using respiration calorimetry chambers. The bison produced an average of 86.4 g/day (6.6 percent GEI). Using a detailed method of calculation to estimate historical bison emissions, Kelliher and Clark (2010) estimated that grazing bison would produce 72 kg $CH_4$/year or 197 g $CH_4$/day. Hristov (2012) estimated present day bison produce 21 g $CH_4$/kg DMI/day, eat about 12.8 kg DM/day, and produce 268 g $CH_4$/day. The differences between these estimates result from differences in animal weights, DMI, limited measurements of bison emissions, and assumed MCFs.

In terms of uncertainty, for American bison the recommended estimation methods for enteric $CH_4$ emissions are based on the IPCC Tier 1 approach, which has an uncertainty of ±30 to 50 percent.

## 4-B.7 Enteric Methane Emissions From Other Animals (Deer, Llamas, Alpaca, Elk)

Currently the IPCC Tier 1 methodology is the best option to estimate enteric $CH_4$ emissions from llamas, alpaca and deer. Galbraith et al. (1998) measured enteric $CH_4$ from white-tailed deer (n=8) fed alfalfa pellets in the winter–spring (February–March) and spring (April–May) using respiration calorimetry chambers. The deer produced an average of 23.6 g/day $CH_4$ (3.3 percent GEI). The New Zealand Ministry for the Environment (2010) uses a factor of 6.4 percent of GEI to predict enteric $CH_4$ emissions from farmed red deer and projects an emission rate per year of 23.7 kg $CH_4$/head/year. The values used to make these calculations are from measurements of deer $CH_4$ emissions using the $SF_6$ tracer method. Elk, white-tailed, and mule deer enteric $CH_4$ emissions were estimated by Hristov (2012) to be 86.4, 16, and 17 g $CH_4$/head/day respectively.

In terms of uncertainty, for llamas, alpacas, and managed wildlife (including deer), the recommended estimation methods for enteric $CH_4$ emissions are based on the IPCC Tier 1 approach, which has an uncertainty of ±30 to 50 percent.

## 4-B.8 Housing and Manure Management Emissions

### 4-B.8.1 Rationale for Methods

The rationale for housing and manure management method section is presented below in table 4B-3.

**Table 4B-3. Housing and Manure Management Emission Methodology Documentation**

| Housing and Manure Management Parameters | Recommended Method |
|---|---|
| Estimating $CH_4$ Emissions From Freestall Dairy Barn Floors | The only published equation for estimating $CH_4$ emissions from barn floors was developed by Chianese et al. (2009). |
| $CH_4$ Emissions From Housing and Manure Storage | The IPCC (2019) equation for estimating $CH_4$ emissions from manure in housing and storage was used. |
| Daily VS Excretion Rates | The IPCC (2019) equation for estimating VS excretion was used. |
| $N_2O$ Emissions From Housing | The IPCC (2019) equation for estimating $N_2O$ emissions from manure in housing and storage was used. |
| Total Nitrogen Entering Manure Storage and Treatment | Total N entering manure is based on professional judgment regarding N losses from housing and ammonia emissions data developed for a variety of housing in the United States (Koelsch and Stowell, 2005) |
| Nitrogen Excretion From Lactating Cows | The equation by Bougouin et al. (2022) is based on a current meta-analysis and has performed well for lactating cows in the United States. |
| Nitrogen Excretion From Nonlactating Cows and Heifers | Equation by Reed et al. (2015) represents the most up to date estimates for N excretion. The simpler equation based on nitrogen intake developed by Reed et al. (2015) to predict total manure nitrogen in heifers and nonlactating cows consistently outperformed more complex equations. |

| Housing and Manure Management Parameters | Recommended Method |
|---|---|
| Nitrogen Excretion From Feedlot Cattle | Equation by Dong et al. (2014) represents the most up to date estimates for N excretion.<br>When feed intake is unknown, the equation for DMI as a percent of body weight and kg/day by Anele et al. (2014), and subsequently NASEM (2016), are the most complete estimate. |
| Monthly Beef Feedlot $NH_3$ Emissions | The equation by Todd et al. (2013) is based on empirical data collected on farm and is the most robust estimation. |
| Nitrogen Excretion From Swine | The IPCC (2019) equation for estimating N excretion was used. |
| Nitrogen Excretion From Growing Pigs | The IPCC (2019) equation for estimating N excretion was used. |
| Nitrogen Excretion From Breeding Sows | The IPCC (2019) equation for estimating N excretion was used. |
| Nitrogen Excretion From Poultry Produced for Meat | The IPCC (2019) equation for estimating N excretion was used. |
| Nitrogen Excretion From Egg Laying Poultry | The IPCC (2019) equation for estimating N excretion was used. |
| IPCC Tier 2 Approach for Estimating $N_2O$ Emissions Manure Storage | The IPCC (2019) equation for estimating $N_2O$ emissions from manure in housing and storage was used. |
| $N_2O$ Emissions From Anaerobic Lagoon, Runoff Holding Ponds, and Storage Tanks | The most readily available option, an EF developed in the United States based on lagoon surface area was used. |
| $CH_4$ Emissions From Anaerobic Digesters | The IPCC (2019) equation for estimating $CH_4$ emissions from anaerobic digesters was used. |

## 4-B.8.2 Technical Documentation

### *Housing Uncertainty*

Current available default values of uncertainty for dairy housing are listed in table 4B-4.

**Table 4B-4. Available Uncertainty Information for Activity and Ancillary Data Used to Estimate Emissions From Dairy Housing**

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Maximum $CH_4$ producing capacities—dairy replacement | $B_0$ | $m^3$ $CH_4$/kg VS | 0.17 | -20 | 20 | IPCC (2019) |
| Maximum $CH_4$ producing capacities—dairy cow | $B_0$ | $m^3$ $CH_4$/kg VS | 0.24 | -20 | 20 | IPCC (2019) |
| VS—dairy replacement | VS | kg/1,000 kg animal mass/day | 9.3 | -20 | 20 | IPCC (2019) |
| VS—dairy cattle | VS | kg/1,000 kg animal mass/day | 9.3 | -20 | 20 | IPCC (2019) |
| MCF—dairy cow | MCF | % | Varies | -30 | 30 | IPCC (2019) |

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Typical $NH_3$ losses from dairy housing facilities—dry lot including housing with barn and lot combination | $NH_3$ loss | % of $N_{ex}$ | 36 | — | — | Bougouin et al. (2016), Hristov et al. (2011), Liu et al. (2017) |
| Typical $NH_3$ losses from dairy housing facilities—barn (natural or mechanical ventilation) | $NH_3$ loss | % of $N_{ex}$ | 15.5 | — | — | Bougouin et al. (2016), Hristov et al. (2011), Liu et al. (2017) |
| Typical $NH_3$ losses from dairy housing facilities—roofed facility (bedded pack, no mix) | $NH_3$ loss | % of $N_{ex}$ | 25 | -60 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from dairy housing facilities—roofed facility (bedded pack, active mix) | $NH_3$ loss | % of $N_{ex}$ | 50 | -86 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from dairy housing facilities—pasture | $NH_3$ loss | % of $N_{ex}$ | 7 | — | — | Voglmeier et al. (2018), Sommer et al. (2019), Adhikari et al. (2020), Fischer et al. (2015) |
| Typical N leaching losses from dairy housing facilities—dry lot including housing with barn and lot combination | N leaching loss | % of $N_{ex}$ | 3.5 | -100 | 100 | IPCC (2019) |
| Typical N leaching losses from dairy housing facilities—barn (natural or mechanical ventilation) | N leaching loss | % of $N_{ex}$ | 0 | — | — | IPCC (2019) |
| Typical $NH_3$ losses from dairy housing facilities—bedded pack (no mix) | N leaching loss | % of $N_{ex}$ | 3.5 | -100 | 100 | IPCC (2019) |
| Typical $NH_3$ losses from dairy housing facilities—bedded pack (active mix) | N leaching loss | % of $N_{ex}$ | 3.5 | -100 | 100 | IPCC (2019) |
| Typical $NH_3$ losses from dairy housing facilities—pasture | N leaching loss | % of $N_{ex}$ | — | — | — | |
| $N_2O$ emission factor for dairy housing facilities—open dry lots | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.02 | -100 | 100 | IPCC (2019) |

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| $N_2O$ emission factor for dairy housing facilities—roofed facility—pit below animal confinement | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.002 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor for dairy housing facilities—roofed facility—bedded pack (no mix) | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.01 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor for dairy housing facilities—roofed facility—bedded pack (active mix) | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.07 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor for dairy housing facilities—roofed facility—compost barn | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.005 | -100 | 100 | IPCC (2019) |

All default values have a triangular distribution.

The authors chose the most accurate empirical equations by evaluating the root mean square error to assess prediction accuracy and other available model performance indicators to assess bias. The corresponding root mean square error and coefficient of determination are 0.121 and 0.62, respectively, for equation 4-27, while the root mean square error and coefficient of determination are 0.44 and 0.88, respectively, for equation 4-28.

Current available default values of uncertainty for beef housing are listed in table 4B-5.

**Table 4B-5. Available Uncertainty Data for Emissions From Beef Cattle Housing**

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Maximum $CH_4$ producing capacities—mature beef cows | $B_0$ | $m^3$ $CH_4$/kg VS | 0.33 | -20 | 20 | IPCC (2019) |
| Maximum $CH_4$ producing capacities—steers (> 500 lbs) | $B_0$ | $m^3$ $CH_4$/kg VS | 0.33 | -20 | 20 | IPCC (2019) |
| Maximum $CH_4$ producing capacities—stockers (all) | $B_0$ | $m^3$ $CH_4$/kg VS | 0.17 | -20 | 20 | IPCC (2019) |
| Maximum $CH_4$ producing capacities—cattle on feed | $B_0$ | $m^3$ $CH_4$/kg VS | 0.33 | -20 | 20 | IPCC (2019) |
| Maximum $CH_4$ producing capacities—cattle | $B_0$ | $m^3$ $CH_4$/kg VS | 0.19 | -20 | 20 | IPCC (2019) |
| VS rate—all beef cattle | VS | kg/1,000 kg animal mass/day | 7.6 | -20 | 20 | IPCC (2019) |
| MCF—beef cattle | MCF | % | Varies | -30 | 30 | IPCC (2019) |

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Typical $NH_3$ losses from beef housing facilities—feedlot/dry lot | $NH_3$ loss | % of $N_{ex}$ | 65 | — | — | Hristov et al. (2011), Liu et al. (2017) |
| Typical $NH_3$ losses from beef housing facilities—bedded pack (no mix) | $NH_3$ loss | % of $N_{ex}$ | 25 | -60 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from beef housing facilities—bedded pack (active mix) | $NH_3$ loss | % of $N_{ex}$ | 60 | -80 | 8 | IPCC (2019) |
| Typical $NH_3$ losses from beef housing facilities—pasture | $NH_3$ loss | % of $N_{ex}$ | 7 | — | — | Voglmeier et al. (2018), Sommer et al. (2019), Adhikari et al. (2020), Fischer et al. (2015) |
| Typical N leaching losses from beef housing facilities—feedlot/dry lot | N leaching loss | % of $N_{ex}$ | 3.5 | -100 | 100 | IPCC (2019) |
| Typical N leaching losses from beef housing facilities—bedded pack (no mix) | N leaching loss | % of $N_{ex}$ | 3.5 | -100 | 100 | IPCC (2019) |
| Typical N leaching losses from beef housing facilities—bedded pack (active mix) | N leaching loss | % of $N_{ex}$ | 3.5 | -100 | 100 | IPCC (2019) |
| Typical N leaching losses from beef housing facilities—pasture | N leaching loss | % of $N_{ex}$ | — | — | — | |
| $N_2O$ emission factor for beef housing facilities—open dry lots | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.02 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor for beef housing facilities—roofed facility—bedded pack (no mix) | $EF_{N2O}$ | kg $N_2O$-N/ kg $N_{ex}$ | 0.01 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor for beef housing facilities—roofed facility—bedded pack (active mix) | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.07 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor for beef housing facilities—roofed facility (compost barn) | $EF_{N2O}$ | kg N2O-N/kg Nex | 0.005 | -100 | 100 | IPCC (2019) |

All default values have a triangular distribution.

Current available default values of uncertainty for GHG emission estimation of swine housing are listed in table 4B-6.

**Table 4B-6. Available Uncertainty Data for Emissions From Swine Housing**

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Maximum $CH_4$ producing capacities—growing swine | $B_0$ | $m^3$ $CH_4$/kg VS | 0.48 | -30 | 30 | IPCC (2019) |
| Maximum $CH_4$ producing capacities—breeding swine | $B_0$ | $m^3$ $CH_4$/kg VS | 0.48 | -30 | 30 | IPCC (2019) |
| VS—growing swine | VS | kg/1,000 kg animal mass | 3.9 | -20 | 20 | IPCC (2019) |
| VS—breeding swine | VS | kg/1,000 kg animal mass | 1.8 | -20 | 20 | IPCC (2019) |
| MCF—swine | MCF | % | Varies | -30 | 30 | IPCC (2019) |
| Nitrogen gain—nursery (4–7 kg) | $N_{gain}$ | kg N/kg BW | 0.031 | | | IPCC (2019) |
| Nitrogen gain—nursery (7–20 kg) | $N_{gain}$ | kg N/kg BW | 0.028 | | | IPCC (2019) |
| Nitrogen gain—grower (20–40 kg) | $N_{gain}$ | kg N/kg BW | 0.025 | | | IPCC (2019) |
| Nitrogen gain—grower (40–80 kg) | $N_{gain}$ | kg N/kg BW | 0.024 | | | IPCC (2019) |
| Nitrogen gain—finisher (80–120 kg) | $N_{gain}$ | kg N/kg BW | 0.021 | | | IPCC (2019) |
| Typical $NH_3$ losses from swine housing facilities—roofed facility (bedded pack, no mix) | $NH_3$ loss | % of $N_{ex}$ | 40 | -75 | 50 | IPCC (2019) |
| Typical $NH_3$ losses from swine housing facilities—roofed facility (bedded pack, active mix), including compost barns | $NH_3$ loss | % of $N_{ex}$ | 65 | -78 | 8 | IPCC (2019) |
| Typical $NH_3$ losses from swine housing facilities—roofed facility (pit under floor) | $NH_3$ loss | % of $N_{ex}$ | 25 | -40 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from swine housing facilities—pasture | $NH_3$ loss | % of $N_{ex}$ | 19 | — | — | Sommer et al. (2019) |
| Typical N leaching losses from swine housing facilities—roofed facility (bedded pack, no mix) | N leaching loss | % of $N_{ex}$ | 3.5 | -100 | 100 | IPCC (2019) |

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Typical N leaching losses from swine housing facilities—roofed facility (bedded pack, active mix), including compost barns | N leaching loss | % of $N_{ex}$ | 3.5 | -100 | 100 | IPCC (2019) |
| Typical N leaching losses from swine housing facilities—roofed facility (pit under floor) | N leaching loss | % of $N_{ex}$ | 0 | — | — | IPCC (2019) |
| Typical N leaching losses from swine housing facilities—pasture | N leaching loss | % of $N_{ex}$ | — | — | — | |
| $N_2O$ emission factor for swine housing facilities—pit storage under confinement | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.002 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor for swine housing facilities—roofed facility—bedded pack (no mix) | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.01 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor for swine housing facilities—roofed facility—bedded pack (active mix) | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.07 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor for swine housing facilities—roofed facility (compost barn) | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.005 | -100 | 100 | IPCC (2019) |

All default values have a triangular distribution.

Current available default values of uncertainty for greenhouse emission estimation of poultry housing are listed in table 4B-7.

**Table 4B-7. Available Uncertainty Data for Emissions From Poultry Housing**

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Maximum $CH_4$ producing capacities—layer poultry | $B_0$ | $m^3$ $CH_4$/kg VS | 0.39 | -15 | 15 | IPCC (2019) |
| Maximum $CH_4$ producing capacities—meat poultry | $B_0$ | $m^3$ $CH_4$/kg VS | 0.36 | -15 | 15 | IPCC (2019) |
| VS—layer poultry | VS | kg/1,000 kg animal mass | 9.4 | -20 | 20 | IPCC (2019) |
| VS—meat poultry | VS | kg/1,000 kg animal mass | 16.8 | -20 | 20 | IPCC (2019) |
| MCF—poultry manure with and without litter | MCF | % | Varies | -30 | 30 | IPCC (2019) |

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Typical $NH_3$ losses from poultry housing—roofed facility—with litter | $NH_3$ loss | % of $N_{ex}$ | 40 | -75 | 50 | Koelsch and Stowell (2005) |
| Typical $NH_3$ losses from poultry housing—roofed facility—without litter | $NH_3$ loss | % of $N_{ex}$ | 48 | -69 | 25 | IPCC (2019) |
| Typical $NH_3$ losses from poultry housing—use of alum or another acidifying agent in litter | $NH_3$ loss | % of $N_{ex}$ | 20 | — | — | Anderson et al. (2020), Eugene et al. (2015), Madrid et al. (2012), and Moore et al. (2008) |

All default values have a triangular distribution.

Current available default values of uncertainty for greenhouse emission estimation of other animal housing are listed in table 4B-8.

**8. Available Uncertainty Data for Emissions From Other Animal Housing**

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Maximum $CH_4$ producing capacities—other animals | $B_0$ | $m^3$ $CH_4$/kg VS | Varies | -15 | 15 | IPCC (2019) |
| MCF—other animals | MCF | % | Varies | -30 | 30 | IPCC (2019) |
| VS—other animals | VS | kg/1,000 kg animal mass | Varies | -20 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from dry lot housing | $NH_3$ loss | % of $N_{ex}$ | Varies | -100 | 100 | IPCC (2019) |

### *Manure Management Uncertainty*

Current default values of uncertainty for temporary and long-term stockpile storage are listed in table 4B-9.

**Table 4B-9. Available Uncertainty Data for Emissions From Solid Storage**

| Parameter | Variable | Data Input Unit | Default Value | Relative Uncertainty Low (%) | Relative Uncertainty High (%) | Data Source |
|---|---|---|---|---|---|---|
| Maximum $CH_4$ producing capacities | $B_0$ | $m^3$ $CH_4$/kg VS | — | -15 | 15 | IPCC (2019) |
| MCF—solid storage | MCF | % | — | -30 | 30 | IPCC (2019) |

| Parameter | Variable | Data Input Unit | Default Value | Relative Uncertainty Low (%) | Relative Uncertainty High (%) | Data Source |
|---|---|---|---|---|---|---|
| $N_2O$ emission factor—storage of solid manure | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.01 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor—solid storage covered/compacted | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.01 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor—solid storage bulking agent added | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.005 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor—solid storage additives | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.005 | -100 | 100 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage of manure (swine, other cattle) | $NH_3$ loss | % of $N_{ex}$ | 45 | -78 | 44 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage of manure (dairy cow) | $NH_3$ loss | % of $N_{ex}$ | 30 | -67 | 33 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage of manure (poultry) | $NH_3$ loss | % of $N_{ex}$ | 40 | -70 | 50 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage of manure (other animals) | $NH_3$ loss | % of $N_{ex}$ | 12 | -58 | 67 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage covered/compacted (swine) | $NH_3$ loss | % of $N_{ex}$ | 22 | -82 | 18 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage covered/compacted (other cattle) | $NH_3$ loss | % of $N_{ex}$ | 22 | -86 | 18 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage covered/compacted (dairy cow) | $NH_3$ loss | % of $N_{ex}$ | 14 | -86 | 21 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage covered/compacted (poultry) | $NH_3$ loss | % of $N_{ex}$ | 20 | -80 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage covered/compacted (other animals) | $NH_3$ loss | % of $N_{ex}$ | 5 | -100 | 40 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage bulking agent added (swine) | $NH_3$ loss | % of $N_{ex}$ | 58 | -81 | 21 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage bulking agent added (other cattle) | $NH_3$ loss | % of $N_{ex}$ | 58 | -86 | 21 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage bulking agent added (dairy cow) | $NH_3$ loss | % of $N_{ex}$ | 38 | -84 | 21 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage bulking agent added (poultry) | $NH_3$ loss | % of $N_{ex}$ | 54 | -81 | 20 | IPCC (2019) |

| Parameter | Variable | Data Input Unit | Default Value | Relative Uncertainty Low (%) | Relative Uncertainty High (%) | Data Source |
|---|---|---|---|---|---|---|
| Typical $NH_3$ losses from solid storage bulking agent added (other animals) | $NH_3$ loss | % of $N_{ex}$ | 15 | -60 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage additives (swine) | $NH_3$ loss | % of $N_{ex}$ | 17 | -82 | 24 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage additives (other cattle) | $NH_3$ loss | % of $N_{ex}$ | 17 | -88 | 24 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage additives (dairy cow) | $NH_3$ loss | % of $N_{ex}$ | 11 | -91 | 27 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage additives (poultry) | $NH_3$ loss | % of $N_{ex}$ | 16 | -81 | 25 | IPCC (2019) |
| Typical $NH_3$ losses from solid storage additives (other animals) | $NH_3$ loss | % of $N_{ex}$ | 4 | -75 | 25 | IPCC (2019) |
| Typical N leaching losses from solid storage of manure | N leaching loss | % of $N_{ex}$ | 2 | — | — | IPCC (2019) |
| Typical N leaching losses from solid storage covered/compacted | N leaching loss | % of $N_{ex}$ | 0 | — | — | IPCC (2019) |
| Typical N leaching losses from solid storage bulking agent added | N leaching loss | % of $N_{ex}$ | 2 | — | — | IPCC (2019) |
| Typical N leaching losses from solid storage additives | N leaching loss | % of $N_{ex}$ | 2 | — | — | IPCC (2019) |

All default values have a triangular distribution.

Table 4B-10 lists confidence intervals for emission factors and input variables for the activity data used for composting, based on IPCC's estimation.

**Table 4B-10. Available Uncertainty Data for Emissions From Manure Composting**

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Maximum $CH_4$ producing capacities | $B_0$ | $m^3$ $CH_4$/kg VS | Varies | -15 | 15 | IPCC (2019) |
| MCF—solid storage—composting | MCF | % | Varies | -30 | 30 | IPCC (2019) |
| $N_2O$ emission factor—composting (in-vessel) | $EF_{N2O}$ | kg $N_2O$-N/kg | 0.006 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor—composting (static pile) | $EF_{N2O}$ | kg $N_2O$-N/kg | 0.01 | -100 | 100 | IPCC (2019) |

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| $N_2O$ emission factor—composting (intensive windrow) | $EF_{N2O}$ | kg $N_2O$-N/kg | 0.005 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor—composting (passive windrow) | $EF_{N2O}$ | kg $N_2O$-N/kg | 0.005 | -100 | 100 | IPCC (2019) |
| Typical $NH_3$ losses from composting (in-vessel) (swine, poultry, and other cattle) | $NH_3$ loss | % of $N_{ex}$ | 60 | -80 | 8 | IPCC (2019) |
| Typical $NH_3$ losses from composting (in-vessel) (dairy cow) | $NH_3$ loss | % of $N_{ex}$ | 45 | -84 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from composting (in-vessel) (other animal) | $NH_3$ loss | % of $N_{ex}$ | 18 | -78 | 17 | IPCC (2019) |
| Typical $NH_3$ losses from composting (static pile) (swine, poultry, and other cattle) | $NH_3$ loss | % of $N_{ex}$ | 65 | -78 | 8 | IPCC (2019) |
| Typical $NH_3$ losses from composting (static pile) (dairy cow) | $NH_3$ loss | % of $N_{ex}$ | 50 | -86 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from composting (static pile) (other animal) | $NH_3$ loss | % of $N_{ex}$ | 20 | -75 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from composting (intensive windrow) (swine, poultry, and other cattle) | $NH_3$ loss | % of $N_{ex}$ | 65 | -78 | 8 | IPCC (2019) |
| Typical $NH_3$ losses from composting (intensive windrow) (dairy cow) | $NH_3$ loss | % of $N_{ex}$ | 50 | -86 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from composting (intensive windrow) (other animal) | $NH_3$ loss | % of $N_{ex}$ | 20 | -75 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from composting (passive windrow) (swine, poultry, and other cattle) | $NH_3$ loss | % of $N_{ex}$ | 60 | -80 | 8 | IPCC (2019) |
| Typical $NH_3$ losses from composting (passive windrow) (dairy cow) | $NH_3$ loss | % of $N_{ex}$ | 45 | -84 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from composting (passive windrow) (other animal) | $NH_3$ loss | % of $N_{ex}$ | 18 | -78 | 17 | IPCC (2019) |

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Typical N leaching losses composting (in-vessel) | N leaching loss | % of $N_{ex}$ | 0 | — | — | IPCC (2019) |
| Typical N leaching losses from composting (static pile) | N leaching loss | % of $N_{ex}$ | 6 | — | — | IPCC (2019) |
| Typical N leaching losses from composting (intensive windrow) | N leaching loss | % of $N_{ex}$ | 6 | — | — | IPCC (2019) |
| Typical N leaching losses from composting (passive windrow) | N leaching loss | % of $N_{ex}$ | 4 | — | — | IPCC (2019) |

All default values have a triangular distribution.

Table 4B-11 lists confidence intervals for emission factors and input variables for the activity data used for aerobic lagoons, based on IPCC's estimation.

**Table 4B-11. Available Uncertainty Data for Aerobic Lagoon Emission Factors**

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| $N_2O$ emission factor—aerobic lagoon—natural aeration | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.01 | -100 | 100 | IPCC (2019) |
| $N_2O$ emission factor—aerobic lagoon—forced aeration | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | 0.005 | -100 | 100 | IPCC (2019) |
| Typical $NH_3$ losses from aerobic lagoon—natural aeration (swine, dairy, and other cattle) | $NH_3$ loss | % of $N_{ex}$ | — | — | — | IPCC (2019) |
| Typical $NH_3$ losses from aerobic lagoon—forced aeration (swine, dairy, and other cattle) | $NH_3$ loss | % of $N_{ex}$ | 85 | -68 | 18 | IPCC (2019) |
| Typical $NH_3$ losses aerobic lagoon—forced aeration (other animals) | $NH_3$ loss | % of $N_{ex}$ | 27 | — | — | IPCC (2019) |
| Typical N leaching losses from aerobic lagoon—natural aeration | N leaching loss | % of $N_{ex}$ | 0 | — | — | IPCC (2019) |

| Parameter | Variable | Data Input Unit | Default Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Typical N leaching aerobic lagoon—forced aeration | N leaching loss | % of $N_{ex}$ | 0 | — | — | — |

All default values have a triangular distribution.

Table 4B-12 lists confidence intervals for emission factors and input variables for the activity data used for liquid manure storage, based on IPCC's estimation.

**Table 4B-12. Available Uncertainty Data for Anaerobic Lagoons, Runoff Holding Ponds, and Storage Tanks Emission Factors**

| Parameter | Variable | Data Input Unit | Estimated Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Anaerobic lagoon, runoff holding ponds, and storage tanks—$N_2O$ emission factor | $EF_{N2O}$ | kg $N_2O$-N/kg $N_{ex}$ | Varies | -100 | 100 | IPCC (2019) |
| Anaerobic lagoon, runoff holding ponds, and storage tanks—MCF | MCF | kg $CH_4$/kg VS | Varies | -100 | 100 | IPCC (2019) |
| Typical $NH_3$ losses from anaerobic lagoon (swine, poultry) | $NH_3$ loss | % of $N_{ex}$ | 40 | -38 | 88 | IPCC (2019) |
| Typical $NH_3$ losses from anaerobic lagoon (dairy, other cattle, and other animals) | $NH_3$ loss | % of $N_{ex}$ | 35 | -43 | 129 | IPCC (2019) |
| Typical $NH_3$ losses from anaerobic digester | $NH_3$ loss | % of $N_{ex}$ | Varies | — | — | IPCC (2019) |
| Typical $NH_3$ losses from liquid/slurry—with natural crust over (swine, dairy cow, other cattle) | $NH_3$ loss | % of $N_{ex}$ | 30 | -70 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from liquid/slurry—with natural crust over (other animals) | $NH_3$ loss | % of $N_{ex}$ | 9 | — | — | IPCC (2019) |
| Typical $NH_3$ losses from liquid/slurry—without natural crust cover (swine, dairy cow, other cattle) | $NH_3$ loss | % of $N_{ex}$ | 48 | -69 | 25 | IPCC (2019) |
| Typical $NH_3$ losses from liquid/slurry—without natural crust cover (poultry) | $NH_3$ loss | % of $N_{ex}$ | 40 | -38 | 88 | IPCC (2019) |

| Parameter | Variable | Data Input Unit | Estimated Value | Lower Uncertainty (%) | Upper Uncertainty (%) | Data Source |
|---|---|---|---|---|---|---|
| Typical $NH_3$ losses from liquid/slurry—with natural cover (other animals) | $NH_3$ loss | % of $N_{ex}$ | 15 | — | — | IPCC (2019) |
| Typical $NH_3$ losses from liquid/slurry—with cover (swine, dairy cow, and other cattle) | $NH_3$ loss | % of $N_{ex}$ | 10 | -70 | 20 | IPCC (2019) |
| Typical $NH_3$ losses from liquid/slurry—with cover (poultry) | $NH_3$ loss | % of $N_{ex}$ | 8 | -38 | 88 | IPCC (2019) |
| Typical $NH_3$ losses from liquid/slurry—with cover (other animals) | $NH_3$ loss | % of $N_{ex}$ | 3 | — | — | IPCC (2019) |
| Typical N leaching | N leaching loss | % of $N_{ex}$ | 0 | — | — | IPCC (2019) |

All default values have a triangular distribution.

Confidence intervals for emission factors and input variables for the activity data used for $CH_4$ leaking from digesters are listed in table 4B-13.

**Table 4B-13. Uncertainty Data for $CH_4$ Leaking From Digesters**

| Parameter | Variable | Data Input Unit | Estimated Value | Lower Uncertainty (%) | Upper Uncertainty (%) |
|---|---|---|---|---|---|
| Digesters with steel or lined concrete or fiberglass digesters with a gas holding system (egg-shaped digesters) and monolithic construction | $EF_{CH4,leakage}$ | % | 2.8 | - 100 | 100 |
| UASB-type digesters with floating gas holders and no external water seal | $EF_{CH4,leakage}$ | % | 5 | - 100 | 100 |
| Digesters with unlined concrete/ ferrocement/brick masonry arched-type gas holding section; monolithic fixed-dome digesters | $EF_{CH4,leakage}$ | % | 10 | - 100 | 100 |
| Other digester configurations | $EF_{CH4,leakage}$ | % | 10 | - 100 | 100 |

Uncertainty based on authors' expert opinion.

# Appendix 4-C: Summary of Research and Data Gaps for Animal Production

This appendix discusses research gaps associated with animal production GHG emissions. The list is not exhaustive: it highlights key gaps, subjects that will need further research or development before there is enough information on them to be included in the methodology.

## 4-C.1 Enteric $CH_4$ Emissions From Ruminants

Better estimates of enteric $CH_4$ emissions from dairy cattle, beef cattle, sheep and goats would require:

- Better diet characterization data and improved estimation of nutrient excretion, at a national level, to move to a Tier 3 approach.
- Improved understanding of dietary and ruminal factors affecting enteric $CH_4$ production in all cattle, including finishing cattle. This fundamental research is needed as a basis for strategies to reduce emissions while not affecting animal health and well-being.
- A more thorough database of enteric $CH_4$ production of cattle grazing native range and other unimproved and improved pastures throughout the year.
- A more complete understanding of the effects of forage quality, forage intake, and supplementation strategies on all groups of cattle, particularly grazing cattle. Understanding the link between plant chemical composition and ruminal fermentation would make it possible to use information about strategic supplementation to reduce emissions.
- Continued refinement and development of $CH_4$ measurement techniques. There are more and more options for scientists and increasingly the methods can enable producers to use the data. More of these methods are going to be needed with carbon trading.

As well as more research in the following areas is needed to refine equations:

- Enteric $CH_4$ production of finishing and dairy cattle, considering dietary factors such as grain processing/starch availability. For ruminants that are fed grains, the form of that supplement can affect $CH_4$ emissions and animal performance and thus the models that are used for inventorying.
- Enteric $CH_4$ production of grazing cattle based on changes in forage quality and management throughout the year. Without this information, the models to predict emissions too fraught with large uncertainties to be useful.
- Methods to measure DMI measurements on pasture or range. These are the foundation of all models, but for many ruminants they are not particularly robust.
- A survey of diets and ingredients currently fed to ruminants. This would make certain that predictions of $Y_m$ are valid and account for inhibitors currently fed.

## 4-C.2 Enteric $CH_4$ Emissions Mitigation

There is a need for enteric $CH_4$ inhibitors and mitigation strategies that are practical, safe, and effective in real-world situations. They must also be consumer-acceptable practices.

In addition, more research for the following is needed to bolster and refine the usability of the mitigation equations:

- Additive effects of using multiple mitigation strategies (e.g., 3-NOP and lipid supplementation). In particular, are the additive reductions cumulative or do factors such as hydrogen accumulation cause the mitigation practices to not meet the full reduction potential.
- The length of time that is both reasonable and physically possible to achieve the reduction potential. Timelines outside of the presented studies are unknown and factors such as rumen bacteria adaption would likely affect reduction potential over time.
- More research quantifying emission reductions from drugs or feed additives (for example, there are few studies on red algae).

## 4-C.3 Manure Storage and Treatment and Housing Emissions

The following information would improve the estimation of housing and manure storage and treatment emissions:

- Better equations to predict manure $CH_4$ and $N_2O$ emissions that take into account dietary factors (nutrient composition, grain and forage processing, etc.) and their effects on the form and degradability of volatile solids (all volatile solids are not the same—starch vs. fiber, undigestible fiber, etc.) and excretion of nitrogen. As diets change, the ability to reflect these changes on GHG generation in housing and manure handling systems is essential to improve on-farm and inventory estimates.
- A national dataset evaluating the effects of dietary factors, climate, and manure handling systems on maximum $CH_4$ production potential ($B_0$) and MCFs. At present, data on $B_0$ are based on very limited and outdated information. In addition, there have been limited data available to determine MCF values across a range of manure types, climate, and storage characteristics. As all housing and manure storage estimates depend heavily on these factors, they are a research priority.
- Better $N_2O$ emission factors for housing and manure management. Data quantifying the effects of diet, manure characteristics, and climate on $N_2O$ emissions, over a range of housing and manure management systems, are very limited. More data are needed to improve these estimates to better quantify on-farm and national emissions.
- More research and updated methodologies to account for methane emissions from digestate from anaerobic digestion. Remaining volatile solids could vary greatly depending on the system and its operation. The maximum methane producing capacity of the digestate is also unknown; research is needed to determine these values.
- While IPCC (2019) offers guidance on indirect $N_2O$ emissions estimates, the authors recognize the uncertainty surrounding this methodology and associated variables. The methods are recommended here to acknowledge that these emissions do occur and would have an impact on an entity's calculated emissions but note that the uncertainty of these estimates are higher and need further research and development. It is expected that future versions of these methods will refine these methodologies.
- Continued research and compilation (meta-analyses) on volatile solids and nitrogen removal from manure through solid-liquid separation. While some data exist, the range of removal is often large and therefore increases the uncertainty on provided default data. In addition, nitrogen removal was not added to this version of the report due to the preferred

methodology not indicating total nitrogen within the system. In addition, the VS loss after housing before additional manure storage and treatment is expected to be minor, though currently is not accounted in the methods (unlike losses to total nitrogen).

- The next version of the report should consider if emissions from belt poultry housing are captured completely within the current methodology. While there will be ammonia emissions, they will likely be less than normal roofed housing as is currently presented in the chapter.
- The emissions from housing and manure storage and treatment do not currently include bedding inputs. The addition of these inputs may be considered for future version of this report.

The following data would improve the estimation of manure management emissions, especially at a larger (e.g., regional or national) scale:

- Characterization of manure management systems in the United States. Reliable data describing the range of manure management systems in the United States, and the amount of manure stored in each system, are scarce. This severely hinders the ability to produce reliable emissions estimates at larger scales such as regions, States, and the entire country.

## 4-C.4 Uncertainty Data Gaps

While there are some known default values (see appendix 5-B), quantifying uncertainty as an implicit, explicit-model, or explicit-measurement based method, as discussed in chapter 8, requires more information than was available for this version of the report. To encourage transparency, USDA noted this gap within the chapter and hopes to prioritize this improvement in the next version of the report.

# Appendix 4-D Background on Management Factors that Do Not Affect $Y_m$

This appendix discusses the background on management factors that do not affect $Y_m$, and subsequently were not included in the baseline scenario but that do affect lifetime GHG emissions of beef cattle. As noted in section 4.2.2, a modified IPCC (2006, 2019) Tier 2 method is proposed to estimate enteric $CH_4$ emissions from finishing beef cattle and established a baseline scenario using typical U.S. beef cattle feeding conditions and set baseline values using published research. To estimate $CH_4$ emissions, emission values are modified using adjustment factors based on changes in animal management and feeding conditions from the baseline scenario. Section 4.2.2.1 and appendix 4-B discuss the background information on the base diet and $Y_m$ adjustment factors. This appendix summarizes several management and dietary factors not included in the $Y_m$ adjustment factors for feedlot cattle that do not affect enteric $CH_4$ emissions but do potentially affect GHG production per unit of beef production.[2]

- **Beta-agonists:** Beta-agonists do not directly affect ruminal fermentation; therefore, no adjustment factor is recommended. Although Hales et al. (2017a) reported that the beta agonist zilpaterol hydrochloride (Zilmax, Merck & Co.) decreased enteric $CH_4$ emissions, possibly due to changes in ruminal rate of passage, Walter et al. (2016) noted no effect of zilpaterol on ruminal $CH_4$ production. However, because of a 4-percent increase in feed efficiency, a 2.5- to 3.5-percent increase in hot carcass weight and an increase in live body weight (Delmore et al., 2010; Elam et al., 2009; Montgomery et al., 2009; Radunz, 2011; Vasconcelos et al., 2008), enteric $CH_4$ emissions per unit of production are decreased when beta-agonists are fed.
- **Melengestrol acetate, or MGA (heifers only):** Feeding MGA (Zoetis, Parsippany, NJ) to heifers does not directly affect enteric $CH_4$ emissions. However, because of a 9-percent increase in the gain:feed ratio (Hill et al., 1988; Kreikemeier and Mader, 2004), enteric $CH_4$ emissions per unit of production decrease when heifers are fed MGA.
- **Direct Fed Microbials (DFM):** Most DFM do not appear to directly affect enteric $CH_4$ emissions, and the effects of DFM on animal performance are somewhat variable (Krehbiel et al., 2003). Therefore, no adjustment factor is recommended for the feeding of DFM.
- **Dietary CP and ruminal degradable protein (RDP):** Dietary CP may affect animal performance and enteric $CH_4$ emissions via effects on ruminal fermentation. However, there is no readily available data on modern feedlot diets with which to compare varying levels of CP and resulting $CH_4$ emissions (Berger and Merchen, 1995; Cole et al., 2006; Gleghorn et al., 2004; Jennings et al., 2018; Robinson and Okine, 2001; Wagner et al., 2010). Therefore, there is no recommended $Y_m$ adjustment factor for dietary protein. However, dietary protein may affect emissions of manure management $N_2O$ emissions and unquestionably affects $NH_3$ emissions (Todd et al., 2005; 2013).
- **Implanting regimens:** Growth-promoting implants do not directly affect enteric $CH_4$ emissions. However, because of an increase in feed efficiency, live body weight, and hot carcass weight (Herschler et al., 1995; Robinson and Okine, 2001; Wileman et al., 2009), enteric $CH_4$ emissions per unit of production decrease when implants are used.

[2] Hence, in evaluating $CH_4$ intensity per unit of production, these factors would have an impact.

- **Ambient temperature:** Cold and hot temperatures may affect enteric $CH_4$ emissions due to effects on feed intake, ruminal digestion, and rate of passage (Young, 1981); however, the actual effects are not clear. Therefore, no adjustment factor for environmental temperature is used. Cold temperatures may decrease $CH_4$, $N_2O$, and $NH_3$ losses from the pen surface.

# Appendix 4-E: Feedstuffs Composition Table

| Feedstuff | DM% | CP% | DE (mcal/ kg) | GE (mcal/ kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] DE (% of GE) | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] GE (mcal/kg) | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Alfalfa *(Medicago sativa)*** | | | | | | | | | | | | | | | |
| Fresh, late vegetative | 21 | 20 | 2.78 | 3.763 | 2.7 | 9.8 | *66.78* | 63 | 67.5 | 4.185 | | | 38.9 | 29 | 7 |
| Fresh, early bloom | 23 | 19 | 2.65 | 3.763 | 3.1 | 9.5 | *63.34* | 60 | 68.4 | 4.204 | | | 40.1 | 36 | 7 |
| Fresh, midbloom | 24 | 18.3 | 2.56 | 3.763 | 2.6 | 8.7 | *61.24* | 58 | 70.4 | 4.200 | | | 46 | 35 | 9 |
| Fresh, full bloom | 25 | 14 | 2.43 | 3.763 | 2.8 | 8.5 | *58.76* | 55 | 74.7 | 4.154 | | | 52 | 37 | 10 |
| Hay, sun-cured, early bloom | 90 | 18 | 2.65 | 3.763 | 3 | 9.6 | *63.72* | 60 | 69.4 | 4.179 | | | 42 | 31 | 8 |
| Hay, sun-cured, midbloom | 90 | 17 | 2.56 | 3.763 | 2.6 | 9.1 | *61.79* | 58 | 71.3 | 4.164 | | | 46 | 35 | 9 |
| Hay, sun-cured, late bloom | 90 | 14 | 2.29 | 3.763 | 1.8 | 7.8 | *55.71* | 52 | 76.4 | 4.131 | | | 52 | 39 | 12 |
| Hay, sun-cured, mature | 91 | 12.9 | 2.21 | 3.763 | 1.3 | 7.5 | *54.18* | 50 | 78.3 | 4.101 | | | 58.8 | 44 | 14 |
| Meal dehydrated, 17% protein | 93.83 | 18.49 | 2.69 | 3.764 | 3.99 | 10.29 | *64.18* | 61 | 67.23 | 4.210 | 5.67 | 2.08 | 46.6 | 35.4 | 7.44 |
| Silage wilted, early bloom | 35 | 17 | 2.65 | | 3.2 | 8.2 | *62.85* | 60 | 71.6 | 4.233 | | | 43 | 33 | 10 |
| Silage wilted, midbloom | 38 | 15.5 | 2.56 | | 3.1 | 7.9 | *60.93* | 58 | 73.5 | 4.217 | | | 47 | 35 | 11 |
| Silage wilted, full bloom | 45 | 14 | 2.43 | | 2.7 | 7.7 | *58.34* | 55 | 75.6 | 4.182 | | | 51 | 38 | 12 |
| Alfalfa cubes | 91.04 | 18.1 | 2.47 | | 2.13 | 11.98 | *61.65* | 56 | 67.79 | 4.036 | | 1.35 | 45.46 | 35.41 | 7.57 |
| **Almond *(Prunus amygdalus)*** | | | | | | | | | | | | | | | |
| Hulls | 89.21 | 5.47 | 2.61 | | 2.8 | 8.29 | *64.97* | 55 | 83.44 | 4.035 | 15.05 | 2.5 | 38.96 | 32.73 | 11.06 |
| **Apple *(Malus spp.)*** | | | | | | | | | | | | | | | |
| Pomace oat hulls added, dehydrated | 89 | 5.1 | 2.47 | | 5.2 | 3.5 | *56.69* | 56 | 86.2 | 4.354 | | 3.98 | 45.56 | 38.72 | 14.85 |
| **Bahiagrass *(Paspalum notatum)*** | | | | | | | | | | | | | | | |
| Fresh | 30 | 8.9 | 2.38 | | 1.6 | 11.1 | *61.38* | 54 | 78.4 | 3.907 | | | 68 | 38 | 7 |
| Hay, sun-cured | 91 | 8.2 | 2.25 | | 2.1 | 6.4 | *54.85* | 51 | 83.3 | 4.118 | | | 72 | 41 | 8 |
| **Bakery** | | | | | | | | | | | | | | | |
| Waste, dehydrated (dried bakery product) | 88.86 | 13.14 | 3.13 | | 10.04 | 4.08 | *66.27* | 89 | 72.74 | 4.705 | 11.2 | 34.03 | 14.98 | 7.87 | 2.59 |
| **Barley *Hordeum vulgare*** | | | | | | | | | | | | | | | |
| Grain | 89.69 | 12.78 | 3.71 | 4.332 | 2.2 | 2.77 | *85.56* | 84 | 82.25 | 4.342 | 10.65 | 56.74 | 18.29 | 7.09 | 1.75 |

| Feedstuff | DM% | CP% | DE (mcal/kg) | GE (mcal/kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] DE (% of GE) | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] GE (mcal/kg) | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grain, Pacific coast | 89 | 10.8 | 3.79 | | 2 | 3.1 | *88.54* | 86 | 84.1 | 4.288 | | | 21 | 9 | |
| Grain screenings | 89 | 13.1 | 3.53 | | 2.6 | 3.4 | *81.42* | 80 | 80.9 | 4.342 | | | | | |
| Hay, sun-cured | 87.99 | 10.95 | 2.65 | | 2.41 | 8.36 | *65.04* | 56 | 78.28 | 4.094 | 10.31 | 5.66 | 56.88 | 33.88 | 4.32 |
| Silage | 33.63 | 12.05 | 2.67 | | 3.47 | 8.65 | *64.53* | 51 | 75.83 | 4.154 | 5.53 | 9.17 | 54.77 | 34.73 | 4.77 |
| Straw | 85.07 | 6.08 | 1.76 | | 1.9 | 7.1 | *43.69* | 40 | 84.92 | 4.046 | | | 71.63 | 50.09 | 5.16 |
| **Bean, navy *(Phaseolus vulgaris)*** | | | | | | | | | | | | | | | |
| Seeds | 89 | 25.3 | 3.7 | | 1.5 | 5.2 | *84.52* | 84 | 68 | 4.392 | 7.03 | 29.27 | 17.77 | 11.96 | 1.8 |
| **Beet, mangel *(Beta vulgaris macrorrhiza)*** | | | | | | | | | | | | | | | |
| Roots, fresh | 11 | 11.8 | 3.53 | | 0.7 | 9.6 | *89.67* | 80 | 77.9 | 3.965 | | | | | |
| **Beet, sugar *(Beta vulgaris altissima)*** | | | | | | | | | | | | | | | |
| Aerial part with crowns, silage | 22 | 13.4 | 2.25 | | 2.8 | 32.5 | *73.27* | 51 | 51.3 | 3.149 | | | | | |
| Pulp, dehydrated | 91.49 | 9.07 | 2.94 | | 1.14 | 6.84 | *72.74* | 74 | 82.95 | 4.062 | 8.55 | 0.93 | 41.33 | 26.35 | 3.94 |
| Pulp, wet | 21..95 | 9.55 | 2.94 | | 0.86 | 8.59 | *74.31* | 72 | 81 | 3.982 | 23.21 | 1.65 | 48.23 | 28.06 | 4.37 |
| Pulp with molasses, dehydrated | 92 | 10.1 | 3.35 | | 0.6 | 6.1 | *82.52* | 76 | 83.2 | 4.080 | | | 44 | 25 | 3 |
| **Bermudagrass *(Cynodon dactylon)*** | | | | | | | | | | | | | | | |
| Fresh | 34.94 | 15.16 | 2.53 | | 2.76 | 8.63 | *61.03* | 60 | 73.45 | 4.164 | | 1.79 | 66.6 | 36.14 | 5.03 |
| Hay, sun-cured | 92.99 | 11.11 | 2.48 | | 1.86 | 7.94 | *61.02* | 46 | 79.09 | 4.085 | 5.8 | 4.78 | 66.98 | 35.65 | 5.41 |
| **Bermudagrass, coastal *(Cynodon dactylon)*** | | | | | | | | | | | | | | | |
| Fresh | 29 | 15 | 2.82 | | 3.8 | 6.3 | *65.53* | 64 | 74.9 | 4.313 | | | | | |
| Hay, sun-cured | 90 | 6 | 2.16 | | 2.3 | 6.6 | *53.05* | 49 | 85.1 | 4.087 | 5.83 | 3.98 | 66.2 | 35.2 | 5.18 |
| **Bluegrass, Canada *(Poa compressa)*** | | | | | | | | | | | | | | | |
| Fresh, early vegetative | 26 | 18.7 | 3.13 | | 3.7 | 9.1 | *73.99* | 71 | 68.5 | 4.247 | | | | | |
| Hay, sun-cured, late vegetative | 97 | 0 | 2.12 | | | | | 48 | 100 | | | | | | |
| **Bluegrass, Kentucky *(Poa pratensis)*** | | | | | | | | | | | | | | | |
| Fresh, early vegetative | 31 | 17.4 | 3.17 | | 3.6 | 9.4 | *75.62* | 72 | 69.6 | 4.210 | | | 55 | 29 | 3 |
| Fresh, mature | 42 | 9.5 | 2.47 | | 3.1 | 6.2 | *59.00* | 56 | 81.2 | 4.198 | | | 73.3 | 36.8 | 6 |
| Hay, sun-cured | 89 | 13 | 2.47 | | 3.5 | 6.6 | *58.21* | 56 | 76.9 | 4.255 | | | 68.83 | 40.4 | |

| | | | | | | | Calculated: Ewan, 1989[a] | | | Calculated: NASEM, 2016[a] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Feedstuff** | **DM%** | **CP%** | **DE (mcal/kg)** | **GE (mcal/kg)** | **EE (%)** | **Ash (%)** | **DE (% of GE)** | **TDN (%)** | **Total $(CH_2O)_n$ (%)** | **GE (mcal/kg)** | **Total Sugars (%)** | **Total Starch (%)** | **NDF (%)** | **ADF (%)** | **Lignin (%)** |
| Hay, sun-cured, full bloom | 92 | 8.9 | 2.12 | | 3.3 | 5.9 | *50.46* | 48 | 81.9 | 4.212 | | | | | |
| **Bluestem *(Andropagon spp.)*** | | | | | | | | | | | | | | | |
| Fresh, early vegetative | 27 | 12.8 | 3 | | 2.8 | 8.9 | *73.17* | 68 | 75.5 | 4.120 | | | | 43.51 | |
| Fresh, mature | 59 | 5.8 | 2.34 | | 2.4 | 5.6 | *56.82* | 53 | 86.2 | 4.131 | | | | | |
| Hay, sun-cured | 89.19 | 6.02 | 2.21 | | 1.35 | 9.7 | *56.93* | 50 | 82.93 | 3.909 | | | 69.71 | 43.32 | |
| **Brewers** | | | | | | | | | | | | | | | |
| Grains, dehydrated | 93.16 | 25.02 | 3.17 | 5.03 | 8.52 | 4.57 | *66.12* | 66 | 61.89 | 4.783 | 3.23 | 5.77 | 52.12 | 25.39 | 6.65 |
| Grains, wet | 25.96 | 28.52 | 3.26 | 5.03 | 9.51 | 4.38 | *66.39* | 66 | 57.59 | 4.895 | 0.5 | 4.81 | 49.99 | 24.32 | 6.74 |
| **Brome *(Bromus spp.)*** | | | | | | | | | | | | | | | |
| Fresh, early vegetative | 34 | 18 | 3.26 | | 3.7 | 10.7 | *78.57* | 74 | 67.6 | 4.170 | | | 47.9 | 31 | 4 |
| Hay, sun-cured, late vegetative | 88 | 16 | 2.65 | | 2.6 | 9.4 | *64.40* | 60 | 72 | 4.136 | 9.85 | 2.64 | 65.92 | 40.29 | |
| Hay, sun-cured, late bloom | 89 | 10 | 2.43 | | 2.3 | 8.4 | *59.97* | 55 | 79.3 | 4.072 | | | 68 | 43 | 8 |
| **Brome, smooth *(Bromus inermis)*** | | | | | | | | | | | | | | | |
| Fresh, early vegetative | 30 | 21.3 | 3.22 | | 4.2 | 10.1 | *75.71* | 73 | 64.4 | 4.271 | | | 47.9 | 31 | 4 |
| Fresh, mature | 55 | 6 | 2.34 | | 2.4 | 6.9 | *57.58* | 53 | 84.7 | 4.080 | | | | | |
| Hay, sun-cured, midbloom | 90 | 14.6 | 2.47 | | 2.6 | 10 | *60.72* | 56 | 72.8 | 4.091 | | | 57.7 | 36.8 | 4 |
| **Buckwheat, common *(Fagopyrum sagittatum)*** | | | | | | | | | | | | | | | |
| Grain | 88 | 12.5 | 3.17 | | 2.8 | 2.3 | *72.27* | 72 | 82.4 | 4.389 | | | | | |
| **Buffalograss *(Buchloe dactyloides)*** | | | | | | | | | | | | | | | |
| Fresh | 46 | 10.3 | 2.47 | | 1.9 | 12.4 | *64.02* | 56 | 75.4 | 3.890 | | 5.49 | 74 | 36 | 6 |
| **Canarygrass, beed *(Phalaris arundinacea)*** | | | | | | | | | | | | | | | |
| Fresh | 27 | 11.6 | 2.65 | | 3.5 | 8.3 | *63.89* | 60 | 76.6 | 4.163 | | | 46.4 | 28.3 | 4 |
| Hay, sun-cured | 91 | 10.3 | 2.43 | | 3.1 | 7.9 | *58.93* | 55 | 78.7 | 4.139 | | | 70.5 | 36.6 | 4 |
| **Canola *(Brassica)*** | | | | | | | | | | | | | | | |
| Grain | 94.72 | 23.9 | 4.81 | | 39.79 | 4.33 | *73.56* | 109.2 | 31.98 | 6.418 | | 1.4 | 28.25 | 21.99 | 6.4 |
| Canola meal | 90.43 | 40.86 | 3.13 | | 7.32 | 7.41 | *64.67* | 71.1 | 44.41 | 4.840 | 8.75 | 1.29 | 30.16 | 21.42 | 8.83 |

| Feedstuff | DM% | CP% | DE (mcal/kg) | GE (mcal/kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | DE (% of GE) | | | GE (mcal/kg) | | | | | |
| **Carrot *(Daucus spp.)*** | | | | | | | | | | | | | | | |
| Roots, fresh | 12 | 9.9 | 3.7 | | 1.4 | 8.2 | *92.29* | 84 | 80.5 | 4.032 | 19.09 | 2.09 | 23.78 | 19.94 | 2.72 |
| **Cassava, common *(Manihot esculenta)*** | | | | | | | | | | | | | | | |
| Tubers, meal | 88 | 2.6 | 3.75 | | 0.8 | 3.3 | *91.88* | 85 | 93.3 | 4.094 | | | | | |
| Tubers, fresh | 37 | 3.6 | 3.53 | | 1 | 3.9 | *86.49* | 80 | 91.5 | 4.095 | | | | | |
| **Cereals** | | | | | | | | | | | | | | | |
| Grain screenings | 90 | 13.4 | 3 | | 4.1 | 6 | *69.61* | 68 | 76.5 | 4.317 | | | | | |
| Grain screenings refuse | 91 | 14.1 | 2.65 | | 4.9 | 9.8 | *63.13* | 60 | 71.2 | 4.212 | | | | | |
| Grain screenings, uncleaned | 92 | 15.1 | 2.87 | | 5.9 | 9.3 | *66.89* | 65 | 69.7 | 4.300 | | | | | |
| **Citrus *(Citrus spp.)*** | | | | | | | | | | | | | | | |
| Pulp, silage | 21 | 7.3 | 3.88 | | 9.7 | 5.5 | *85.21* | 88 | 77.5 | 4.541 | | | | | |
| Pulp without fines, dehydrated (dried citrus pulp) | 91 | 6.7 | 3.62 | | 3.7 | 6.6 | *87.01* | 82 | 83 | 4.171 | 19.47 | 1 | 24.02 | 20.43 | 2.45 |
| Citrus pulp, wet | 19.41 | 8.58 | 3.1 | | 3.17 | 6.78 | *74.68* | 70.2 | 81.47 | 4.164 | 0.9 | 1.7 | 26.29 | 23.16 | 3.21 |
| **Clover, alsike *(Trifolium hybridum)*** | | | | | | | | | | | | | | | |
| Fresh, early vegetative | 19 | 24.1 | 2.91 | | 3.2 | 12.8 | *70.62* | 66 | 59.9 | 4.148 | | | | | |
| Hay, sun-cured | 88 | 14.9 | 2.56 | | 3 | 8.7 | *61.66* | 58 | 73.4 | 4.170 | | | | | |
| **Clover, crimson *(Trifolium incarnatum)*** | | | | | | | | | | | | | | | |
| Fresh, early vegetative | 18 | 17 | 2.78 | | | | | 63 | 83 | 4.405 | | | | | |
| Hay, sun-cured | 87 | 18.4 | 2.51 | | 2.4 | 11 | *61.68* | 57 | 68.2 | 4.096 | | | | | |
| **Clover, ladino *(Trifolium repens)*** | | | | | | | | | | | | | | | |
| Fresh, early vegetative | 19 | 27.2 | 3 | 4.64 | 2.5 | 13.5 | *73.22* | 68 | 56.8 | 4.129 | | | 35 | 33 | |
| Hay, sun-cured | 90 | 22 | 2.65 | 4.64 | 2.7 | 10.1 | *63.40* | 60 | 65.2 | 4.203 | | | 36 | 32 | 7 |
| **Clover, red *(Trifolium pratense)*** | | | | | | | | | | | | | | | |
| Fresh, early bloom | 20 | 19.4 | 3.04 | | 5 | 10.2 | *71.27* | 69 | 65.4 | 4.280 | | | 40 | 31 | |
| Fresh, full bloom | 26 | 14.6 | 2.82 | | 2.9 | 7.8 | *67.44* | 64 | 74.7 | 4.198 | | | 43 | 35 | |
| Fresh, regrowth early vegetative | 18 | 21 | 3 | | | | | 68 | 79 | 4.465 | | | | | |
| Hay, sun-cured | 89 | 16 | 2.43 | | 2.8 | 8.5 | *58.33* | 55 | 72.7 | 4.184 | | | 46.9 | 36 | 10 |

| Feedstuff | DM% | CP% | DE (mcal/ kg) | GE (mcal/ kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] DE (% of GE) | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] GE (mcal/kg) | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Coconut *(Cocos nucifera)*** | | | | | | | | | | | | | | | |
| Kernels with coats, meal mechanical extracted (copra meal) | 92 | 22.4 | 3.62 | | 6.9 | 7.3 | *79.66* | 82 | 63.4 | 4.545 | | | | | |
| Kernels with coats, meal solvent extracted (copra meal) | 91 | 23.4 | 3.31 | | 3.9 | 6.6 | *74.85* | 75 | 66.1 | 4.432 | 7.88 | 0.73 | 52.26 | 32.23 | 10.34 |
| **Corn, dent yellow *(Zea mays indentata)*** | | | | | | | | | | | | | | | |
| Aerial part with ears, sun-cured (fodder) | 81 | 8.9 | 2.87 | | 2.4 | 6.8 | *69.80* | 65 | 81.9 | 4.127 | | | 55 | 33 | 3 |
| Aerial part with ears, sun-cured, mature (fodder) | 82 | 8 | 3.04 | | 2.3 | 5.4 | *73.18* | 69 | 84.3 | 4.167 | 4.26 | 32.58 | 43 | 25.46 | 3.17 |
| Aerial part without ears, without husks, sun-cured (stover) (straw) | 85 | 6.6 | 2.21 | | 1.3 | 7.2 | *55.28* | 50 | 84.9 | 4.018 | | | 67 | 39 | 11 |
| Cobs, ground | 90 | 3.2 | 2.21 | | 0.7 | 1.7 | *53.18* | 50 | 94.4 | 4.164 | 3.75 | 14.34 | 78.26 | 42.03 | 4.05 |
| Distillers grains, dehydrated | 94 | 23 | 3.79 | | 9.8 | 2.4 | *76.86* | 86 | 64.8 | 4.910 | | | 43 | | |
| Distillers grains with solubles, dehydrated | 92 | 25 | 3.88 | | 10.3 | 4.8 | *79.45* | 88 | 59.9 | 4.867 | 1.16 | 5.88 | 33.66 | 16.17 | 4.96 |
| Distillers solubles, dehydrated | 93 | 29.7 | 3.88 | | 9.2 | 7.8 | *81.50* | 88 | 53.3 | 4.755 | | | 23 | 7 | 1 |
| Distillers grains with solubles, wet (corn-based) | 31.44 | 30.63 | 4.32 | | 10.84 | 5.13 | *86.68* | 98 | 53.4 | 4.966 | 0.9 | 6.06 | 31.52 | 15.27 | 4.7 |
| Ears, ground (corn and cob meal) | 87 | 9 | 3.66 | | 3.7 | 1.9 | *83.15* | 83 | 85.4 | 4.400 | | | | | |
| Ears with husks, silage | 44 | 8.9 | 3.26 | | 3.8 | 2.8 | *74.67* | 74 | 84.5 | 4.367 | 1.29 | 60.16 | 21.04 | 9.89 | 1.74 |
| Gluten, meal | 91 | 46.8 | 3.79 | | 2.4 | 3.4 | *78.47* | 86 | 47.4 | 4.837 | | | | | |
| Gluten, meal 60% protein | 90 | 67.2 | 3.92 | | 2.4 | 1.8 | *75.29* | 89 | 28.6 | 5.209 | 0.23 | 15.42 | 8.07 | 4.81 | 2.26 |
| Gluten with bran (corn gluten feed) | 90 | 25.6 | 3.66 | 4.73 | 2.4 | 7.5 | *84.50* | 83 | 64.5 | 4.349 | 3.4 | 15.23 | 38.53 | 11.78 | 1.6 |
| Grain, grade 2, 69.5 kg/hl | 88 | 10.1 | 3.97 | 4.5445 | 4.2 | 1.4 | *88.85* | 90 | 84.3 | 4.464 | 2.72 | 69.7 | 9.95 | 3.72 | 1.15 |
| Grain, flaked | 86 | 11.2 | 4.19 | | 2.2 | 1 | *95.44* | 95 | 85.6 | 4.392 | 2.48 | 76.24 | 8.97 | 3.59 | 1.25 |
| Grain, high moisture | 72 | 10.7 | 4.1 | | 4.3 | 1.6 | *91.64* | 93 | 83.4 | 4.470 | 2.16 | 71.3 | 9.86 | 3.69 | 1.15 |
| Grits, by-products (hominy feed) | 90 | 11.5 | 4.14 | 4.693 | 7.7 | 3.1 | *89.80* | 94 | 77.7 | 4.598 | 1.1 | 56.77 | 16.79 | 5.62 | 1.48 |
| Silage, aerial part without ears, without husks (stalklage) (stover) | 31 | 6.3 | 2.43 | | 2.1 | 11.6 | *63.20* | 55 | 80 | 3.873 | | | 68 | 55 | 7 |
| Silage, few ears | 29 | 8.4 | 2.73 | | 3 | 7.2 | *66.26* | 62 | 81.4 | 4.135 | | | | | |

| Feedstuff | DM% | CP% | DE (mcal/kg) | GE (mcal/kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] DE (% of GE) | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] GE (mcal/kg) | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Silage, well-eared | 33 | 8.1 | 3.09 | | 3.1 | 4.5 | 72.88 | 70 | 84.3 | 4.248 | 4.26 | 32.58 | 42.98 | 25.46 | 3.17 |
| Corn snaplage | 58.94 | 8.08 | 3.61 | | 3.46 | 1.99 | 82.60 | 82 | 86.47 | 4.370 | | 57.02 | 23.28 | 11.24 | 1.95 |
| Corn stalkage | 40.74 | 6.81 | 2.36 | | 1.99 | 12.15 | 61.75 | 53.6 | 79.05 | 3.852 | | 5.98 | 63.78 | 45.61 | 6.12 |
| Corn gluten feed (sweet bran) | 60.07 | 23.76 | 3.92 | | 4.65 | 6.4 | 87.54 | 89 | 65.19 | 4.485 | | | 26.75 | 9.79 | |
| Corn gluten feed, wet | 43.76 | 21.7 | 3.79 | | 4.29 | 6.4 | 85.61 | 86 | 67.61 | 4.435 | 3.4 | 15.23 | 38.53 | 11.78 | 1.6 |
| Corn gluten feed, dry | 88.92 | 22.64 | 3.53 | | 3.32 | 6.4 | 80.47 | 80 | 67.64 | 4.398 | 2.68 | 16.92 | 35.05 | 11.18 | 1.86 |
| Corn germ meal | 90.59 | 22.14 | 3.46 | | 11.5 | 4.31 | 70.19 | 78.6 | 62.05 | 4.907 | | 19.68 | 39.41 | 12.27 | 2.44 |
| Corn stalks | 85.81 | 6.07 | 2.32 | | 1.44 | 11.1 | 60.63 | 52.7 | 81.39 | 3.856 | 3.1 | 10.8 | 70.83 | 46.75 | 6.31 |
| Corn grain, dry-rolled | 87.22 | 8.79 | 3.86 | | 3.81 | 1.44 | 87.23 | 87.6 | 85.96 | 4.422 | 1.81 | 72.07 | 9.72 | 3.56 | 1.18 |
| Corn steep liquor | 46.41 | 31.78 | 4.32 | . | 4.51 | 11.29 | 98.73 | 98 | 52.42 | 4.395 | 15.03 | 11.4 | 3.55 | 2.72 | . |
| Hominy feed | 88.74 | 10.27 | 3.85 | | 7.15 | 2.64 | 84.04 | 87.2 | 79.94 | 4.570 | 1.1 | 56.77 | 16.79 | 5.62 | 1.48 |
| **Corn, sweet *(Zea mays saccharate)*** | | | | | | | | | | | | | | | |
| Process residue, fresh (cannery residue) | 77 | 8.8 | 3.09 | | 2.3 | 3.3 | 72.56 | 70 | 85.6 | 4.266 | | | | | |
| Process residue, silage (cannery residue) | 32 | 7.7 | 3.17 | | 5.2 | 4.9 | 73.14 | 72 | 82.2 | 4.335 | | | | | |
| **Cotton *(Gossypium spp.)*** | | | | | | | | | | | | | | | |
| Bolls, sun-cured | 92 | 11 | 1.94 | | 2.7 | 7.7 | 47.08 | 44 | 78.6 | 4.137 | | | | | |
| Hulls | 91.43 | 6.68 | 1.85 | | 2.71 | 3.62 | 43.68 | 42 | 86.99 | 4.242 | 1.13 | 2.71 | 81.07 | 65.1 | 19.29 |
| Seeds | 92.63 | 22.87 | 4.23 | | 19.45 | 4.12 | 78.42 | 96 | 53.56 | 5.343 | 3.96 | 2.2 | 47.82 | 42.85 | 11.58 |
| Seeds, meal mechanical extracted, 41% protein | 93 | 44.3 | 3.44 | 4.78 | 5 | 6.6 | 71.71 | 78 | 44.1 | 4.803 | | | 28 | 20 | 6 |
| Seeds, meal prepressed extracted, 41% protein | 91 | 45.6 | 3.53 | 4.692 | 1.3 | 7 | 76.88 | 80 | 46.1 | 4.612 | | | 26 | 19 | 6 |
| Seeds, meal solvent extracted, 41% protein | 91 | 45.2 | 3.35 | 4.705 | 1.6 | 7.1 | 72.85 | 76 | 46.1 | 4.617 | 1.7 | 3.93 | 33.6 | 23.67 | 8.51 |
| Seeds without hulls, meal prepressed solvent extracted 50% protein | 93 | 54 | 3.31 | | 1.4 | 7.1 | 70.14 | 75 | 37.5 | 4.739 | | | | | |
| Cotton burrs | 90.55 | 8.66 | 1.99 | | 2.48 | 15.34 | 53.25 | 45.2 | 73.52 | 3.773 | 2.7 | 6.03 | 60.9 | 55.93 | 16.6 |
| Cotton gin trash | 90.87 | 12.29 | 2.14 | | 3.64 | 12.05 | 53.49 | 48.5 | 72.02 | 4.025 | | 1.06 | 60.57 | 52.26 | 15.85 |

| | | | | | | | Calculated: Ewan, 1989[a] | | | Calculated: NASEM, 2016[a] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Feedstuff** | **DM%** | **CP%** | **DE (mcal/ kg)** | **GE (mcal/ kg)** | **EE (%)** | **Ash (%)** | **DE (% of GE)** | **TDN (%)** | **Total $(CH_2O)_n$ (%)** | **GE (mcal/kg)** | **Total Sugars (%)** | **Total Starch (%)** | **NDF (%)** | **ADF (%)** | **Lignin (%)** |
| **Cowpea, common *(Vigna sinensis)*** | | | | | | | | | | | | | | | |
| Hay, sun-cured | 90 | 19.4 | 2.6 | | 3.1 | 11.3 | *63.25* | 59 | 66.2 | 4.135 | | | | | |
| **Dropseed, sand *(Sporobolus cryptandrus)*** | | | | | | | | | | | | | | | |
| Fresh, stem-cured | 88 | 5 | 2.6 | | 1.4 | 6.3 | *64.69* | 59 | 87.3 | 4.037 | | | | | 6 |
| **Fats and oils** | | | | | | | | | | | | | | | |
| Fat, animal, dehydrated | 99 | 0 | 7.8 | | 99.5 | 0 | *80.29* | 177 | 0.5 | 9.374 | 0 | 0 | 0 | 0 | 0 |
| Fat, animal-poultry | 99 | 0 | 7.8 | | 100 | 0 | *80.06* | 177 | 0 | 9.400 | 0 | 0 | 0 | 0 | 0 |
| Oil, vegetable | 100 | 0 | 7.8 | 9.396 | 99.9 | 0 | *80.10* | 177 | 0.1 | 9.395 | 0 | 0 | 0 | 0 | 0 |
| **Fescue *(Festuca spp.)*** | | | | | | | | | | | | | | | |
| Hay, sun-cured, early vegetative | 91 | 12.4 | 2.69 | | 3.4 | 12 | *67.39* | 61 | 72.2 | 4.017 | | | 57 | 32 | 3 |
| Hay, sun-cured, early bloom | 92 | 9.5 | 2.12 | | 2 | 10 | *53.57* | 48 | 78.5 | 3.983 | | | 72 | 39 | 5 |
| **Fish** | | | | | | | | | | | | | | | |
| Fish meal | 92.3 | 66.24 | 3.61 | | 11.89 | 20.02 | *73.35* | 81.9 | 1.85 | 4.937 | | 5.82 | 13.6 | 3.14 | |
| **Flax, common *(Linum usitatissimum)*** | | | | | | | | | | | | | | | |
| Seed screenings | 91 | 18.2 | 2.82 | | 10.2 | 6.8 | *60.15* | 64 | 64.8 | 4.676 | | | | | |
| Seeds, meal mechanical extracted, linseed meal | 91 | 37.9 | 3.62 | | 6 | 6.3 | *75.89* | 82 | 49.8 | 4.772 | | | 25 | 17 | 7 |
| Seeds, meal solvent extracted, linseed meal | 90 | 38.3 | 3.44 | | 1.5 | 6.5 | *76.18* | 78 | 53.7 | 4.534 | | | 25 | 19 | 6 |
| Flax seed, whole | 91.63 | 28.68 | 3.6 | | 27.67 | 5.12 | *61.04* | 81.6 | 38.53 | 5.820 | | 1.98 | 31.84 | 18.94 | 5.75 |
| **Galeta *(Hilaria jamesii)*** | | | | | | | | | | | | | | | |
| Fresh, stem-cured | 71 | 5.5 | 2.12 | | 1.8 | 16.2 | *58.67* | 48 | 76.5 | 3.655 | | | | | |
| Glycerin | 80.25 | 0.84 | 3.04 | | 6.24 | 6.69 | *72.20* | 69 | 86.23 | 4.213 | 1.4 | 0.4 | 0.3 | 0.2 | |
| **Grama *(Bouteloua spp.)*** | | | | | | | | | | | | | | | |
| Fresh, early vegetative | 41 | 13.1 | 2.65 | | 2 | 11.3 | *67.02* | 60 | 73.6 | 3.983 | | | | | |
| Fresh, mature | 63 | 6.5 | 2.43 | | 1.7 | 11.4 | *63.38* | 55 | 80.4 | 3.864 | | | | | |

| | | | | | | | Calculated: Ewan, 1989[a] | | | Calculated: NASEM, 2016[a] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Feedstuff** | **DM%** | **CP%** | **DE (mcal/kg)** | **GE (mcal/kg)** | **EE (%)** | **Ash (%)** | **DE (% of GE)** | **TDN (%)** | **Total $(CH_2O)_n$ (%)** | **GE (mcal/kg)** | **Total Sugars (%)** | **Total Starch (%)** | **NDF (%)** | **ADF (%)** | **Lignin (%)** |
| **Grape *(Vitis spp.)*** | | | | | | | | | | | | | | | |
| Marc, dehydrated (pomace) | 91.81 | 12.27 | 2.07 | | 8.87 | 9.65 | *47.05* | 27 | 69.21 | 4.399 | | 0.97 | 51.78 | 46.28 | 31.91 |
| Mark, wet (pomace) | 41.88 | 11.69 | 2.47 | | 8.95 | 15.11 | *59.45* | 28 | 64.25 | 4.168 | | 0.99 | 50.06 | 43.43 | 27.6 |
| Hemicellulose extract (masonex) | 76 | 0.7 | 2.65 | | 0.4 | 4.1 | *66.32* | 60 | 94.8 | 4.011 | | | | | |
| **Lespedeza, common, and lespedeza, Korean *(Lespedeza striata)*** | | | | | | | | | | | | | | | |
| Fresh, late vegetative | 32 | 16.4 | 2.6 | | | | | 59 | 83.6 | 4.396 | | | | | |
| Fresh, early bloom | 28 | 16.4 | 2.43 | | | | | 55 | 83.6 | 4.396 | | | | | |
| Hay, sun-cured, early bloom | 93 | 15.5 | 2.43 | | | | | 55 | 84.5 | 4.383 | | | | | |
| Hay, sun-cured, midbloom | 93 | 14.5 | 2.21 | | | | | 50 | 85.5 | 4.368 | | | | | |
| Hay, sun-cured, full bloom | 93 | 13.4 | 2.07 | | | | | 47 | 86.6 | 4.351 | | | | | |
| **Lignin sulfonate, calcium** | | | | | | | | | | | | | | | |
| Dehydrated | 97 | 0.5 | 0.35 | | 0.5 | 4 | *8.74* | 8 | 95 | 4.018 | | | | | 76 |
| **Linseed *(Linum)*** | | | | | | | | | | | | | | | |
| Linseed meal | 90.47 | 36.93 | 3.24 | | 11.96 | 6.18 | *63.59* | 73.6 | 44.93 | 5.075 | | 2.54 | 32.1 | 17.28 | 5.72 |
| **Meadow plants, intermountain** | | | | | | | | | | | | | | | |
| Hay, sun-cured | 95 | 8.7 | 2.56 | | 2.5 | 8.5 | *63.37* | 58 | 80.3 | 4.059 | 13.95 | | 60.85 | 35.79 | |
| **Millet, foxtail *(Setaria italica)*** | | | | | | | | | | | | | | | |
| Fresh | 28 | 9.5 | 2.78 | | 3.1 | 8.7 | *68.20* | 63 | 78.7 | 4.094 | 7.89 | 2.69 | 65.28 | 34.53 | 7.13 |
| Grain | 86.7 | 11.27 | 3.36 | | 3.46 | 5.34 | *78.67* | 85 | 79.93 | 4.279 | 3.7 | 49.27 | 21.61 | 13.88 | 3.21 |
| Hay, sun-cured | 87 | 8.6 | 2.6 | | 2.9 | 8.6 | *64.10* | 59 | 79.9 | 4.074 | 5.64 | 3.15 | 60.3 | 42.03 | 5.73 |
| **Millet, proso *(Panicum miliaceum)*** | | | | | | | | | | | | | | | |
| Grain | 90 | 12.9 | 3.7 | | 3.9 | 2.9 | *83.57* | 84 | 80.3 | 4.428 | 3.7 | 45.45 | 23.16 | 14.54 | 3.8 |
| **Molasses and syrup *(Beta vulgaris altissima)*** | | | | | | | | | | | | | | | |
| Beet, sugar, molasses, more than 48% invert sugar, more than 79.5% degrees brix | 78 | 8.5 | 3.48 | | 0.2 | 11.3 | *91.95* | 79 | 80 | 3.819 | 35.5 | 0.6 | 0.77 | 0.36 | 0.16 |

| Feedstuff | DM% | CP% | DE (mcal/kg) | GE (mcal/kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] DE (% of GE) | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] GE (mcal/kg) | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Molasses and syrup *(Citrus spp.)*** | | | | | | | | | | | | | | | |
| Citrus, syrup (citrus molasses) | 68 | 8.2 | 3.31 | | 0.3 | 7.9 | *84.11* | 75 | 83.6 | 3.961 | | | | | |
| **Molasses and syrup *(Saccharum officinarum)*** | | | | | | | | | | | | | | | |
| Sugarcane, molasses, dehydrated | 94 | 10.3 | 3.09 | | 0.9 | 13.3 | *82.12* | 70 | 75.5 | 3.800 | | | | | |
| Sugarcane, molasses, more than 46% invert sugars, more than 79.5 degrees brix (black strap) | 66.04 | 8.59 | 3.17 | | 1.86 | 12.2 | *82.57* | 72 | 77.35 | 3.870 | 60.04 | 11.98 | | | |
| **Napiergrass *(Pennisetum purpureum)*** | | | | | | | | | | | | | | | |
| Fresh, late vegetative | 20 | 8.7 | 2.43 | | 3 | 8.6 | *59.81* | 55 | 79.7 | 4.081 | | | 70 | 45 | 10 |
| Fresh, late bloom | 23 | 7.8 | 2.34 | | 1.1 | 5.3 | *57.24* | 53 | 85.8 | 4.105 | | | 75 | 47 | 14 |
| **Needleandthread *(Stipa comata)*** | | | | | | | | | | | | | | | |
| Fresh, stem-cured | 92 | 4.1 | 2.16 | | 5.4 | 21.1 | *60.36* | 49 | 69.4 | 3.619 | | | 83 | 43 | 14 |
| **Oats *(Avena sativa)*** | | | | | | | | | | | | | | | |
| Grain | 89.96 | 13.3 | 3.4 | 4.667 | 5.4 | 3.4 | *75.63* | 77 | 77.9 | 4.492 | 2.18 | 44.09 | 26.65 | 13.3 | 3 |
| Grain, Pacific coast | 91 | 10 | 3.44 | | 5.5 | 4.2 | *77.90* | 78 | 80.3 | 4.414 | | | | | |
| Groats | 90 | 17.7 | 4.14 | | 6.9 | 2.4 | *88.29* | 94 | 73 | 4.678 | | | | | |
| Hay, sun-cured | 89.61 | 8.73 | 2.64 | | 2.22 | 7.07 | *64.59* | 55 | 81.98 | 4.104 | 10.9 | 3.97 | 59.13 | 37.08 | 4.69 |
| Hulls | 91.6 | 6.1 | 2.49 | | 2.8 | 5.24 | *59.85* | 35 | 85.86 | 4.171 | 3.03 | 15.83 | 64.44 | 35.87 | 5.54 |
| Silage, late vegetative | 23 | 12.8 | 2.87 | | 2.5 | 6.5 | *68.51* | 65 | 78.2 | 4.204 | 5.08 | 3.11 | 58.88 | 38.49 | 5.33 |
| Silage, dough stage | 35 | 10 | 2.51 | | 4.1 | 6.9 | *59.49* | 57 | 79 | 4.229 | | | | | |
| Straw | 84.19 | 4.83 | 1.98 | | 1.33 | 6.92 | *49.68* | 45 | 86.92 | 4.005 | | 1.35 | 73.75 | 49.29 | 7.07 |
| **Orchardgrass *(Dactylis glomerata)*** | | | | | | | | | | | | | | | |
| Fresh, early vegetative | 23 | 18.4 | 3.17 | | 4.9 | 11.3 | *75.54* | 72 | 65.4 | 4.214 | | | 58.1 | 30.7 | |
| Fresh, midbloom | 31 | 11 | 2.51 | | 3.5 | 7.5 | *60.13* | 57 | 78 | 4.188 | | | 57.6 | 35.6 | |
| Hay, sun-cured, early bloom | 89 | 15 | 2.87 | | 2.8 | 8.7 | *69.29* | 65 | 73.5 | 4.161 | | | 59.6 | 33.8 | |
| Hay, sun-cured, late bloom | 91.47 | 13.77 | 2.38 | | 2.3 | 10.54 | *59.28* | 54 | 73.39 | 4.040 | | | 65 | 37.8 | |

| Feedstuff | DM% | CP% | DE (mcal/ kg) | GE (mcal/ kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | DE (% of GE) | | | GE (mcal/kg) | | | | | |
| **Pangolagrass *(Digitaria decumbens)*** | | | | | | | | | | | | | | | |
| Fresh | 21 | 10.3 | 2.43 | | 2.3 | 9.6 | *60.69* | 55 | 77.8 | 4.027 | | | | 38 | 5 |
| Hay, sun-cured, 15 to 28 days growth | 91 | 11.5 | 2.25 | | 2.2 | 8.5 | *55.35* | 51 | 77.8 | 4.085 | | | 70 | 41 | 6 |
| Hay, sun-cured, 29 to 42 days growth | 91 | 7.1 | 1.98 | | 2 | 8 | *49.38* | 45 | 82.9 | 4.030 | | | 73 | 43 | 6 |
| Hay, sun-cured, 43 to 56 days growth | 91 | 5.5 | 1.76 | | 2 | 7.6 | *43.97* | 40 | 84.9 | 4.022 | | | 77 | 46 | 7 |
| **Pea *(Pisum spp.)*** | | | | | | | | | | | | | | | |
| Seeds | 89 | 25.3 | 3.84 | | 1.4 | 3.3 | *86.18* | 87 | 70 | 4.466 | | 42.66 | 13.67 | 9.23 | 1.06 |
| Straw | 87 | 8.9 | 2.03 | | 1.8 | 6.5 | *49.62* | 46 | 82.8 | 4.108 | | | | | |
| Vines without seeds, silage | 25 | 13.1 | 2.51 | | 3.3 | 9 | *60.80* | 57 | 74.6 | 4.146 | | 5.58 | 59 | 49 | 9 |
| Field peas | 89.9 | 14.8 | 2.6 | | 1.9 | 8 | *63.12* | 59 | 75.3 | 4.140 | | 46.3 | 13.1 | 7.16 | |
| **Peanut *(Arachis hypogaea)*** | | | | | | | | | | | | | | | |
| Hay, sun-cured | 91 | 10.8 | 2.43 | | 3.4 | 8.6 | *59.02* | 55 | 77.2 | 4.134 | 7.42 | 4 | 47.4 | 39.13 | 8.45 |
| Hulls (pods) | 91 | 7.8 | 0.97 | | 2 | 4.2 | *23.17* | 22 | 86 | 4.198 | 6.52 | 1.24 | 68.46 | 58.87 | 23.03 |
| Kernels, meal mechanical extracted (peanut meal) | 93 | 52 | 3.66 | | 6.3 | 5.5 | *72.71* | 83 | 36.2 | 5.033 | 9.96 | 6.93 | 19.89 | 13.15 | 3.3 |
| Kernels, meal solvent extracted (peanut meal) | 92 | 52.3 | 3.4 | | 1.4 | 6.3 | *71.90* | 77 | 40 | 4.747 | | | | | |
| **Pearlmillet *(Pennisetum glaucum)*** | | | | | | | | | | | | | | | |
| Fresh | 21 | 8.5 | 2.69 | | 2.2 | 10 | *68.04* | 61 | 79.3 | 3.978 | | | | | |
| **Pineapple *(Ananas comosus)*** | | | | | | | | | | | | | | | |
| Aerial part without fruit, sun-cured (pineapple hay) | 89 | 7.8 | 2.69 | | 2.8 | 6.1 | *64.84* | 61 | 83.3 | 4.161 | | | | | |
| Process residue, dehydrated (pineapple bran) | 87 | 4.6 | 3 | | 1.5 | 3.5 | *72.43* | 68 | 90.4 | 4.153 | | | 73 | 37 | 7 |
| **Potato *(Solanum tuberosum)*** | | | | | | | | | | | | | | | |
| Process residue, dehydrated | 89 | 8.4 | 3.97 | | 4 | 3.4 | *91.40* | 90 | 84.2 | 4.345 | 3.7 | 44.34 | 18.38 | 13.31 | 3.2 |
| Tubers, fresh | 23.54 | 10.11 | 3.38 | | 7.52 | 6.3 | *76.15* | 81 | 76.07 | 4.435 | 11.91 | 60.87 | 11.19 | 7.32 | 1.1 |
| Tubers, silage | 25 | 7.6 | 3.62 | | 4 | 5.5 | *85.40* | 82 | 82.9 | 4.246 | | | | | |

| Feedstuff | DM% | CP% | DE (mcal/kg) | GE (mcal/kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] DE (% of GE) | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] GE (mcal/kg) | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Poultry** | | | | | | | | | | | | | | | |
| Feathers, hydrolyzed | 93 | 91.3 | 3.09 | | 3.2 | 3.8 | *55.93* | 70 | 1.7 | 5.530 | | | | | |
| **Prairie plants, Midwest** | | | | | | | | | | | | | | | |
| Hay, sun-cured | 92 | 5.8 | 2.25 | | 2.4 | 7.1 | *55.53* | 51 | 84.7 | 4.068 | | | 66.58 | 41.45 | 2.05 |
| **Rape *(Brassica napus)* (Canola)** | | | | | | | | | | | | | | | |
| Fresh, early bloom | 11 | 23.5 | 3.31 | | 3.8 | 14 | *80.88* | 75 | 58.7 | 4.121 | | | | | |
| Seeds, meal mechanical extracted | 92 | 38.7 | 3.35 | | 7.9 | 7.5 | *69.27* | 76 | 45.9 | 4.834 | | | | | |
| Seeds, meal solvent extracted | 91 | 40.6 | 3.04 | | 1.8 | 7.5 | *67.21* | 69 | 50.1 | 4.542 | 8.75 | 1.29 | 30.16 | 21.42 | 8.83 |
| **Redtop *(Agrostis alba)*** | | | | | | | | | | | | | | | |
| Fresh | 29 | 11.6 | 2.78 | | 3.9 | 8.1 | *66.52* | 63 | 76.4 | 4.193 | | | 64 | 45 | 8 |
| Hay, sun-cured, midbloom | 94 | 11.7 | 2.51 | | 2.6 | 6.5 | *60.08* | 57 | 79.2 | 4.192 | | | | | |
| **Rice *(Oryza sativa)*** | | | | | | | | | | | | | | | |
| Bran with germs (rice, bran) | 91 | 14.1 | 3.09 | | 15.1 | 12.8 | *66.64* | 70 | 58 | 4.623 | 6.33 | 20.17 | 26.22 | 15.51 | 5.34 |
| Grain, ground (ground rough rice) | 88.81 | 8.37 | 3.65 | | 1.84 | 3.19 | *86.26* | 79 | 86.6 | 4.240 | 3.35 | 57.19 | 16.17 | 5.9 | 1.88 |
| Hulls | 91.95 | 5.39 | 31.5 | | 4.31 | 15.71 | *834.66* | 12 | 74.59 | 3.805 | | | 53.84 | 52.55 | . |
| Straw | 91 | 4.3 | 1.81 | | 1.4 | 17 | *51.16* | 41 | 77.3 | 3.583 | | | 82 | 49 | 16 |
| **Rye *(Secale cereale)*** | | | | | | | | | | | | | | | |
| Distillers grains, dehydrated | 92 | 23.5 | 2.69 | | 7.8 | 2.5 | *55.78* | 61 | 66.2 | 4.808 | | | | | |
| Fresh | 24 | 15.9 | 3.04 | | 3.7 | 8.1 | *71.83* | 69 | 72.3 | 4.247 | | | | | |
| Grain | 88 | 13.8 | 3.7 | | 1.7 | 1.9 | *84.83* | 84 | 82.6 | 4.367 | | 58.25 | 15.39 | 7.53 | 1.57 |
| Mill run, less than 9.5% fiber (rye feed) | 90 | 18.5 | 3.31 | | 3.7 | 4.2 | *74.50* | 75 | 73.6 | 4.447 | | | | | |
| Straw | 90 | 3 | 1.37 | | 1.7 | 5 | *33.72* | 31 | 90.3 | 4.077 | | | | | |
| **Ryegrass, Italian *(Lolium multiflorum)*** | | | | | | | | | | | | | | | |
| Fresh | 25 | 14.5 | 2.65 | 4.5 | 3.2 | 14 | *67.54* | 60 | 68.3 | 3.955 | | | | | |
| Hay, sun-cured, late vegetative | 90.38 | 18.65 | 2.81 | 4.5 | 3.35 | 9.6 | *67.10* | 62 | 68.4 | 4.207 | | 2.26 | 51.5 | 30.89 | 4.32 |
| Hay, sun-cured, early bloom | 83 | 5.5 | 2.38 | 4.5 | 0.9 | 8.4 | *60.93* | 54 | 85.2 | 3.931 | | | | | |

| Feedstuff | DM% | CP% | DE (mcal/kg) | GE (mcal/kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | DE (% of GE) | | | GE (mcal/kg) | | | | | |
| **Ryegrass, Perennial *(Lolium perenne)*** | | | | | | | | | | | | | | | |
| Fresh | 27 | 10.4 | 3 | 4.5 | 2.7 | 8.6 | *73.68* | 68 | 78.3 | 4.091 | | | | | |
| Hay, sun-cured | 86 | 8.6 | 2.65 | 4.5 | 2.2 | 11.5 | *68.14* | 60 | 77.7 | 3.917 | | | 41 | 30 | 2 |
| **Safflower *(Carthamus tinctorious)*** | | | | | | | | | | | | | | | |
| Seeds | 94 | 17.4 | 3.92 | | 35.1 | 3.1 | *62.89* | 89 | 44.4 | 6.125 | | | | | |
| Seeds, meal mechanical extracted | 91 | 22.1 | 2.65 | | 6.7 | 4.1 | *56.75* | 60 | 67.1 | 4.663 | | | 59 | 41 | |
| Seeds, meal solvent extracted | 93.5 | 23.12 | 2.46 | | 12.34 | 4.85 | *49.52* | 57 | 59.69 | 4.943 | 3.96 | 1.15 | 51.48 | 37.62 | 13.45 |
| Seeds without hulls, meal solvent extracted | 92 | 46.9 | 3.22 | | 1.4 | 8.2 | *70.55* | 73 | 43.5 | 4.587 | | | | | |
| **Sage, black *(Salvia mellifera)*** | | | | | | | | | | | | | | | |
| Browse, fresh, stem-cured | 65 | 8.5 | 2.16 | | 10.8 | 5.5 | *46.62* | 49 | 75.2 | 4.616 | | | 42 | 30 | 12 |
| **Sagebrush, big *(Artemisia tridentata)*** | | | | | | | | | | | | | | | |
| Browse, fresh, stem-cured | 65 | 9.3 | 2.21 | | 11 | 6.6 | *47.96* | 50 | 73.1 | 4.593 | | | | | |
| **Sagebrush, bud *(Artemisia spinescens)*** | | | | | | | | | | | | | | | |
| Browse, fresh, early vegetative | 23 | 17.3 | 2.25 | | 4.9 | 21.4 | *60.24* | 51 | 56.4 | 3.779 | | | | | |
| Browse, fresh, late vegetative | 32 | 17.5 | 2.29 | | 2.5 | 21.6 | *63.70* | 52 | 58.4 | 3.647 | | | | | |
| **Sagebrush, fringed *(Artemisia frigida)*** | | | | | | | | | | | | | | | |
| Browse, fresh, midbloom | 43 | 9.4 | 2.56 | | 2 | 6.5 | *62.29* | 58 | 82.1 | 4.126 | | | | | |
| Browse, fresh, mature | 60 | 7.1 | 2.25 | | 3.4 | 17.1 | *61.02* | 51 | 72.4 | 3.725 | | | 46 | 35 | 10 |
| **Saltbush, nuttall *(Atriplex nuttallii)*** | | | | | | | | | | | | | | | |
| Browse, fresh, stem-cured | 55 | 7.2 | 1.59 | | 2.2 | 21.5 | *46.38* | 36 | 69.1 | 3.481 | | | | | |
| **Saltgrass *(Distichlis spp.)*** | | | | | | | | | | | | | | | |
| Fresh, post ripe | 74 | 4.2 | 2.34 | | 2.6 | 7.3 | *58.06* | 53 | 85.9 | 4.047 | | | | | |
| Hay, sun-cured | 89 | 8.9 | 2.25 | | 2.1 | 12.7 | *58.67* | 51 | 76.3 | 3.867 | | | | | |
| **Seaweed, kelp *(Laminariales fucales)*** | | | | | | | | | | | | | | | |
| Whole, dehydrated | 91 | 7.1 | 1.41 | | 0.5 | 38.6 | *54.67* | 32 | 53.8 | 2.681 | | | | | |

| Feedstuff | DM% | CP% | DE (mcal/kg) | GE (mcal/kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] DE (% of GE) | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] GE (mcal/kg) | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sedge *(Carex spp.)*** | | | | | | | | | | | | | | | |
| Hay, sun-cured | 89 | 9.4 | 2.29 | | 2.4 | 7.2 | *55.83* | 52 | 81 | 4.118 | | | | | |
| **Sesame *(Sesamum indicum)*** | | | | | | | | | | | | | | | |
| Seeds, meal mechanical extracted | 93 | 49.1 | 3.4 | | 7.5 | 12.1 | *71.32* | 77 | 31.3 | 4.778 | | | 17 | 17 | 2 |
| Solka Floc | 93 | 0 | 3.09 | | | | | 70 | 100 | 4.150 | | | 99 | 79 | 4 |
| **Sorghum *(Sorghum bicolor)*** | | | | | | | | | | | | | | | |
| Aerial part with heads, sun-cured (fodder) | 89 | 7.5 | 2.56 | | 2.4 | 9.4 | *64.38* | 58 | 80.7 | 3.998 | | | | | |
| Aerial part without heads, sun-cured (stover) | 88 | 5.2 | 2.38 | | 1.7 | 11 | *62.11* | 54 | 82.1 | 3.861 | | 7.33 | 56.44 | 36.49 | 2.9 |
| Distillers grains, dehydrated | 94 | 34.4 | 3.66 | | 9.5 | 3.8 | *72.85* | 83 | 52.3 | 5.007 | | | | | |
| Distillers grains with solubles, wet (sorghum-based) | 31.4 | 34.4 | 3.66 | | 11.25 | 3.8 | *71.46* | 83 | 50.55 | 5.099 | | | 37 | 27.6 | |
| Grain, less than 8% protein | 88 | 7.7 | 3.75 | 4.405 | 3 | | | 85 | 89.3 | 4.423 | | | | | |
| Grain, 8% to 10% protein | 87 | 10.1 | 3.7 | | 3.4 | 2.1 | *84.23* | 84 | 84.4 | 4.393 | | | | | |
| Grain, more than 10% protein | 88.7 | 11.64 | 3.79 | | 3.5 | 2.09 | *85.71* | 83 | 82.77 | 4.422 | 0.1 | 71.16 | 7.2 | 4.57 | 1.15 |
| Grain, flaked | 85 | 10.19 | 4.06 | | 2.4 | 2.1 | *93.59475* | 92 | 85.31 | 4.342 | | 75.18 | 9.7 | 6.26 | |
| Grain, reconstituted | 70 | 10.19 | 4.1 | | 2.4 | 2.1 | *94.51687* | 93 | 85.31 | 4.342 | | 72.89 | 9.28 | 5.52 | |
| Silage | 30 | 7.5 | 2.65 | | 3 | 8.7 | *65.58* | 60 | 80.8 | 4.059 | 0.19 | 4.63 | 49.17 | 31.08 | 5.64 |
| **Sorghum, johnsongrass *(Sorghum halepense)*** | | | | | | | | | | | | | | | |
| Hay, sun-cured | 89 | 9.5 | 2.34 | | 2.4 | 8.2 | *57.65* | 53 | 79.9 | 4.078 | | | | | |
| **Sorghum, sorgo *(Sorghum bicolor saccharatum)*** | | | | | | | | | | | | | | | |
| Silage | 27 | 6.2 | 2.56 | | 2.6 | 6.4 | *62.44* | 58 | 84.8 | 4.114 | 1.44 | 9.79 | 57.71 | 37.02 | 5.34 |
| **Sorghum, sudangrass *(Sorghum bicolor sudanense)*** | | | | | | | | | | | | | | | |
| Fresh, early vegetative | 18 | 16.8 | 3.09 | | 3.9 | 9 | *73.27* | 70 | 70.3 | 4.233 | 8.16 | 2.08 | 61.02 | 37.35 | 4.74 |
| Fresh, midbloom | 23 | 8.8 | 2.78 | | 1.8 | 10.5 | *71.03* | 63 | 78.9 | 3.941 | | | 65 | 40 | 5 |
| Hay, sun-cured | 91 | 8 | 2.47 | | 1.8 | 9.6 | *62.67* | 56 | 80.6 | 3.966 | 7.07 | 1.42 | 65.7 | 41.6 | 5.06 |
| Silage | 28 | 10.8 | 2.43 | | 2.8 | 9.8 | *60.29* | 55 | 76.6 | 4.052 | 4.5 | 3.12 | 61.14 | 39.65 | 5.47 |

| Feedstuff | DM% | CP% | DE (mcal/kg) | GE (mcal/kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | DE (% of GE) | | | GE (mcal/kg) | | | | | |
| **Soybean *(Glycine max)*** | | | | | | | | | | | | | | | |
| Hay, sun-cured, midbloom | 90.5 | 16.54 | 2.65 | | 3.04 | 8.79 | *63.48* | 53 | 71.63 | 4.193 | 4.9 | 5.37 | 44.85 | 37.05 | 7.28 |
| Hulls (seed coats) | 90.04 | 12.37 | 2.76 | | 2.28 | 5.05 | *65.19* | 64 | 80.3 | 4.246 | 2.15 | 1.1 | 64.81 | 46.4 | 2.47 |
| Seeds | 92 | 42.8 | 4.01 | | 18.8 | 5.5 | *71.66* | 91 | 32.9 | 5.551 | | 1.03 | 17.98 | 10.75 | 1.92 |
| Seeds, meal mechanical extracted | 90 | 47.7 | 3.75 | 4.708 | 5.3 | 6.7 | *77.15* | 85 | 40.3 | 4.866 | | | | | |
| Seeds, meal solvent extracted, 44% protein | 91.68 | 46.53 | 3.58 | 4.708 | 8.34 | 6.43 | *71.24* | 84 | 38.7 | 5.019 | 11.55 | 5.05 | 18.78 | 10.93 | 1.48 |
| Seeds without hulls, meal solvent extracted | 89.24 | 52.85 | 3.51 | 4.708 | 1.88 | 7.36 | *74.41* | 87 | 37.91 | 4.736 | 13.3 | 2.02 | 11.33 | 7.48 | 1.17 |
| Silage | 37.35 | 17.08 | 2.55 | | 4.29 | 9.81 | *60.60* | 55 | 68.82 | 4.224 | | 4.21 | 47.53 | 36.86 | 8.01 |
| Straw | 88 | 5.2 | 1.85 | | 1.5 | 6.4 | *45.98* | 42 | 86.9 | 4.041 | | | 70 | 54 | 16 |
| **Spelt *(Triticum spelta)*** | | | | | | | | | | | | | | | |
| Grain | 90 | 13.3 | 3.31 | | 2.1 | 3.9 | *77.18* | 75 | 80.7 | 4.298 | | | | | |
| **Squirreltail *(Stanion spp.)*** | | | | | | | | | | | | | | | |
| Fresh, stem-cured | 50 | 3.1 | 2.21 | | 2.2 | 17 | *62.00* | 50 | 77.7 | 3.607 | | | | | |
| **Sugarcane *(saccharum officinarum)*** | | | | | | | | | | | | | | | |
| Bagasse, dehydrated | 91 | 1.6 | 2.12 | | 0.7 | 3.2 | *52.15* | 48 | 94.5 | 4.078 | | 0.87 | 75.58 | 62.11 | 17.31 |
| Stems, fresh | 15 | 7.6 | 2.69 | | 0.7 | 6 | *66.71* | 61 | 85.7 | 4.052 | 12.33 | 1.08 | 74 | 44 | 11 |
| Sugar | 100 | 0 | 4.32 | | 0 | 0 | | 98 | 100 | 4.150 | 100 | 0 | 0 | 0 | 0 |
| **Summercypress, gray *(Kochia vestita)*** | | | | | | | | | | | | | | | |
| Fresh, stem-cured | 85 | 9 | 2.21 | | 3.7 | 24.8 | *65.11* | 50 | 62.5 | 3.450 | | | | | |
| **Sunflower, common *(Helianthus annuus)*** | | | | | | | | | | | | | | | |
| Seeds, meal solvent extracted | 90.44 | 35.01 | 2.93 | | 10.8 | 6.41 | *58.71* | 44 | 47.78 | 4.976 | 6.6 | 1 | 40.51 | 29.46 | 9.12 |
| Seeds without hulls, meal mechanical extracted | 93 | 44.6 | 3.26 | | 8.7 | 7.1 | *65.37* | 74 | 39.6 | 4.981 | | | | | |
| Seeds without hulls, meal solvent extracted | 93 | 49.8 | 2.87 | | 3.1 | 8.1 | *60.97* | 65 | 39 | 4.724 | | 1.07 | 41.71 | 30.34 | 9.04 |
| **Sweetclover, yellow *(Melilotus officinalis)*** | | | | | | | | | | | | | | | |
| Hay, sun-cured | 87 | 15.7 | 2.38 | | 2 | 8.8 | *58.00* | 54 | 73.5 | 4.125 | | | | | |

| Feedstuff | DM% | CP% | DE (mcal/kg) | GE (mcal/kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | DE (% of GE) | | | GE (mcal/kg) | | | | | |
| **Timothy *(Phleum pratense)*** | | | | | | | | | | | | | | | |
| Fresh, late vegetative | 26 | 18 | 3.17 | | 3.8 | 6.6 | *73.12* | 72 | 71.6 | 4.346 | | | 55.7 | 29 | |
| Fresh, midbloom | 29 | 9.1 | 2.78 | | 3 | 6.6 | *66.87* | 63 | 81.3 | 4.170 | | | 64 | 37 | 4 |
| Hay, sun-cured, late vegetative | 89 | 17 | 2.73 | | 2.8 | 7.1 | *64.35* | 62 | 73.1 | 4.257 | | | 55 | 29 | 3 |
| Hay, sun-cured, early bloom | 90 | 15 | 2.6 | | 2.9 | 5.7 | *60.75* | 59 | 76.4 | 4.291 | | | 61.4 | 35.2 | 4 |
| Hay, sun-cured, midbloom | 87.8 | 9.44 | 2.51 | | 1.93 | 8.5 | *62.46* | 57 | 80.13 | 4.040 | 14.15 | | 63.81 | 38.04 | 5 |
| Hay, sun-cured, full bloom | 89 | 8.1 | 2.47 | | 3.1 | 5.2 | *58.68* | 56 | 83.6 | 4.218 | | | 68 | 38 | 6 |
| Silage, full bloom | 36 | 9.7 | 2.47 | | 3.2 | 6.9 | *59.32* | 56 | 80.2 | 4.177 | | | 64.2 | 37.5 | |
| **Tomato *(Lycopersicon esculentum)*** | | | | | | | | | | | | | | | |
| Pomace, dehydrated | 92 | 23.5 | 2.56 | | 10.3 | 7.5 | *53.98* | 58 | 58.7 | 4.732 | 13.98 | 1 | 43.86 | 37.2 | 15.78 |
| **Trefoil, birdsfoot *(Lotus corniculatus)*** | | | | | | | | | | | | | | | |
| Fresh | 24 | 21 | 2.91 | | 2.7 | 9 | *69.07* | 66 | 67.3 | 4.233 | | | 46.7 | | |
| Hay, sun-cured | 92 | 16.3 | 2.6 | | 2.5 | 7 | *61.62* | 59 | 74.2 | 4.235 | | | 47.5 | 36 | 9 |
| **Triticale *(Triticale hexaploide)*** | | | | | | | | | | | | | | | |
| Grain | 88.84 | 12.13 | 3.65 | | 1.65 | 1.96 | *84.27* | 84 | 84.26 | 4.337 | 2.9 | 61.04 | 14.1 | 4.49 | 1.81 |
| Triticale hay | 91.3 | 11 | 2.58 | | 2.11 | 8.39 | *63.59* | 58.5 | 78.5 | 4.078 | 8.45 | 2.64 | 58.57 | 37.98 | 4.82 |
| **Turnip *(Brassica rapa rapa)*** | | | | | | | | | | | | | | | |
| Roots, fresh | 9 | 11.8 | 3.75 | | 1.9 | 8.9 | *92.94* | 85 | 77.4 | 4.057 | | | 44 | 34 | 0 |
| **Urea** | | | | | | | | | | | | | | | |
| 45% nitrogen, 281% protein equivalent | 99 | 287 | 0 | 0 | 0 | 0 | *0* | 0 | 0 | 0.000 | 0 | 0 | 0 | 0 | 0 |
| **Vetch *(Vicia spp.)*** | | | | | | | | | | | | | | | |
| hay, sun-cured | 89 | 20.8 | 2.51 | | 3 | 9.1 | *59.44* | 57 | 67.1 | 4.242 | | | 48 | 33 | 8 |
| **Wheat *(Triticum aestivum)*** | | | | | | | | | | | | | | | |
| Bran | 90.1 | 17.48 | 3.17 | | 4.32 | 5.48 | *71.95* | 70 | 72.72 | 4.412 | 5.32 | 21.17 | 40.09 | 13.72 | 4.15 |
| Bread, dehydrated | 95 | 13 | 3.79 | | 2.4 | 2.4 | *86.79* | 86 | 82.2 | 4.371 | | | | | |
| Flour by-product, less than 7% fiber (wheat shorts) | 88 | 18.6 | 3.22 | | 5.2 | 4.9 | *71.59* | 73 | 71.3 | 4.499 | | 25.56 | 38.33 | 13.23 | 3.66 |

| Feedstuff | DM% | CP% | DE (mcal/kg) | GE (mcal/kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] DE (% of GE) | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] GE (mcal/kg) | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flour by-product, less than 9.5% fiber (wheat middlings) | 89 | 18.4 | 3.04 | 4.553 | 4.9 | 5.2 | *68.09* | 69 | 71.5 | 4.467 | | | 35.9 | 11.7 | |
| Fresh, early vegetative | 34.11 | 15.32 | 61.7 | | 3 | 8.91 | *1487.19* | 73 | 72.77 | 4.168 | 10.5 | 4.11 | 54.16 | 32.99 | 3.87 |
| Grain | 89 | 16 | 3.88 | 4.434 | 2 | 1.9 | *87.95* | 88 | 80.1 | 4.416 | 8.55 | 62.42 | 12.36 | 4.15 | 1.52 |
| Grain, hard red spring | 88 | 17.2 | 3.92 | | 2 | 1.8 | *88.41* | 89 | 79 | 4.438 | | | | | |
| Grain, hard winter | 88 | 14.4 | 3.88 | | 1.8 | 1.9 | *88.66* | 88 | 81.9 | 4.382 | | | | | |
| Grain, soft red winter | 88 | 13 | 3.92 | | 1.8 | 2.1 | *90.19* | 89 | 83.1 | 4.352 | | | | | |
| Grain, soft white winter | 89 | 11.3 | 3.92 | | 1.9 | 1.8 | *90.33* | 89 | 85 | 4.345 | | | 14 | 4 | |
| Grain, soft white winter, pacific coast | 89 | 11.2 | 3.88 | | 2.2 | 2.1 | *89.36* | 88 | 84.5 | 4.346 | | | | | |
| Grain screenings | 89 | 15.8 | 3.13 | | 3.9 | 6.1 | *72.29* | 71 | 74.2 | 4.339 | 4.23 | 34.22 | 30.41 | 17.76 | 5.07 |
| Grain, steam flaked | 82.96 | 14.42 | 3.82 | | 1.88 | 1.97 | *87.26* | 86.8 | 81.73 | 4.383 | | 64.89 | 13.55 | 5.51 | |
| Hay, sun-cured | 88 | 8.5 | 2.56 | | 2.2 | 7.1 | *62.73* | 58 | 82.2 | 4.098 | 9.35 | 4.68 | 57.89 | 35.89 | 4.82 |
| Mill run, less than 9.5% fiber (midds) | 90 | 17.2 | 3.48 | | 4.6 | 5.9 | *79.11* | 79 | 72.3 | 4.405 | 5.13 | 23.03 | 37.38 | 13.2 | 3.74 |
| Silage, full bloom | 25 | 8.1 | 2.6 | | 3 | 8.4 | *63.99* | 59 | 80.5 | 4.080 | 1.81 | 6.62 | 56.54 | 36.59 | 4.77 |
| Straw | 89 | 3.6 | 1.81 | | 1.8 | 7.8 | *45.77* | 41 | 86.8 | 3.975 | 2.5 | 1.64 | 73.65 | 50.23 | 7.42 |
| **Wheat, durum *(Triticum durum)*** | | | | | | | | | | | | | | | |
| Grain | 88 | 15.9 | 3.75 | | 2 | 1.8 | *84.95* | 85 | 80.3 | 4.419 | | | | | |
| **Wheatgrass, crested *(Agropyron desertorum)*** | | | | | | | | | | | | | | | |
| Fresh, early vegetative | 28 | 21.5 | 3.31 | | 2.2 | 10 | *79.78* | 75 | 66.3 | 4.173 | | | | | |
| Fresh, full bloom | 45 | 9.8 | 2.69 | | 3.6 | 9.3 | *65.89* | 61 | 77.3 | 4.100 | | | | | |
| Fresh, post ripe | 80 | 3.1 | 2.16 | | 1.2 | 4.1 | *52.99* | 49 | 91.6 | 4.089 | | | | | |
| Hay, sun-cured | 95 | 12.4 | 2.34 | | 2.3 | 7.2 | *56.51* | 53 | 78.1 | 4.158 | | | | | |
| **Whey *(Bos taurus)*** | | | | | | | | | | | | | | | |
| Dehydrated (cattle) | 93 | 14.2 | 3.57 | 3.905 | 0.7 | 9.8 | *90.06* | 81 | 75.3 | 3.993 | 56.09 | 1.28 | 0.55 | 0.4 | 0.1 |
| Fresh (cattle) | 7 | 13 | 4.14 | | 4.3 | 8.7 | *98.67* | 94 | 74 | 4.210 | 50.6 | 3.28 | 1.66 | 4.23 | 0.6 |
| Low lactose, dehydrated (dried whey product) (cattle) | 93 | 17.9 | 3.48 | | 1.1 | 16.5 | *92.87* | 79 | 64.5 | 3.792 | | | | | |

| Feedstuff | DM% | CP% | DE (mcal/kg) | GE (mcal/kg) | EE (%) | Ash (%) | Calculated: Ewan, 1989[a] DE (% of GE) | TDN (%) | Total $(CH_2O)_n$ (%) | Calculated: NASEM, 2016[a] GE (mcal/kg) | Total Sugars (%) | Total Starch (%) | NDF (%) | ADF (%) | Lignin (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Winterfat, common *(Eurotia lanata)*** | | | | | | | | | | | | | | | |
| Fresh, stem-cured | 80 | 10.8 | 1.54 | | 2.8 | 15.8 | *40.89* | 35 | 70.6 | 3.803 | | | 72 | 44 | 10 |
| **Yeast, brewers *(Saccharomyces cerevisiae)*** | | | | | | | | | | | | | | | |
| Dehydrated | 93 | 46.9 | 3.48 | | 0.9 | 7.1 | *75.91* | 79 | 45.1 | 4.606 | 9.42 | 8.87 | 7.56 | 4.38 | 1.4 |
| **Yeast, irradiated *(Saccharomyces cerevisiae)*** | | | | | | | | | | | | | | | |
| Dehydrated | 94 | 51.2 | 3.35 | | 1.2 | 6.6 | *71.46* | 76 | 41 | 4.707 | | | | | |
| **Yeast, primary *(Saccharomyces cerevisiae)*** | | | | | | | | | | | | | | | |
| Dehydrated | 93 | 51.8 | 3.4 | | 1.1 | 8.6 | *73.86* | 77 | 38.5 | 4.628 | | | | | |
| **Yeast, torula *(Torulopsis utilis)*** | | | | | | | | | | | | | | | |
| Dehydrated | 93 | 52.7 | 3.44 | | 1.7 | 8.3 | *73.76* | 78 | 37.3 | 4.685 | | | | | |

Sources: Ewan, 1989; NASEM, 2016; Dairy One, 2021.

[a] Calculations for feedstuffs composition table are presented below:

### Calculations For Feedstuffs Composition Table

Calculated gross energy from Ewan (1989):

$$GE = [4143 + (56 \times EE\%) + (15 \times CP\%) - (44 \times Ash)] \div 1{,}000$$

Calculated total carbohydrates $(CH_2O)_n$ from NASEM (2016):

$$Carb = CP\% - EE\% - Ash$$

Calculated gross energy from NASEM (2016):

$$GE = [(5.65 \times CP\%) + (9.4 \times EE\%) + (4.15 \times Carb)] \div 100$$

Where:

| | | |
|---|---|---|
| *GE* | = | calculated gross energy (mcal/kg) |
| *EE%* | = | percent ether extract |
| *CP%* | = | percent crude protein |
| *Ash* | = | percent ash |
| *Carb* | = | percent total carbohydrates $(CH_2O)_n$ |

# Appendix 4-F: IPCC (2019) Equations

Equation 4-11 and equation 4-14 within chapter 4 require several calculated values to calculate gross energy. The following equations and tables are provided as published in IPCC (2019) guidelines for convenience to the users of this report. equation 4-12 may require reference to IPCC (2019) Table 10.12.

**IPCC (2019) Equation 10.3: Net Energy for Maintenance**

$$NE_m = Cf_i \times (Weight)^{0.75}$$

Where:

| | | |
|---|---|---|
| $NE_m$ | = | net energy required by the animal for maintenance (MJ/day) |
| $Cf_i$ | = | a coefficient which varies for each animal category as shown in table 10.4 (MJ/day/kg) |
| $Weight$ | = | live weight of animal (kg) |

**IPCC (2019) Table 10.4. (Updated) Coefficients for Calculating Net Energy for Maintenance ($NE_m$)**

| Animal Category | $Cf_i$ (MJ/day/kg) | Comments |
|---|---|---|
| Cattle/Buffalo | 0.322 | All nonlactating cows, steers, heifers, and calves |
| Cattle/Buffalo (lactating cows) | 0.386 | Maintenance energy requirements are 20% higher during lactation |
| Cattle/Buffalo (bulls) | 0.370 | Maintenance energy requirements are 15% higher for intact males than nonlactating females |
| Sheep (lamb to 1 year) | 0.236 | This value can be increased by 15% for intact males. |
| Sheep (older than 1 year) | 0.217 | This value can be increased by 15% for intact males. |
| Goats | 0.315 | |

**IPCC (2019) Equation 10.4: Net Energy for Activity (for Cattle and Buffalo)**

$$NE_a = C_a \times NE_m$$

Where:

| | | |
|---|---|---|
| $NE_a$ | = | net energy for animal activity (MJ/day) |
| $C_a$ | = | coefficient corresponding to animal's feeding situation (table 10.5) (MJ/day/kg) |
| $NE_m$ | = | net energy required by the animal for maintenance (MJ/day) |

**IPCC (2019) Equation 10.5: Net Energy for Activity (for Sheep and Goats)**

$$NE_a = C_a \times (Weight)$$

Where:

| | | |
|---|---|---|
| $NE_a$ | = | net energy for animal activity (MJ/day) |
| $C_a$ | = | coefficient corresponding to animal's feeding situation (table 10.5) (MJ/day/kg) |
| $Weight$ | = | live weight of animal (kg) |

**IPCC (2019) Table 10.5. (Updated) Activity Coefficients Corresponding to Animal's Feeding Situation**

| Situation | Definition | $C_a$ |
|---|---|---|
| **Cattle and Buffalo (unit for $C_a$ is dimensionless)** | | |
| Stall | Animals are confined to a small area (i.e., tethered, pen, barn) with the result that they expend very little or no energy to acquire feed. | 0 |
| Pasture | Animals are confined in areas with sufficient forage requiring modest energy expense to acquire feed | 0.17 |
| Grazing large areas | Animals graze in open ranged land or hilly terrain and expend significant energy to acquired feed. | 0.36 |
| **Sheep and goats (unit for $C_a$= MJ/day/kg)** | | |
| Housed ewes | Animals are confined due to pregnancy in final trimester (50 days). | 0.0096 |
| Grazing flat pasture | Animals walk up to 1,000 meters per day and expend very little energy to acquire feed. | 0.0107 |
| Grazing hilly pasture | Animals walk up to 5,000 meters per day and expend significant energy to acquire feed. | 0.024 |
| Housed fattening lambs | Animals are housed for fattening. | 0.0067 |
| Lowland goats | Animals walk and graze in lowland pasture. | 0.019 |
| Hill and mountain goats | Animals graze in open range land or hilly terrain and expend significant energy to acquire feed. | 0.024 |

**IPCC (2019) Equation 10.6: Net Energy for Growth (For Cattle and Buffalo)**

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

Where:

$NE_g$ = net energy needed for growth (MJ/day)

$BW$ = the average live body weight of the animals in the population (kg)

$C$ = a coefficient with a value of 0.8 for females, 1.0 for castrates and 1.2 for bulls (NRC 1996)

MW = the mature body weight of an adult animal individually, mature females, mature males and steer in moderate body condition (kg)

$WG$ = the average daily weight gain of the animals in the population (kg/day)

**IPCC (2019) Equation 10.7: Net Energy for Growth (For Sheep and Goats) (Updated)**

$$NE_g = \frac{WG_{lamb/kid} \times \left(a + 0.5b\left(BW_i + BW_f\right)\right)}{365}$$

Where:

$NE_g$ = net energy needed for growth (MJ/day)
$WG_{lamb/kid}$ = the weight gain ($BW_f$—$BW_i$) (kg/year)
$BW_i$ = the live body weight at weaning (kg)
$BW_f$ = the live body weight at 1-year old or at slaughter (live weight) if slaughtered prior to 1 year of age (kg)
*a, b* = constants from table 10.6

**IPCC (2019) Table 10.6. (Updated) Constants for Use in Calculating $NE_G$ for Sheep and Goats**

| Animal species/category | a (MG/kg) | b (MG/kg) |
|---|---|---|
| Intact males (Sheep) | 2.5 | 0.35 |
| Castrates (Sheep) | 4.4 | 0.32 |
| Females (Sheep) | 2.1 | 0.45 |
| Goats (All categories) | 5.0 | 0.33 |

Source: Cited within IPCC (2019) as AFRC (1993; 1995).

**IPCC (2019) Equation 10.8: Net Energy for Lactation (Beef Cattle, Dairy Cattle and Buffalo)**

$$NE_l = Milk \times (1.47 + 0.40 \times Fat)$$

Where:

$NE_l$ = net energy for lactation (MJ/day)
*Milk* = amount of milk produced (kg of milk/day)
*Fat* = fat content of milk (% by weight)

**IPCC (2019) Equation 10.9: (Updated) Net Energy for Lactation for Sheep and Goats (Milk Production Known)**

$$NE_l = Milk \times EV_{milk}$$

Where:

$NE_l$ = net energy for lactation (MJ/day)
*Milk* = amount of milk produced (kg of milk/day)
$EV_{milk}$ = net energy required to produce 1 kg of milk

**IPCC (2019) Equation 10.10: Net Energy for Lactation for Sheep and Goats (Milk Production Unknown)**

$$NE_l = \left[\frac{(5 \times WG_{wean})}{365}\right] \times EV_{milk}$$

Where:

| | | |
|---|---|---|
| $NE_l$ | = | net energy for lactation (MJ/day) |
| $WG_{wean}$ | = | the weight gain of the lamb between birth and weaning (kg) |
| $EV_{milk}$ | = | the energy required to produce 1 kg of milk (MJ/kg) |

A default $EV_{milk}$ value of 4.6 MJ/kg (sheep) (AFRC 1993; AFRC 1995) and 3 MJ/kg (goats) (AFRC 1998) can be used which corresponds to a milk fat content of 7% and 3.8% by weight for sheep and goats, respectively. Milk fat can vary greatly among breeds.

**IPCC (2019) Equation 10.11: Net Energy for Work (for Cattle and Buffalo)**

$$NE_{work} = 0.10 \times NE_m \times Hours$$

Where:

| | | |
|---|---|---|
| $NE_{work}$ | = | net energy for work (MJ/day) |
| $NE_m$ | = | net energy required by the animal for maintenance (equation 10.3) (MJ/day) |
| $Hours$ | = | number of hours of work/day |

**IPCC (2019) Equation 10.12: (Updated) Net Energy to Produce Wool (For Sheep and Goats)**

$$NE_{wool} = \left(\frac{EV_{milk} \times Pr_{wool}}{365}\right)$$

Where:

| | | |
|---|---|---|
| $NE_{wool}$ | = | net energy required to produce wool (MJ/day) |
| $EV_{milk}$ | = | the energy value of each kg of wool produced (weighed after drying but before scouring) (MJ/kg).<br>A default value of 24 MJ/kg can be used for sheep estimate. For goats this energy value is not considered unless fiber-producing goat numbers are relevant for a country (AFRC 1995). |
| $Pr_{wool}$ | = | annual wool production per sheep/goat (kg/year) |

**IPCC (2019) Equation 10.13: Net Energy for Pregnancy (for Cattle/Buffalo and Sheep and Goats)**

$$NE_p = C_{pregnancy} \times NE_m$$

Where:

| | | |
|---|---|---|
| $NE_p$ | = | net energy required for pregnancy (MJ/day) |
| $C_{pregnancy}$ | = | pregnancy coefficient (0.10 for Cattle and Buffalo, from table 10.7) |
| $NE_m$ | = | net energy required by the animal for maintenance (equation 10.3), (MJ/day) |

**IPCC (2019) Table 10.7. (Updated) Constants for Use in Calculating $NE_P$ in Equation 10.13**

| Animal Category | $C_{pregnancy}$ |
|---|---|
| Cattle and Buffalo | 0.10 |
| Sheep/Goats | |
| Single Birth | 0.077 |
| Double birth (twins) | 0.126 |
| Triple birth or more (triplets) | 0.150 |

**IPCC (2019) Equation 10.14: Ratio of Net Energy Available in a Diet for Maintenance to Digestible Energy**

$$REM = \left[1.123 - (0.004092 \times DE) + (0.00001126 \times (DE)^2) - \left(\frac{25.4}{DE}\right)\right]$$

Where:

$REM$ = ratio of net energy available in diet for maintenance to digestible energy

$DE$ = digestibility of feed expressed as a fraction of gross energy (digestible energy/gross energy)

**IPCC (2019) Equation 10.15: Ratio of Net Energy Available for Growth in a Diet to Digestible Energy Consumed**

$$REG = \left[1.164 - (0.00516 \times DE) + (0.00001308 \times (DE)^2) - \left(\frac{37.4}{DE}\right)\right]$$

Where:

$REG$ = ratio of net energy available for growth in a diet to digestible energy consumed

$DE$ = digestibility of feed expressed as a fraction of gross energy (digestible energy/gross energy)

**IPCC (2019) Equation 10.16: Gross Energy for Cattle/Buffalo, Sheep and Goats**

$$GE = \left[ \frac{\left(\frac{NE_m + NE_a + NE_l + NE_{work} + NE_p}{REM}\right) + \left(\frac{NE_g + NE_{wool}}{REG}\right)}{DE} \right]$$

Where:

$GE$ = gross energy (MJ/day)
$NE_m$ = net energy required by the animal for maintenance (equation 10.3) (MJ/day)
$NE_a$ = net energy for animal activity (equation 10.4 and equation 10.5) (MJ/day)
$NE_l$ = net energy for lactation (equation 10.8 for cattle, equation 10.9 or equation 10.10 for sheep and goats) (MJ/day)
$NE_{work}$ = net energy for work (equation 10.11) (MJ/day)
$NE_p$ = net energy required for pregnancy (equation 10.13) (MJ/day)
$REM$ = ratio of net energy available in a diet for maintenance to digestible energy (equation 10.14)
$NE_g$ = net energy needed for growth (equation 10.6 for cattle, equation 10.7 for sheep and goats) (MJ/day)
$REG$ = ratio of net energy available for growth in a diet to digestible energy consumed (equation 10.15)
$NE_{wool}$ = net energy required to produce a year of wool (equation 10.12) (MJ/day)
$DE$ = digestibility of feed expressed as a fraction of gross energy) digestible energy/gross energy)

**IPCC (2019) Table 10.12. (Updated) Cattle/Buffalo Methane Conversion Factors ($Y_m$)**

| Livestock Category | Description | Feed Quality Digestibility (DE, %) and Neutral Detergent Fiber (NDF, %DMI) | MY, g $CH_4$/kg DMI | $Y_m$ |
|---|---|---|---|---|
| Dairy cows and buffalo | High-producing cows (> 8500 kg/head/year) | DE ≥ 70<br>NDF ≤ 35 | 19.0 | 5.7 |
| | | DE ≥ 70<br>NDF ≥ 35 | 20.0 | 6.0 |
| | Medium-producing cows (5000 -8500 kg/head/year) | DE 63-70<br>NDF > 37 | 21.0 | 6.3 |
| | Low-producing cows (< 5000 kg/head/year) | DE ≤ 62<br>NDF > 38 | 21.4 | 6.5 |
| Nondairy and multipurpose cattle and buffalo | > 75% forage | DE ≤ 62 | 23.3 | 7.0 |
| | Rations of >75% high quality forage and/or mixed rations, forage of between 15 and 75% the total ration mixed with grain, and/or silage. | DE 62-71 | 21.0 | 6.3 |
| | Feedlot (all other grains, 0–15% forage) | DE ≥ 72 | 13.6 | 4.0 |
| | Feedlot (steam-flaked corn ionophore supplement, 0–10% forage) | DE > 75 | 10.0 | 3.0 |