ABSTRACT

Dairy farms have been identified as an important source of greenhouse gas emissions. Within the farm, important emissions include enteric CH4 from the animals, CH4 and N2O from manure in housing facilities during long-term storage and during field application, and N2O from nitrification and denitrification processes in the soil used to produce feed crops and pasture. Models using a wide range in level of detail have been developed to represent or predict these emissions. They include constant emission factors, variable process-related emission factors, empirical or statistical models, mechanistic process simulations, and life cycle assessment. To fully represent farm emissions, models representing the various emission sources must be integrated to capture the combined effects and interactions of all important components. Farm models have been developed using relationships across the full scale of detail, from constant emission factors to detailed mechanistic simulations. Simpler models, based upon emission factors and empirical relationships, tend to provide better tools for decision support, whereas more complex farm simulations provide better tools for research and education. To look beyond the farm boundaries, life cycle assessment provides an environmental accounting tool for quantifying and evaluating emissions over the full cycle, from producing the resources used on the farm through processing, distribution, consumption, and waste handling of the milk and dairy products produced. Models are useful for improving our understanding of farm processes and their interacting effects on greenhouse gas emissions. Through better understanding, they assist in the development and evaluation of mitigation strategies for reducing emissions and improving overall sustainability of dairy farms.

Key words: greenhouse gas, model, dairy, methane, carbon footprint

INTRODUCTION

Greenhouse gas (GHG) emissions have gained international attention due to their effect on global climate. There are many sources of GHG emissions, with agriculture estimated to contribute about 11% of all global emissions (Smith et al., 2014) and 8.4% of US emissions (EPA, 2017). Livestock have received extra attention for their contribution to GHG emissions along with other environmental impacts (Steinfeld et al., 2006). Globally, cattle are estimated to produce 5,335 Mt of CO2 equivalents (CO2e) per year, which is about 11% of all human-induced GHG emissions (Smith et al., 2014). Within the United States, cattle are estimated to produce 212 Mt of CO2e per year, or 3.4% of total GHG emissions, with dairy cattle responsible for 83.5 Mt of CO2e, or 1.3% of the US total (EPA, 2017).

Dairy farms are a major contributor to the total GHG emissions over the life cycle of milk and other dairy products. In an evaluation of GHG emissions from the national supply chain of fluid milk, Thoma et al. (2013) found that 72% of the emissions occurred in processes prior to the milk leaving the farm. Thus, it is important to know farm emission sources and to understand the processes creating those emissions. Knowing more about these emission sources and the processes involved leads to opportunities for mitigation.

Important sources of GHG emissions from dairy farms include CH4 and N2O from enteric fermentation, manure storage and handling, and crop and pasture land (Figure 1). Anthropogenic CO2 emissions from fossil fuel combustion and the decomposition of lime applied to crop and pasture land also contribute. Nitrous oxide emissions include both direct emissions from the farm and indirect emissions from ammonia and nitrates leaving the farm that may ultimately transform into N2O in other ecosystems. Although these are often treated as independent sources, interactions do occur, which affect the overall emission.

Much effort has been given to measuring GHG emissions from each important source on dairy farms, but
monitoring and simultaneously quantifying all emissions from a given farm or production system is essentially impossible and prohibitively expensive. Thus, some type of model is required to quantify and evaluate GHG emissions from dairy production systems. Models can range from relatively simple emission factors to very detailed process-level simulations. All model forms have appropriate applications; an emission factor provides a quick assessment, but to fully understand the emission processes and their interactions a detailed process model is needed. The objective of the current study was to review the more important models used to evaluate GHG emissions from dairy farms across this full continuum of modeling approaches.

MODELING GHG SOURCES

Across the continuum of model complexity, models can be categorized as (1) emission factors, (2) process-driven emission factors, (3) empirical or statistical relationships, and (4) mechanistic process simulation. The simplest emission factors consist of 1 value to represent the production system. For example, the GHG emission for US dairy farms could be defined as 8,000 kg of CO₂e/cow. Although crude, this would provide a very general number that may be appropriate for certain applications. More often, factors are used to quantify the important individual processes of a dairy farm. When they represent the underlying process, they can be classified as process-driven emission factors. The IPCC (2006a) has defined these as tier 2 factors; an example is when enteric CH₄ is represented as a function of gross energy intake of the animal. A similar, but usually more detailed model, is an empirical relationship where a process is described as a function of multiple factors. This may be a purely statistical model based upon measured data without much understanding of the underlying process or a relationship developed to represent the process using linear or nonlinear functions. The most detailed model is a more mechanistic process simulation that uses multiple relationships to represent the dynamics within the process. Examples

Figure 1. Important direct and indirect greenhouse gas sources and relative amounts (differently sized arrows) emitted from dairy farms. Color version available online.
of the various types of models will be discussed for each of the important sources of GHG emission on a dairy farm.

**Enteric**

Enteric emissions are normally the largest source of GHG on a dairy farm. On well-managed confinement farms, they contribute about 45% of the total GHG emission of the full farm system, and on more-extensive grazing farms the proportion may be a little greater (Rotz and Thoma, 2017). Models using each level of detail have been used to represent enteric GHG production, which is primarily CH₄ but may include minor amounts of N₂O (Hamilton et al., 2009). In the simplest form, enteric CH₄ production on North American dairy farms can be represented as 121 kg of CH₄/cow per year and, for smaller animals on grazing operations in New Zealand, may be 81 kg of CH₄/cow per year (IPCC, 2006a). A more process-oriented emission factor is normally recommended though, where enteric methane is predicted to be proportional to gross energy intake of feed. An emission factor of this form recommended by the IPCC (2006a), as a tier 2 factor is widely accepted and used to represent enteric methane production.

Feed characteristics other than gross energy content are known to affect enteric production, and representing those effects requires a more detailed model. Through a meta-analysis of 89 published studies, Liu et al. (2017) expanded the IPCC tier 2 approach by developing a CH₄ conversion factor based upon digestible energy, which better represented the effects of the large variation in cattle diets. Statistical models have been developed relating enteric CH₄ to combinations of the intake of DM, gross energy, ME, ADF, hemicellulose, cellulose, starch, and so on (Ellis et al., 2007). Many of these models have used linear relationships (Appuhamy et al., 2016; Bell et al., 2016; Santiago-Juarez et al., 2016), but enteric production is not necessarily a linear process in relation to diet characteristics. Thus, these relationships are not robust in predicting beyond the bounds of the data from which they were developed. When predicting emission over a full range of feed characteristics, a nonlinear relationship is more appropriate where emission rate gradually approaches upper and lower bounds (Ramin and Huhtanen, 2012). A nonlinear model developed by Mills et al. (2003) that represents enteric CH₄ as a function of metabolic energy intake, and starch-to-fiber ratio has proven effective in predicting CH₄ production over a wide range of forage content in diets (Stackhouse-Lawson et al., 2012).

Enteric fermentation is a complex process that cannot be fully represented by an equation. For a better understanding of the various processes involved and their interactions in producing gaseous emissions, a dynamic process simulation is required. A model that simulates the digestion, absorption, and outflow of nutrients in the rumen and hindgut has been used to predict enteric emissions over a range of diets (Dijkstra et al., 1992; Ellis et al., 2012). Another model, known as Molly, uses multiple relationships to represent digestion, metabolism, and production of a dairy cow (Baldwin, 1995). This model has been refined and used to predict CH₄ production from grass-fed dairy cows (Gregorini et al., 2013). This type of model provides better understanding of the processes controlling gas production and emission. A model with this level of detail, however, may be cumbersome for use in modeling a herd of dairy cattle in a whole-farm system or for applications other than research.

Enteric N₂O is also produced by cattle (Hamilton et al., 2009). The mechanism and amount produced are not well understood, but the amount may be related to nitrate concentration in the diet. Relative to enteric CH₄, the amount produced is small and is normally ignored. Given that the global warming potential of this compound is about 10 times greater than that of CH₄, even a small amount may have importance. Emission factors that can be used to represent this source are 0.4 g of N₂O/cow per day or 0.8 g of N₂O/kg of N intake (Rotz et al., 2016). For typical dairy cow diets, enteric N₂O has about 1% of the global warming potential of the enteric CH₄ produced. Until more is known about this GHG source, a more detailed model is not justified.

**Manure**

Greenhouse and related gases are emitted from manure from the point of excretion by the animal until they are incorporated into soil or another final destination. The IPCC (2006a) provides very general CH₄ emission factors for the manure produced by dairy cattle as influenced by average annual ambient temperature and region. These emission factors vary from 48 kg of CH₄/cow per year in the northern United States to 78 kg of CH₄/cow per year in the southern part of the country, with annual N₂O emissions from manure vary from 0 to 25 g of N₂O/kg of cattle BW, primarily dependent upon the type of manure management used. This provides the most basic models, which should only be used to obtain general emission values. More specific estimations can be obtained by considering the individual components making up the production system, which include housing facilities, long-term storage, and field application.

**Housing Facilities.** Emissions from animal housing vary with the type of manure handling used. Major...
housing types on dairy farms include freestall barns with solid floors, barns with slatted floors and a collection pit below, bedded pack barns, and open lots. In freestall barns, manure is normally removed every few hours or once per day by scraping or flushing. With this rapid removal of the manure, CH₄ and N₂O do not have time to form and emissions are low. With a slatted floor, manure accumulates in a pit under the floor from a few weeks up to several months. In a bedded pack barn, manure accumulates on the floor for a few months or more along with the bedding material added to absorb moisture. The aerobic and anaerobic conditions within the pit or manure pack lead to much greater CH₄ and N₂O emissions. Manure also accumulates on an open lot, but the manure is spread in a thinner layer where the more aerobic conditions create less GHG emission.

Housing GHG emissions are normally small on dairy farms compared with total farm emissions. For a freestall facility, housing emissions make up less than 5% of the total farm emission (Rotz and Thoma, 2017). Open lot emissions are greater, but they are normally less than 10% of total farm emissions. A slatted floor or bedded pack facility can essentially combine housing and long-term manure storage, which leads to much greater (up to 35% of total farm) emissions.

Emissions from animal housing manure can be represented by emission factors derived from measured data. For example, Groenestein et al. (2012) presented annual GHG emission factors for dairy cows in permanent housing of 177 kg of CH₄ and 0.16 kg of N₂O per cow. Adviento-Borbe et al. (2010) found daily CH₄ emission rates from the manure of lactating cows in a freestall barn to be about 18.5 g/500 kg of animal unit (AU) in late winter and spring and 30 g/AU in the summer. They found N₂O emissions to be negligible, at less than 0.1 g/AU per day. Chianese et al. (2009b) used these data to create a simple process-related emission factor, where the daily emission rate was proportional to the floor area and the temperature in the barn when above 0°C; they assumed N₂O emissions were zero for freestall housing.

For systems where manure accumulates in the housing facility, the IPCC (2006a) tier 2 approach is often used. This process-related emission factor estimates an annual CH₄ emission rate based upon the daily volatile solids excretion of the cattle, a maximum CH₄ producing capacity of the manure, and a CH₄ conversion capacity (MCF) of the manure management system (IPCC, 2006a). Values for MCF vary with average annual temperature as well as the type of housing used. For North American temperatures, the MCF of an open lot is relatively small (about 1%) compared with those for the slatted floor and bedded pack designs (17–27% increasing with temperature). For N₂O, emission factors predict the N₂O-N emission in proportion to the N excreted by the cattle. These factors are 0, 2, 0.2, and 1% for daily removal, open lot, slatted floor and pit, and bedded pack systems, respectively (IPCC, 2006a). The uncertainty of these factors is large, but they provide a general estimate of the GHG emissions from dairy housing facilities.

More detailed process simulation models have been developed for some housing systems. For freestall facilities, the manure residence time and resulting GHG emissions are low, so a dynamic process model is not warranted. Li et al. (2012) provide a dynamic simulation of feedlot emissions. A comprehensive model simulates important biogeochemical processes including decomposition, hydrolysis, nitrification, denitrification, and fermentation to predict the various transformations of carbon and nitrogen and the resulting gaseous emissions. A similar but less detailed approach was used by Bonifacio et al. (2015) to represent these processes using relationships from the DayCent model (Del Grosso et al., 2000a,b; DayCent, 2008). These dynamic models track processes in the manure through time, predicting daily emissions based upon the manure and environmental conditions of the day. A similar process model has been developed to represent bedded pack facilities (Rotz et al., 2016), but to date this component has not been verified and published due to a lack of measured data for evaluating model performance.

Cattle housing facilities are also a major source of NH₃ emissions. After leaving the farm, the NH₃ can transform to other forms of N, including N₂O; thus, these facilities can be an important indirect source of GHG. The IPCC (2006b) provides a simple emission factor for this source, with 1% of the NH₃-N emitted ultimately transforming to N₂O-N. Dynamic models of atmospheric chemistry and transport better represent this process. Bash et al. (2013) coupled regional air quality and agroecosystem models to reduce the error and biases in estimating ambient aerosol concentrations and NH₃ and ammonium depositions for the continental United States.

Because NH₃ emissions can be very large, modeling those emissions from housing facilities is important in quantifying whole-farm GHG emissions. The IPCC (2006a) provides a series of emission factors expressing the loss in proportion to the total N excreted; these losses were 7% with no long-term storage and 20, 28, and 30% for open lot, under-floor pit, and bedded pack facilities, respectively. Many factors affect NH₃ emissions, so process simulation provides a more robust estimation across variable conditions. Rotz et al. (2014) provide a detailed model of the NH₃ formation, speciation, aqueous-gas partitioning, and mass transfer processes to predict daily emissions, as influenced by

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the type of facility, manure characteristics, and environmental conditions.

**Manure Storage and Handling.** Many methods are used to handle dairy cattle manure, and the amount and type of GHG emissions varies greatly with the methods used. A large portion of dairy farms still use a daily hauling system with no storage or short-term storage of a few days to a few weeks. Under these conditions, GHG emissions during the handling process are minimal. However, ammonia emission can still be large, contributing to indirect emissions of N₂O. Farms using daily hauling are typically small in size, so a major portion of the manure from dairy cattle is stored long-term (4–12 mo) in some type of facility.

For long-term storage, manure can be handled and stored as a liquid (about 5% DM), slurry (8–12% DM), semisolid (12–15% DM), or solid (greater than 15% DM). Manure is excreted in a slurry form. Separators can be used to remove a portion of the solids leaving both liquid and solid streams for storage and handling. Manure deposited on an open lot dries, also providing a solid material. Manure solids can be stored in a stack without further treatment or periodically turned to promote composting. The amount of aeration received effects both from methanogenesis and denitrification processes and the resulting gaseous emissions. When oxygen is available, microbial decomposition primarily occurs through respiration producing CO₂, but without oxygen methanogens produce CH₄.

The anaerobic conditions of liquid or slurry manure provide a good environment for CH₄ production. Nitrous oxide emission is minimal unless a crust forms on the surface; particles of bedding and undigested feed will float to the surface, forming a crust. The moist aerobic and anaerobic conditions within this crust provide an environment for incomplete denitrification and the creation of N₂O. In the more aerobic conditions of semisolid and solid manure storage, methanogenesis is reduced and microbial respiration produces CO₂. This also provides a suitable environment for nitrification and denitrification processes producing N₂O.

The amount of GHG emitted from manure storage and handling varies from negligible to one of the largest sources on dairy farms. Without storage, the GHG emission during manure handling can be ignored. During long-term storage, emissions are primarily related to oxygen availability (DM content), volatile solids content, temperature, and length of storage. Simple emission factors can be developed from experimental measurements. For example, Kaharabata and Schuepp (1998) developed an emission factor for the annual emission from a slurry tank in Canada to be 74 kg of CH₄ · m⁻² of surface area, and used it to estimate the total emissions from slurry tanks in Canada. Through a literature review, Chianese et al. (2009c) found average annual emissions of 6.5 kg of CH₄ · m⁻³ of stored manure for slurry tanks and 2.3 kg of CH₄ · m⁻³ for solid manure in stacks. Corresponding annual N₂O emissions for slurry without a surface crust, slurry with a crust, and solid stacks were 0.01, 0.13, and 0.1 kg of N₂O · m⁻³, respectively.

The most commonly used emission factors for representing manure storage are the tier 2 factors recommended by the IPCC (2006a). As noted for housing emissions, these process-related factors predict CH₄ emission as a function of the daily volatile solids excretion of the cattle, a maximum CH₄-producing capacity of the manure, and an MCF for the manure system. Values for MCF vary with average annual temperature from 10 to 50% for a slurry tank with a natural crust cover and from 17 to 80% without the crust. For solid manure stored in stacks, the MCF is much lower, ranging from 2 to 5%; with active composting, this range drops to 0.5 to 1.5%. For N₂O, emission factors are 0, 5, and 100 g of N₂O-N/kg of N excreted for liquid or slurry storage without a crust, slurry with a crust, solid stack, and actively composted stacks, respectively (IPCC, 2006a). VanderZaag et al. (2013) reviewed modeling approaches and recommended an expansion of the IPCC model to better reflect the effects of specific farm management practices by developing a matrix of CH₄ conversion factors that account for key factors known to affect CH₄ emissions (temperature, retention time, and inoculum).

Nonlinear empirical models better describe the emission processes over a wide range of conditions. Sommer and Peterson (2004) developed a model that predicts CH₄ emission rate from slurry or liquid manure using an Arrhenius relationship, describing the effects of temperature and degradable and nondegradable volatile solids contents. This provides a suitable model for use in dynamic simulation of manure systems where daily emission rates are predicted based upon the manure and environmental conditions of the day (Chianese et al., 2009a).

Process-level dynamic simulations are also used to represent manure storage and treatment systems. The model by Li et al. (2012) is used to represent compost, lagoon, and anaerobic digestion facilities on dairy farms. The manure undergoes a series of reactions of decomposition, hydrolysis, volatilization, nitrification, denitrification, and fermentation to predict nutrient transformations and gaseous emissions. Environmental factors based upon the technical specification of the facility are used to drive these biogeochemical reactions. Bonifacio et al. (2017) developed a process simulation to predict C and N transformations and emissions from static stacks and turned windrows of composting cattle.
manure. The model predicts changes in C (organic and microbial) and N (organic, microbial, ammonium, and nitrate) contents within the stack, CO$_2$, CH$_4$, N$_2$O, and NH$_3$ emissions throughout composting and corresponding C and N losses to the environment.

Anaerobic digestion of manure is recognized as an important strategy for mitigating GHG emissions from dairy farms. Several process-based models have been developed to better understand and refine anaerobic digestion. Through a comprehensive literature review, Yu et al. (2013) has described the complex biochemical kinetics of anaerobic digestion and reviewed models used to represent these processes.

Dairy manure is normally applied to cropland for disposal and recycling of remaining nutrients. The most common application method is through broadcast spreading on the soil surface, where volatile emissions occur for a few days or until the manure is incorporated into the soil. Methane and N$_2$O emissions during the application process are often assumed negligible and are ignored. Rotz et al. (2016) modeled this source by predicting the amount of CH$_4$ remaining in the manure following long-term storage. This gas is assumed to be released within a few hours during the handling and spreading processes, creating a relatively small emission compared with other farm sources. Ammonia emissions following land application can be large and should be considered due to their potential for indirect N$_2$O emission; this emission source has been modeled using emission factors (IPCC, 2006a), empirical relationships (Sommer and Hutchings, 2001), and detailed process simulation (Rotz et al., 2014). Manure can be injected below the soil surface or incorporated into the soil by a tillage operation immediately after application. With soil incorporation, emissions during application are small and can be represented by an emission factor or process simulation based upon any manure left exposed on the surface (Rotz et al., 2011).

**Pasture and Cropland**

Emission processes continue after manure and inorganic fertilizers are incorporated into soil. Three important processes affect GHG emissions from cropland and pasture: oxidation, nitrification, and denitrification. Under most soil conditions, atmospheric methane is oxidized to form CO$_2$, thus creating a net sink (Boeckx et al., 1997). Through a review of published values for crops commonly grown on dairy farms, Chianese et al. (2009c) found an average annual absorption of 1.5 kg of CH$_4$/ha. To better represent the processes involved, Del Grosso et al. (2000c) developed an empirical model of CH$_4$ oxidation in natural and managed soil systems. On dairy farms, the amount of CH$_4$ oxidized is very small (typically <1%) compared with all GHG emissions (Chianese et al., 2009c); because of its small effect on the overall system, this sink is often ignored in modeling GHG emissions from dairy farms.

Nitrogen transformations in the soil include nitrification and denitrification processes, both of which can create N$_2$O. The N$_2$O produced by these processes is an important contribution to total farm GHG emissions. Nitrification is an aerobic process that oxidizes NH$_4$ to NO$_3$, with the production of NO and N$_2$O as intermediates. Denitrification is a microbial process that reduces nitrate to N$_2$. Depending upon the soil conditions, this process can be incomplete, also producing NO and N$_2$O. These processes are sometimes combined in an emission factor. The IPCC (2006b) recommends a N$_2$O-N emission of 1% of the N incorporated into soil and 2% of the N deposited by grazing cattle. Thus, emissions are 1.6 and 3.1 kg of N$_2$O/kg of N applied to cropland and pasture, respectively. This factor provides a general representation of these direct emissions, but great uncertainty exists in this estimation (IPCC, 2006b).

Nitrogen emitted from crop and pasture land on dairy farms in the form of NH$_3$ and nitrate can be large. As noted, this N can be transformed to N$_2$O in environments beyond the farm, creating indirect GHG emission. The IPCC (2006b) provides emission factors for estimating these emissions as a fraction of the N leaving the farm. For volatilized ammonia, indirect N$_2$O-N can be estimated as 1% of the N lost. For runoff to surface water and leaching to ground water, the suggested factor is 0.75% of the N lost through these pathways (IPCC 2006b).

Empirical relationships have also been used to estimate N$_2$O emissions. Heinen (2005) reviewed 50 empirically based models for predicting denitrification emissions. The majority of the models were based upon a potential denitrification rate as controlled by soil characteristics of nitrate–N content, temperature, acidity, and easily decomposable organic carbon content. Bouwman et al. (2002) proposed a relationship using the sum of many parameters representing management conditions to estimate soil N$_2$O and NO emissions. The model was further refined by Stehfest and Bouwman (2006) and used to calculate global annual emissions from fertilized cropland and grassland.

Simulation of soil processes provides a more robust prediction of emissions as they relate to soil and weather conditions. Del Grosso et al. (2000a) and Parton et al. (2001) developed and evaluated a series of empirical relationships to describe soil nitrification and denitrification processes. These relationships have been integrated along with models of soil carbon dynamics to form the DayCent model. A more process-based simulation of soil nitrogen and carbon dynamics is provided by the
DNDC model (Giltrap et al., 2010); DNDC consists of 5 interacting submodels, which represent thermal–hydraulic, aerobic decomposition, denitrification, fermentation, and plant growth processes. A similar level of detail is used in ECOSYS, a dynamic model that simulates microbial oxidation and reduction reactions with different soil amendments, such as crop residue, fertilizer, or manure, and under different soil management practices, such as crop rotation, tillage practice, and irrigation use (Metivier et al., 2009). These models are widely used to evaluate N₂O emissions from field to national scales.

Another consideration in modeling GHG emissions from the crop and pasture land on dairy farms is soil carbon sequestration. Soil provides a sink for long-term storage of carbon. The amount of carbon contained in soil always moves toward an equilibrium between emission and retention, as controlled by the environment and soil and crop management practices. Management changes, such as reducing the amount of tillage, increasing manure application rates, and conversion of annual crops to perennial crops, can disturb this equilibrium, leading to an increase in the storage of carbon in the soil. If this change in management is maintained, the soil carbon level will increase through time until a new equilibrium is attained. During this transition period, substantial amounts of carbon drawn from the atmosphere are stored in the soil, providing a reduction in overall farm GHG emission. This reduction is temporary, only occurring during this transition period. If this change in management is ever reversed, the sequestered carbon will be lost, increasing the overall farm GHG emission.

Accurate modeling of carbon sequestration is challenging. Soil properties, climate, and management practices influence the rate and total amount of stored carbon. Many experiments have provided empirical data on carbon sequestration for specific soils, climates, and management changes (e.g., Franzluebbers, 2005). These empirical data can be used to estimate the effect on farm GHG emissions (Rotz et al., 2009). Process simulation is also used in several models to predict C sequestration for specific conditions. Process models include Century (Parton et al., 1994), DayCent (Del Grosso et al., 2000a), DNDC (Giltrap et al., 2010), and Roth C (Coleman and Jenkinson. 1999). Through whole-farm simulation, Rotz et al. (2009) estimated that a transition from annual row crops to perennial grassland systems for a representative Pennsylvania dairy farm could reduce the carbon footprint by 0.14 to 0.46 kg of CO₂e/kg of ECM produced for the 20- to 30-yr period following the change. Although this provides a substantial benefit during this period, this has little effect on whole-farm GHG emissions for the very long term. If the farm ever reverts back to tilled cropland, the benefit is lost.

### Anthropogenic Sources

Carbon dioxide is an important GHG, but its role in dairy farm emissions is generally small. Carbon dioxide is considered as either biogenic or anthropogenic; biogenic is produced by living organisms, and anthropogenic is produced or created through human activities. Biogenic CO₂ comes through the recycling of carbon within our environment, and thus has no long-term effect on the atmosphere. Anthropogenic emissions contribute to global warming by adding new CO₂ to the atmosphere from carbon extracted from long-term storage in the earth.

Large amounts of CO₂ are emitted from dairy production systems through plant, animal, and microbial respiration. This is considered as biogenic, because the carbon was originally extracted from the atmosphere by plant fixation and now is returned to the atmosphere. With no long-term effect on the atmosphere, this source is normally ignored in modeling farm emissions.

The 2 important sources of anthropogenic CO₂ in dairy production are the combustion of fossil fuels and the decomposition of lime or urea used as a soil amendments. Each of these transform carbon from long-term storage in the earth to atmospheric CO₂. Together, these sources contribute around 5% of the total GHG emission from dairy farms (Rotz and Thoma, 2017).

Simple models can be used to represent these emission sources based upon the amount of carbon stored in the fuel or lime used. For each liter of diesel fuel consumed, about 2.7 kg of CO₂ are released. For gasoline, natural gas, and liquid petroleum gas, emissions are about 2.3 kg CO₂/L, 2.2 kg CO₂/m³, and 1.6 kg CO₂/L, respectively. When fuel consumption is known, CO₂ emission can be accurately predicted using these emission factors.

The challenge in modeling emissions associated with fuel use is to predict the amount of fuel used in the production system. Database models based upon empirical fuel use factors are often used to integrate fuel use over all operations in the production system (Camargo et al., 2013). A more mechanistic approach has also been applied, where machinery operations are dynamically simulated to estimate fuel consumption on the farm (Rotz et al., 2016).

Lime is a common amendment for increasing soil pH, and urea has become widely used for nitrogen fertilization. Lime is mined from the earth and urea is produced using fossil fuel, so the carbon contained is considered an anthropogenic source. As lime gradually decomposes and urea transforms to other nitrogen
forms in the soil following application, CO₂ is released and emitted to the atmosphere. About 0.45 kg of CO₂ are released per kilogram of lime applied, with 0.7 kg of CO₂ released per kilogram of urea applied (IPCC, 2006b). Multiplying the amounts used by these factors models this emission source with the assumption that none of the carbon remains in the soil long-term.

**PRODUCTION SYSTEM EMISSIONS**

Modeling of individual emission sources has limited value until those models are integrated to evaluate full production systems. Interactions exist among sources, so the whole is not equal to the sum of the parts. For example, C and N emissions from the housing system will control the amounts of these compounds moving on to storage and field application. When more C or N is lost in the first processes, fewer nutrients are moved on to the succeeding processes, and thus later emissions will be reduced. Feeding and management practices also affect the various processes differently, so a comprehensive assessment of the full system is required to quantify the total farm emission.

**Whole-Farm Models**

Several farm-scale models have been developed to quantify GHG emissions from dairy production systems. As with individual source models, these farm models vary widely in the detail used to represent various emission processes. The simplest models use emission factors and simple empirical functions to represent the various processes. More complex models use many interacting relationships to describe farm processes. All model types can have a useful purpose when appropriately applied.

An important reason for the diversity in available farm models is the purpose for which they were created. Important purposes for models are decision support, education, and research. Normally models cannot function well for all 3 of these purposes; the simplest models are most often developed and are most suitable for decision support. The more complex dynamic simulation models developed are best suited for research purposes. Research models are not very useful for decision support and decision support tools are not very useful for research purposes. There is often a strong desire for applying research models in decision support, but this has had little success. Both decision support and research models can be useful in education. Model users can learn more about the interacting effects of management changes on the overall efficiency and emissions of the production system. The more complex simulation models may be most useful in college level work, whereas simpler tools may be more useful for general education.

Several farm-scale models that can be used to represent dairy production systems are listed in Table 1 with a brief description. This is not intended to be a complete list of all available models, but common or available models of each type are represented. Decision support tools incorporate the simplest, emission factor-based models that can be easily adapted to a wide range of production practices. Thus, models such as AgRE Calc, COMET-Farm, and Cool Farm Tool (Table 1) work across a wide range of production systems, including dairy. When properly calibrated or verified with measured data or more complex models, they provide useful tools for guiding decisions in the strategic design and tactical management of production systems. Weaknesses of this type of model are that they may not appropriately represent individual farm processes over the full range of possible conditions, and they may not capture the interactions among sources as well as process simulation models.

Farm-scale process simulation models include DairyMod, MELODIE, FASSET, SIMS(Dairy), IFSM, and Manure DNDC (Table 1). These models were primarily developed by scientists to better understand the processes involved and predict how they interact; thus, they often provide the best understanding of the effects of farm management changes. A weakness compared with simpler models is that they are not as flexible. The addition of new processes requires detailed process models, which often require much time and effort to develop or adapt to the existing model structure.

Available process simulation models were developed in different countries and often for different types of dairy production systems. DairyMod was developed in Australia solely for pasture-based dairy production, with the major components being pasture production and animal utilization. Models such as MELODIE and SIMS(dairy) were primarily developed around pasture-based dairy production in Europe, but do include other components. Both FASSET and IFSM were developed around confinement production systems but also include pasture and grazing components; IFSM provides one of the most comprehensive tools in that it includes components for tillage, planting, harvest, feed storage, feeding, manure handling, and economics, along with crop and pasture growth and animal consumption and performance (Rotz et al., 2016). Manure DNDC provides the most detailed representation of the biogeochemical processes producing emissions from the soil and manure, but has little or no detail in representing some of the other farm components (Li et al., 2012).

Across the scale of model complexity, DairyGEM, DairyWise, FarmAC and Holos fall in the middle of
the scale (Table 1). These models rely more heavily on process-related emission factors and empirical relationships to describe the emission processes. These are often the tier 2 emission factors documented by the IPCC (2006a,b). DairyGEM includes the animal and manure management routines from IFSM, so these components are process simulations. These tools were developed with a more applied purpose in education and decision support, but they sometimes find application in research as well.

All process simulation models employ a range of relationships for describing emission sources. For minor sources where little is known, empirical emission factors may be the only or best option for representing the process. For enteric fermentation, the most practical model may consist of empirical relationships, because modeling rumen function requires too much detail for application at the whole-farm level. For something such as ammonia emissions, much theory is known, which enables detailed simulation of the formation, transfer,

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Application</th>
<th>Developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>AgRE Calc</td>
<td>Emission factor-based carbon calculator that determines a carbon footprint of various types of farms, including dairy. (<a href="http://www.agrecalc.com">http://www.agrecalc.com</a>)</td>
<td>Decision support and education</td>
<td>SAC Consulting, United Kingdom</td>
</tr>
<tr>
<td>COMET-Farm</td>
<td>Emission factor and process model primarily for estimating carbon sequestration and emissions of various types of farms, including dairy. (<a href="http://cometfarm.urel.colostate.edu/">http://cometfarm.urel.colostate.edu/</a>)</td>
<td>Decision support</td>
<td>USDA/Natural Resource Conservation Service, Colorado State University, Fort Collins</td>
</tr>
<tr>
<td>Cool Farm Tool</td>
<td>Emission factor-based carbon accounting tool for a wide range of cropping systems and includes a dairy livestock component. (<a href="https://coolfarmtool.org/">https://coolfarmtool.org/</a>)</td>
<td>Decision support and education</td>
<td>Cool Farm Alliance, England</td>
</tr>
<tr>
<td>DairyGEM</td>
<td>Emission factor and process simulation tool that estimates GHG, NH3, and other gaseous emissions and the carbon footprint of dairy production systems. (<a href="https://www.ars.usda.gov/northeast-area/up-pa/pswmru/docs/dairy-gas-emissions-model/">https://www.ars.usda.gov/northeast-area/up-pa/pswmru/docs/dairy-gas-emissions-model/</a>)</td>
<td>Education and decision support</td>
<td>USDA-Agricultural Research Service, University Park, PA</td>
</tr>
<tr>
<td>DairyMod</td>
<td>Biophysical process simulation of pastoral dairy systems predicting GHG dynamics including direct and indirect emissions and soil carbon balance. (<a href="http://imj.com.au/dairymod/">http://imj.com.au/dairymod/</a>)</td>
<td>Research and education</td>
<td>IMJ Consultants, Dairy Australia, University of Melbourne, Australia</td>
</tr>
<tr>
<td>DairyWise</td>
<td>An empirical model that simulates the technical, environmental, and financial processes on a dairy farm that includes nitrogen and phosphorus cycling and losses, GHG emissions, and energy use. (Schils et al., 2007)</td>
<td>Research and education</td>
<td>Wageningen UR, the Netherlands</td>
</tr>
<tr>
<td>FarmAC</td>
<td>Process-related emission factors represent carbon and nitrogen flows on arable and livestock farms quantifying GHG, soil C sequestration, and N losses to the environment. (<a href="http://www.farmac.dk/">http://www.farmac.dk/</a>)</td>
<td>Education and decision support</td>
<td>Aarhus University, Denmark</td>
</tr>
<tr>
<td>FASSET</td>
<td>Process simulation used to evaluate consequences of changes in regulations, management, prices and subsidies on farm production, profitability, nitrogen losses, energy consumption and GHG emissions. (<a href="http://www.fasset.dk/">http://www.fasset.dk/</a>)</td>
<td>Research</td>
<td>Aarhus University, Denmark</td>
</tr>
<tr>
<td>Holos</td>
<td>Process-based emission factors estimate all important direct and indirect sources of GHG emissions of livestock operations. (<a href="http://www.agr.gc.ca/eng/science-and-innovation/results-of-agricultural-research/holos/?id=1349181297838">http://www.agr.gc.ca/eng/science-and-innovation/results-of-agricultural-research/holos/?id=1349181297838</a>)</td>
<td>Education, decision support, research</td>
<td>Agriculture and Agri-Food Canada</td>
</tr>
<tr>
<td>IFSM</td>
<td>Process simulation of all important farm components representing the performance, economics, and environmental impacts including direct and indirect GHG emissions and carbon footprint. (<a href="https://www.ars.usda.gov/northeast-area/up-pa/pswmru/docs/integrated-farm-system-model/">https://www.ars.usda.gov/northeast-area/up-pa/pswmru/docs/integrated-farm-system-model/</a>)</td>
<td>Research and education</td>
<td>USDA-Agricultural Research Service, University Park, PA</td>
</tr>
<tr>
<td>ManureDNDC</td>
<td>Simulation of soil and manure biogeochemical processes producing GHG and NH3 emissions. (<a href="http://www.dndc.sr.unh.edu/">http://www.dndc.sr.unh.edu/</a>)</td>
<td>Research</td>
<td>University of New Hampshire, Durham</td>
</tr>
<tr>
<td>MELODIE</td>
<td>Dynamic simulation of the flows of carbon, nitrogen, phosphorus, copper, zinc and water within animal, pasture, crop and manure components. (Chardon et al., 2012)</td>
<td>Education and decision support</td>
<td>French National Institute for Agricultural Research, INRA, France</td>
</tr>
<tr>
<td>SIMS(Dairy)</td>
<td>Process simulation of the effects of management, climate and soil properties on nitrogen, phosphorus, and carbon losses along with profitability, biodiversity, soil quality, and animal welfare. (Del Prado et al., 2011)</td>
<td>Education and research</td>
<td>BC3-Basque Centre for Climate Change, Spain</td>
</tr>
</tbody>
</table>
and emission processes (Rotz et al., 2014). Finding and applying the appropriate model detail for a particular application is an important part of the modeling process. A proper match of model detail to that required for the application is critical for developing robust and efficient farm models. All farm models can have useful applications, and no single model can meet all of the needs or interests in farm modeling.

Life Cycle Assessment

When modeling farm GHG emissions, the ultimate output is usually the intensity or footprint of all emissions combined. For dairy production, this is often referred to as the carbon footprint of the milk produced (Rotz and Thoma, 2017). A farm-gate footprint is defined as the total of all GHG emissions related to the production of the milk divided by the total ECM leaving the farm (IDF, 2010). Methane, N₂O, and CO₂ have different effects on warming potential in the atmosphere. To sum the various sources, CH₄ and N₂O are converted to CO₂e units considering their global warming potential. Although different values have been used, those currently recommended based upon a 100-yr time horizon are 28 kg of CO₂e/kg of CH₄ and 265 kg of CO₂e/kg of N₂O if climate-carbon feedbacks are not considered (Myhre et al., 2013). With feedbacks considered, the values are 34 kg of CO₂e/kg of CH₄ and 298 kg of CO₂e/kg of N₂O. Uncertainty exists in these values, but they provide a general method for converting all important farm GHG emissions to a common unit for a total net farm emission.

To properly represent the carbon intensity or footprint of milk production, a farm-gate life cycle assessment must be used (Rotz and Thoma, 2017). In addition to the direct farm emissions, this comprehensive assessment considers the emissions occurring during the production of resources used on the farm, the indirect emissions associated with NH₃ and nitrate losses from the farm, and the allocation of all emissions among coproducts (Figure 2). Emissions occur during the production of electricity, fuel, fertilizer, purchased feed, and so on, and they must be included in the life cycle of milk. Emission factors are commonly used to represent these emissions, and their values often vary among studies dependent upon location, system boundaries, and other factors. On dairy farms, milk and cull meat animals are coproducts, and total emissions must be allocated between them. Different allocation methods are used by means of mass, biophysical, economic, or system expansion approaches for dividing the total among coproducts (Rotz and Thoma, 2017). The final result can be very sensitive to the approach used and related assumptions (Cederberg and Stadig, 2003).

A wide range of values can be found for the farm-gate carbon footprint of milk. Management practices on individual farms have a substantial effect on the final result. Model assumptions and procedures can also have a major influence, making it difficult to compare values produced by different studies. To compare

Figure 2. Important greenhouse gas emission sources from a dairy farm considered in a life cycle assessment of the milk produced (Adapted from Rotz et al., 2010). Color version available online.
the benefit of changes in farm management, the same model and basic assumptions must be used in representing all production systems. Standard procedures are being developed that should be followed in assessing and comparing production systems. The International Organization for Standardization (ISO, 2006) provides general guidelines, and more specific guidance for dairy is provided by the International Dairy Federation (IDF, 2010) and the Livestock Environmental Assessment and Performance (LEAP) Partnership of the United Nations FAO (LEAP, 2015). Even within these guidelines, there is flexibility in various assumptions, making it difficult to compare among studies.

Farm-gate GHG emissions associated with the production of milk on well managed dairy farms generally fall between 0.8 and 1.2 kg of CO$_2$e/kg of milk corrected to 4% fat and 3.5% protein (Rotz and Thoma, 2017). Factors that have the most influence on this footprint are the milk production level of the herd, animal diets, and manure-handling practices. Strategies used to increase milk production often cause greater emissions from the production system but a lower emission intensity. Emission intensity is expressed per unit of milk, so producing more milk with a proportionally lower increase in GHG emissions leads to a lower intensity or footprint. Feeding nutrients more efficiently reduces nutrient excretion and subsequent emissions. Of primary benefit to GHG emissions is efficient feeding of protein (nitrogen), which reduces the potential emission of N$_2$O, NH$_3$, and nitrates from excreted manure and, thus, both direct and indirect GHG sources. Finally, manure storage can be a major source of emissions, so using a covered storage or anaerobic digester can provide substantial reductions.

**Representative Production Systems**

As an illustration of whole-farm model use, 5 representative production systems were simulated with the Integrated Farm System Model (Table 2). These are provided only to illustrate typical annual emissions from dairy farms and the effect management can have on GHG emissions.

<table>
<thead>
<tr>
<th>Source</th>
<th>Grazing, $^1$ New Zealand</th>
<th>Grazing confinement, $^2$ Ireland</th>
<th>Freestall confinement, $^3$ Pennsylvania</th>
<th>Freestall with digester, $^4$ New York</th>
<th>Freestall and open lot, $^5$ Idaho</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Animal</td>
<td>kg of CH$_4$/cow</td>
<td>161</td>
<td>166</td>
<td>188</td>
<td>188</td>
</tr>
<tr>
<td></td>
<td>kg of N$_2$O/cow</td>
<td>0.18</td>
<td>0.19</td>
<td>0.17</td>
<td>0.19</td>
</tr>
<tr>
<td>Housing facility</td>
<td>kg of CH$_4$/cow</td>
<td>0.5</td>
<td>0.4</td>
<td>3.2</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>kg of N$_2$O/cow</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Manure storage</td>
<td>kg of CH$_4$/cow</td>
<td>3.2</td>
<td>3.5</td>
<td>64</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>kg of N$_2$O/cow</td>
<td>0</td>
<td>0</td>
<td>1.20</td>
<td>0</td>
</tr>
<tr>
<td>Crop and pasture land</td>
<td>kg of N$_2$O/cow</td>
<td>2.8</td>
<td>6.1</td>
<td>2.9</td>
<td>2.8</td>
</tr>
<tr>
<td>Fuel combustion</td>
<td>kg of CO$_2$/cow</td>
<td>80</td>
<td>152</td>
<td>392</td>
<td>187</td>
</tr>
<tr>
<td>Lime decomposition</td>
<td>kg of CO$_2$/cow</td>
<td>0</td>
<td>216</td>
<td>298</td>
<td>139</td>
</tr>
<tr>
<td>Indirect</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Housing facility</td>
<td>kg of NH$_3$/cow</td>
<td>3.3</td>
<td>2.8</td>
<td>16.8</td>
<td>20.1</td>
</tr>
<tr>
<td></td>
<td>kg of NO$_3$/cow</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Manure storage</td>
<td>kg of NH$_3$/cow</td>
<td>1.6</td>
<td>1.2</td>
<td>11.0</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td>kg of NO$_3$/cow</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Crop and pasture land</td>
<td>kg of NH$_3$/cow</td>
<td>47.8</td>
<td>29.7</td>
<td>32.0</td>
<td>31.4</td>
</tr>
<tr>
<td></td>
<td>kg of NO$_3$/cow</td>
<td>28</td>
<td>86</td>
<td>22</td>
<td>40</td>
</tr>
<tr>
<td>Total farm emission</td>
<td>kg of CO$_2$e/cow</td>
<td>8,008</td>
<td>8,294</td>
<td>11,280</td>
<td>9,333</td>
</tr>
<tr>
<td>Milk footprint</td>
<td>kg of CO$_2$e/kg of ECM</td>
<td>1.11</td>
<td>1.21</td>
<td>0.98</td>
<td>0.75</td>
</tr>
</tbody>
</table>

$^1$500 cows (average BW = 500 kg) plus heifers in a spring-calving herd producing 6,552 kg/cow per year (5% fat) on 175 ha of grassland with silt loam soil in northern New Zealand. Cows were on pasture year around, with a 4-mo manure storage period for the milking facility.

$^2$80 cows (average BW = 550 kg) plus heifers in a spring-calving herd producing 5,941 kg/cow per year (4.3% fat) on 45 ha of grassland with loam soil in Ireland. Cows were in a naturally ventilated freestall barn during winter with a 4-mo manure storage period.

$^3$300 cows (average BW = 625 kg) plus heifers in random calving herd producing 10,500 kg/cow per year (3.5% fat) on 275 ha (85 ha of alfalfa, 10 ha of grass, 170 ha of corn, and 10 ha of wheat) of clay loam soil in central Pennsylvania. Cattle were housed in naturally ventilated freestall barns with slurry manure stored in a bottom loaded tank emptied spring and fall.

$^4$1,000 cows (average BW = 600 kg) plus heifers producing 11,360 kg/cow per year (3.5% fat) on 970 ha (300 ha of alfalfa, 60 ha of grass, 530 ha of corn, and 80 ha of wheat) of shallow loam soil in upper New York. Cattle were housed in mechanically ventilated freestall barns where manure was cycled through an anaerobic digester with digestate solids separated, composted, and used for bedding, with liquid stored up to 4 mo in a lined earthen basin.

$^5$3,000 cows (average BW = 650 kg) plus heifers producing 10,700 kg/cow per year (3.5% fat) on 1,214 ha (809 ha of alfalfa and 405 ha of corn) of clay loam soil in southern Idaho. Cattle were housed in naturally ventilated freestall barns with open lots. Solids were separated from barn manure, composted, and used for bedding with liquid stored up to 4 mo in a lined earthen basin. Lot manure was stored in stacks for up to 6 mo.
on predicted GHG emissions. Many factors can influence each emission source, so these results should not be used to represent all dairy farms of the types or locations represented.

The first production system represents a grazing dairy farm in New Zealand with 500 cows plus heifers on 175 ha of perennial grassland (grazing, Table 2). All animals of the spring-calving herd were on pasture throughout the year, except for a couple hours per day during milking. Manure excreted during the milking period was collected and stored in a tank for up to 4 mo and then applied to the pasture land. During the spring and early summer, excess pasture was harvested as baled silage for feed when adequate pasture was not available. Relatively small amounts of grain and protein feeds were fed to meet the nutrient requirements of this relatively low-producing herd.

The second system represents a combined grazing and confinement dairy in Ireland (grazing confinement, Table 2). The spring-calving herd consisted of 80 cows and replacements on 45 ha of perennial grassland. During the winter months, the herd was maintained in a freestall barn and fed bale silage harvested from excess pasture, supplemented with grain and protein feeds. Manure excreted in the housing facility was stored up to 4 mo in a slurry tank and applied to the grassland during the growing season.

The third system represents full confinement of larger and higher producing cattle in central Pennsylvania, with 300 cows plus heifers on 275 ha of land (freestall confinement, Table 2). All animals were maintained in naturally ventilated freestall barns with manure removed daily and stored as slurry in a bottom-loaded tank. The tank was emptied in the spring and fall with broadcast application of the manure in a no-till cropping system.

A fourth system is a larger farm, with 1,000 cows plus young stock on 970 ha of land in New York (freestall with digester, Table 2). All animals were maintained in mechanically ventilated freestall barns where manure is removed daily and cycled through an anaerobic digester. After exiting the digester, manure solids were separated, composted, and used as bedding. The liquid portion was stored in a lined earthen basin for up to 4 mo and applied to cropland with the manure incorporated by tillage on the day of application.

The final system maintained 3,000 cows plus young stock on 1,200 ha of land in southern Idaho (freestall and open lot, Table 2). Animal housing included freestall barns with access to open lots. Manure from the freestall barn was separated and the solids were recycled as bedding. The liquid fraction was stored in a lined earthen basin and surface applied to cropland in the spring and fall. Dry manure was periodically removed from the lot and stored in stacks for up to 6 mo, with partial composting before application to cropland.

On these representative farms, enteric CH$_4$ emission varied with feed intake (i.e., animal size and milk production) and the portion of concentrates fed (Table 2). Emissions per cow were about 15% less for the grazing operations, which used smaller cattle with lower feed intake and milk production. Enteric N$_2$O was small and similar across all systems. Methane emission from housing facilities was also small for all systems, with very little emission from the grazing operations. Nitrous oxide was not produced in the freestall barns, but a substantial amount was emitted from the open lot facility. Manure storage emissions were small on the grazing operations and moderate for the farm using a digester. Slurry manure storage with a surface crust produced substantial amounts of both CH$_4$ and N$_2$O. On the dairy with an open lot, where half of the manure was stored in stacks, emissions per cow were similar to that where all manure was stored in tanks as slurry. Large amounts of N$_2$O were emitted from crop and pasture land, with the greatest emission from the grazing operations due to the emission from concentrated urine deposits on pasture land. The lowest emission came from the dairy farm in Idaho due to relatively dry soil conditions in this semiarid region. Carbon dioxide emission varied with fuel and lime use. Fossil fuel combustion was less on the grazing operations and on the operation with a digester, where some of the biogas was used to heat water.

Indirect emissions of NH$_3$ and NO$_3$ also varied across production systems (Table 2). Ammonia emissions were relatively small from the grazing operations, moderate for the freestall confinement operations, and highest for the open lot. Losses from manure storage were highest from the stacked manure and earthen basin in Idaho. Ammonia losses from crop and pasture land were highest from the grazing operations and lowest for the farm in Idaho. The low losses in Idaho were primarily because a large portion of the ammonium N was lost before field application. Nitrate losses from crop and pasture land were also low in Idaho due to the dry soil conditions and efficient use of irrigation for crop production.

Although we noted large differences among GHG sources across operations, the total farm emissions were not greatly different when expressed per unit of ECM produced (i.e., milk carbon footprint). The lowest emission was from the farm using the anaerobic digester, where the footprint of the milk was about 25% less than that of the other confinement production systems. With a lower milk production per cow and high N$_2$O emissions from pasture, the grazing systems had a 10 to 20% greater footprint for the milk produced compared with the confinement systems.
The contribution of individual emission sources to the total milk footprint varied greatly across these representative farms (Figure 3). Enteric emissions and those from pastureland were relatively high for the grazing operations, but those from manure handling were minimal. Use of the anaerobic digester reduced manure emissions compared with the other confinement operations, with small reductions in some of the other sources. For the open lot in the dry climate of Idaho, housing emissions were relatively high and emissions from cropland were minimal. Prechain emissions (those associated with the production of resource inputs) and fuel combustion emissions were less for the grazing systems and the farm using an anaerobic digester.

These comparisons are specific to the production systems modeled, and thus they should not be generally applied to other similar systems. They are provided only as examples to illustrate the usefulness of whole-farm models in comparing production systems and evaluating mitigation strategies.

**FUTURE NEEDS**

As we look to improve the modeling of GHG emissions at the farm scale, needs exist for more and better data to support model development and evaluation as well as more accurate and robust models. Of all GHG emission processes, the most studied and best understood is that of enteric CH$_4$ emission. As illustrated, this is normally the largest GHG source on dairy farms. A need still exists for better understanding of dietary effects, and particularly for the effects of feed additives that reduce CH$_4$ production. Because this is a large GHG source, feed additives and diet may provide the greatest opportunity for mitigating dairy farm emissions and reducing the carbon footprint of milk. Relatively little is known about enteric N$_2$O emissions; this appears to be a small and relatively unimportant source, but more data are needed over a broad range in diets to ensure that a better model of this source is not needed.

Across all manure-handling systems, most of the research on GHG emissions has focused on CH$_4$ emissions from slurry and liquid manure systems. This is an important source but, due to its high global warming potential, N$_2$O emission is also important. We need to know more about the environmental conditions and processes that produce N$_2$O, including those in surface crusts on slurry storages and in semisolid and solid manure storage and handling systems. The aerobic and anaerobic conditions within this type of manure provide conditions conducive for nitrification and denitrification processes (Li et al., 2012). Methane emissions may also be high, particularly when the manure is high...
in moisture, forming greater anaerobic conditions. Manure of this form is commonly found in tiestall barns, where manure is collected in gutters behind the cattle. This older technology is still commonly found on many dairy farms. For the bedded pack manure system, a particular dearth of data and information on emissions and the factors influencing emission rates exists. The IPCC (2006a) indicate that both CH$_4$ and N$_2$O emissions can be high with this system, but data to support this emission source are limited. Semisolid and solid manure remains an important method of storage and handling, so better information is needed to support models representing these systems.

Much research has been devoted to measuring and understanding N$_2$O emissions from crop and pasture land. The nitrification and denitrification processes creating these emissions are complex and site-specific (Li, 2007); the uncertainty in their prediction also remains very high. Most of these data have been collected with the use of flux chambers covering a small area of the field surface, and the variability across the field is known to be quite high. Larger-scale, continuous measurement, such as with the use of eddy covariance, is needed to get a more average measurement across the field (Jones et al., 2011); this type of measurement better represents the conditions our models predict.

To improve our understanding and prediction of individual GHG sources and whole-farm emissions, better process simulation models are needed. As better data and information become available, more accurate and robust models will be developed representing all farm processes. Models of this type will continue to be important scientific tools to improve our understanding of farm processes and their interactions. For decision support tools, simpler but still accurate and robust models are needed. An opportunity exists for using the complex process simulation models to generate simpler relationships and emission factors for application in decision support. Process simulation models are often too complex for general use, but they can be used to generate large data sets and relationships that lead to simpler and more appropriate models for broader use. More attention needs to be given to using our complex process models to develop simpler tools rather than attempting to adapt these complex models for use outside of research.

Life cycle assessment has become a popular tool for integrating all GHG sources to the farm gate or over the full life cycle of milk and dairy products. Future needs include more accurate inventory data and better standardization of procedures. As we obtain more data and improve our process models, better inventory data will come available to represent the various emissions. Steps are being taken to standardize LCA procedures (ISO, 2006; IDF, 2010; LEAP, 2015), but tighter standards are needed to allow comparisons across studies. A different functional unit may also be useful. Life cycle emissions are often expressed per unit of ECM produced to compare across dairy production systems. To compare with other food products, a more robust functional unit must be developed that integrates a broad range of nutrients to quantify human edible food value.

Net GHG emission or carbon footprint has often been used to quantify the sustainability of a product or service. Sustainability is a much broader term though, including many other environmental impacts along with social and economic factors. If we want to represent the sustainability of dairy products (or any other product or service), much more needs to be done to quantify and integrate these other factors in a full life cycle assessment. Use of GHG emissions as a sole measure of sustainability is not appropriate.

**CONCLUSIONS**

Models of various scales have been developed and used to estimate or predict GHG emissions from various farm sources and the total dairy farm. These include constant emission factors, variable process-related emission factors, empirical or statistical models, detailed process-level simulation, and life cycle assessment. Each has a useful purpose when properly applied. Detailed process simulation models provide vital research tools, whereas simpler models are normally most useful in a decision support role. Important direct emissions from dairy farms include CH$_4$ and N$_2$O from enteric, manure, and soil sources and CO$_2$ from the combustion of fossil fuels and the decomposition of field applied lime and urea. Indirect emissions should also be considered, which include ammonia and nitrate losses that potentially transform to N$_2$O beyond the farm boundaries. Comprehensive whole-farm models provide necessary tools for integrating the effects and interactions of all sources on the farm. Farm models are available where processes may be represented using relationships ranging from emission factors to detailed mechanistic simulations and various combinations of model types. To look beyond the farm, life cycle assessment provides an environmental accounting tool for evaluating emissions over the full life cycle of the milk and dairy products produced. Models provide important tools for quantifying emissions, identifying opportunities for reduction, and evaluating mitigation strategies.

**REFERENCES**

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