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# Life Cycle Assessment of Greenhouse Gas Emissions from Dairy Farms in the Great Lakes Region

## Terminology

| | | |
|---|---|---|
| Allocation | | The process of attributing input and output flows and the associated environmental burdens to each product within a system that produces multiple products. |
| Baseline | | A modeling scenario that includes initial practices which is used for comparisons with alternative scenarios. |
| Biogenic source | | A substance produced by living organisms. |
| Carbon dioxide equivalents | $CO_2$-eq | A measure used to compare the global warming potential of different greenhouse gases. |
| Cradle-to-gate | | A partial life cycle assessment where the system boundary starts with the extraction of raw materials and ends at the farm gate. |
| Enteric methane | Enteric $CH_4$ | A gas that is a co-product of the fermentation process that takes place as part of the digestive process. |
| Fat and protein corrected milk | FPCM | A unit that adjusts milk production values based on a defined percentage of fat and protein in milk. It is a widely used functional unit in milk production life cycle assessment studies that provides a common reference for comparisons. |
| Flow | | Material, energy, and water entering the system under study (input flows) and products and emissions (to air, land, and water) leaving the system under study (output flows). |
| Fossil energy source | | A nonrenewable energy resource (e.g., oil, coal, natural gas) formed over millions of years when prehistoric living organisms died and were buried over layers of rock. |
| Functional unit | FU | A quantified performance of a product system for use as a reference unit to which all inputs and outputs of the system are quantitatively related (e.g., kilograms of fat and protein corrected milk) (ISO 2006). |
| Global warming potential | GWP | The relative measure of the amount of energy that a greenhouse gas traps in the atmosphere over a defined period of time compared to the amount of carbon dioxide. |
| Greenhouse gas | GHG | A gas in the atmosphere that absorbs and emits energy within the thermal infrared range (e.g., methane, carbon dioxide, nitrous oxide, chlorofluorocarbons). |
| Inventory data | | Inventory of input (e.g., water, energy, materials) and output flows (e.g., product(s); emissions to air, land, and water) from a system under study. |
| Life cycle assessment | LCA | A method used to track and assess potential environmental impacts of a product or service throughout all stages of production, use, and final disposal. |
| System boundary | | Defines the processes, inputs, and outputs (including the environmental burdens) that are included in the life cycle assessment. |

## Introduction to Life Cycle Assessment

Life cycle assessment (LCA) is a widely accepted methodology used to estimate the potential environmental impacts of producing goods and services. The International Organization for Standardization (ISO) defines LCA as "the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 2006). Life cycle assessments are conducted in four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (Figure 1).

LCA studies can be classified based on their system boundaries. A complete LCA includes inputs and outputs from cradle-to-grave, which means from the extraction of raw materials to the use of the final product and disposal of any waste or by-products (Figure 2). Partial LCAs exclude one or several steps of the production, use, or disposal stages throughout a product or service lifespan. For example, a cradle-to-gate LCA does not include transport to the consumer or the final disposal at the end of the product's life. Even more narrow in scope, a gate-to-gate LCA includes only a subset of processes in the entire production chain (e.g., the processes in a cheese factory).

Developing LCA studies is complex and time consuming as there are many pieces of information to be collected and modeled. Assumptions are made when data is not available, adding uncertainty to the results. Furthermore, there are methodological decisions made by the LCA modeler, which can be different from one study to the next. Therefore, it is critical to look at the methods of each LCA to understand what has been done and to aid in interpreting the results. Despite its limitations, LCA has become the reference method used to evaluate the environmental impacts of products and services, as it provides a framework to analyze the complete picture of a product throughout its lifespan and can provide valuable information on potential trade-offs for system or practice changes. To provide this information, it is common for LCA studies to define a baseline scenario, which provides estimated results for an initial set of practices for comparisons with alternative scenarios. This comparison of practices allows practitioners and stakeholders to identify changes in environmental burdens and opportunities for improvement.

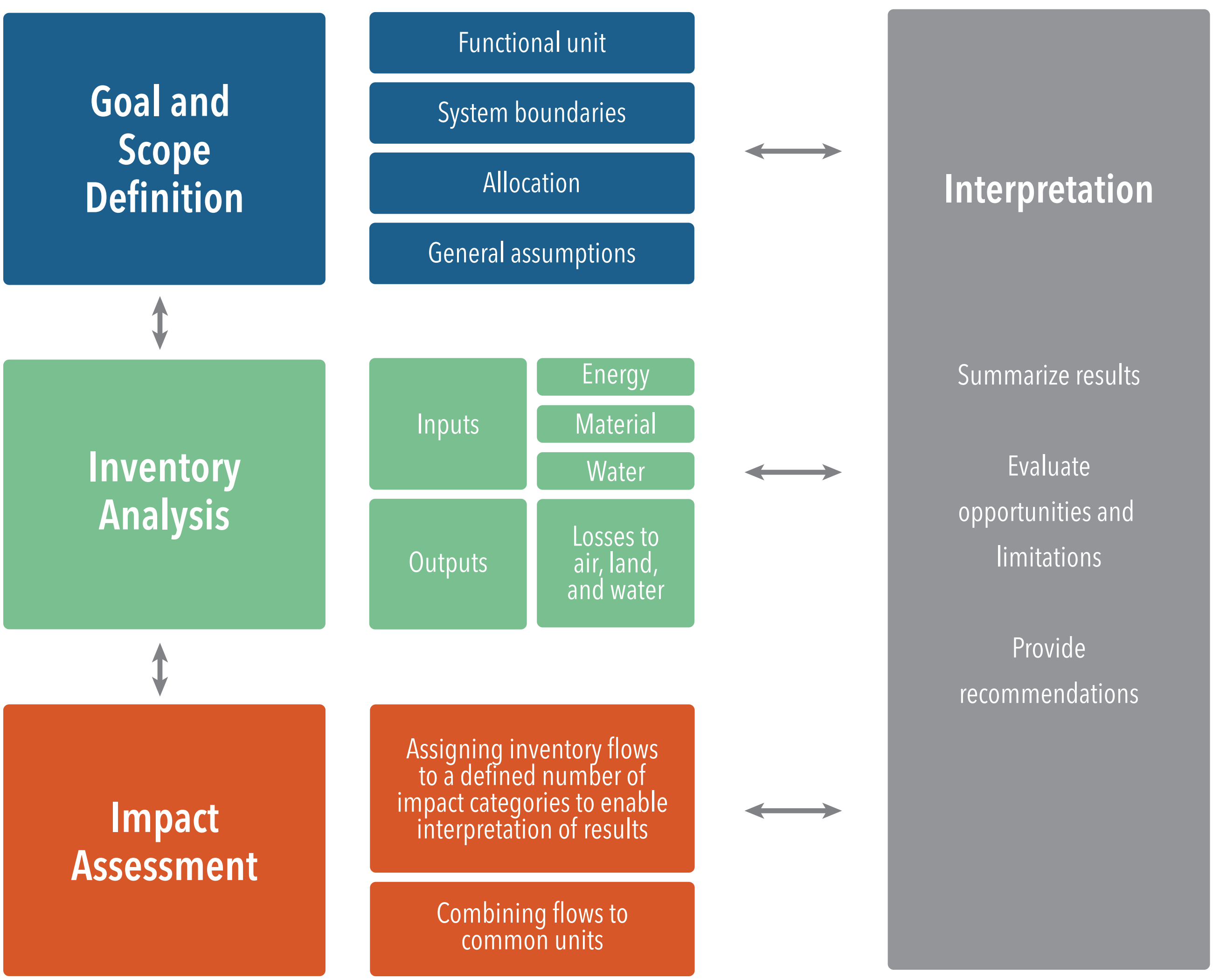


**Figure 1.** Life cycle assessment framework (adapted from ISO 2006).

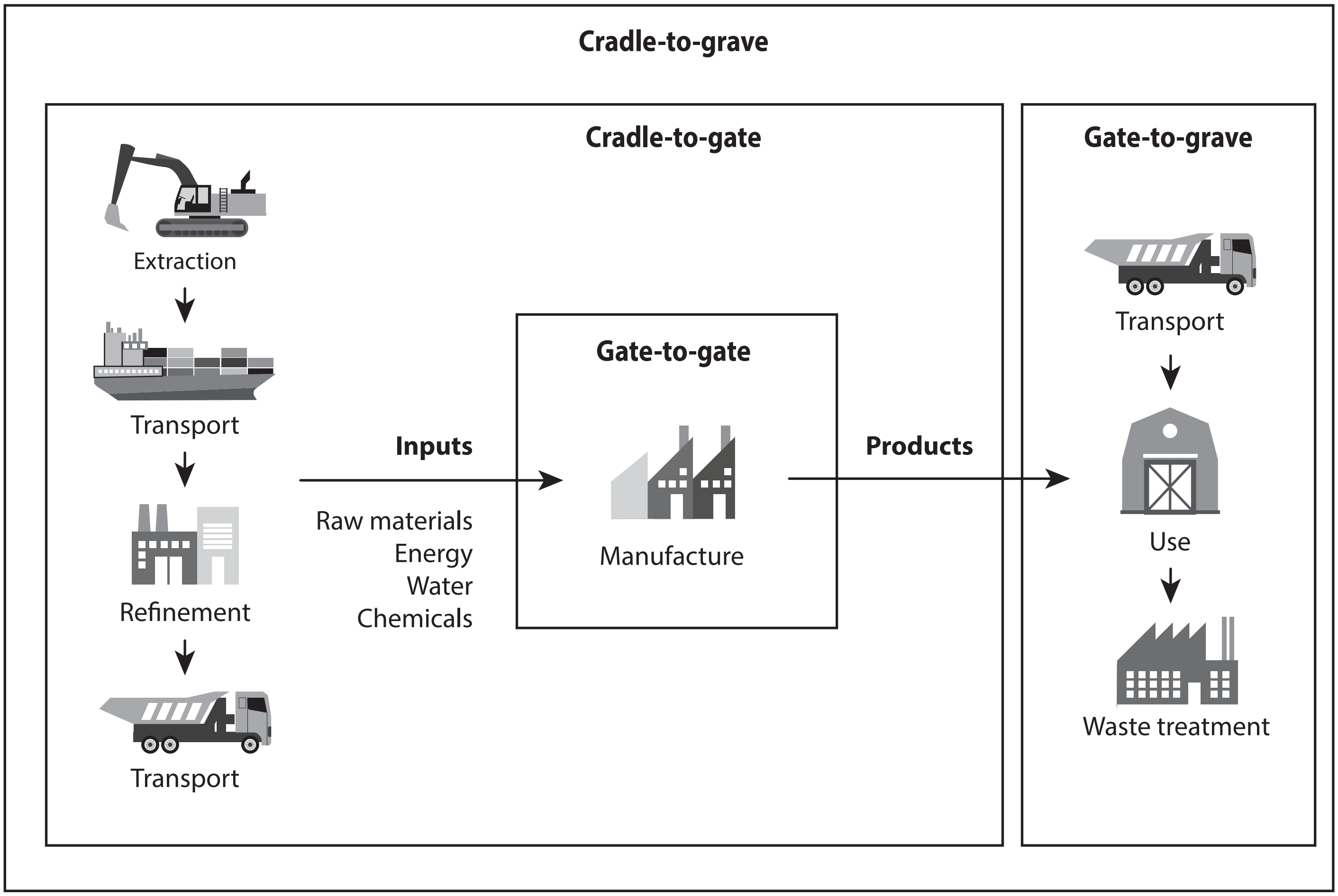


**Figure 2.** System boundaries of a complete life cycle assessment (LCA, cradle-to-grave) and partial LCAs (cradle-to-gate, gate-to-gate, and gate-to-grave).

It is important to understand the assumptions and data used in LCAs as well as to conduct different LCAs for the same product, thus allowing for assessment of general trends. LCAs can help identify activities that are contributing the most to environmental impacts and can provide useful insight on potential strategies to mitigate these impacts without reducing productivity. From a policy design or evaluation perspective, comparing environmental impacts on the same product through multiple LCAs can allow for identifying inputs, processes, and technologies that maximize productivity and minimize environmental impacts.

During the last few decades, LCA has been applied to evaluate the sustainability of fluid milk production (Aguirre-Villegas et al. 2015; Belflower et al. 2012; Cederberg and Stadig 2003; McGeough et al. 2012; Rotz, Montes, and Chianese 2010; (Thoma et al. *Cradle-to-Gate* 2013). A comprehensive LCA study from the Food Agriculture Organization (FAO 2010) evaluated global and regional (North America, Central and South America, Western Europe, Eastern Europe, Russian Federation, West Asia and Northern Africa, Sub-Saharan Africa, South Asia, East Asia, and Oceania) greenhouse gas (GHG) emissions and found significant variation in results from one region to the next.

Thoma and colleagues (*Cradle to Farm-Gate* 2013) conducted a regional LCA finding that GHG emissions per kilogram of fat and protein corrected milk (FPCM) at the farm gate vary from 1.1 to 2.8 kilograms of carbon dioxide equivalents (kg $CO_2$-eq) across U.S. dairy farms. The differences across the United States are mainly attributed to differences in production and management practices on-farm, highlighting the need to understand the practices adopted by dairy operations.

## Methods used in this LCA

This fact sheet summarizes the results of an LCA on GHG emissions from dairy operations in the Great Lakes Region of the United States. The LCA was conducted by modeling a 150-cow farm located in Wisconsin and a 1,500-cow farm located in New York. Another fact sheet presents the effect of different management practices on dairy farm GHG emissions (Aguirre-Villegas et al. 2018).

LCA assumptions

The specific LCA outputs presented in this fact sheet are from cradle-to-farm gate. This means the analysis starts from the extraction of raw materials used in the dairy system and ends when the products, milk and meat, leave the farm (Figure 3). Two archetypical baseline farms of 150 and 1,500

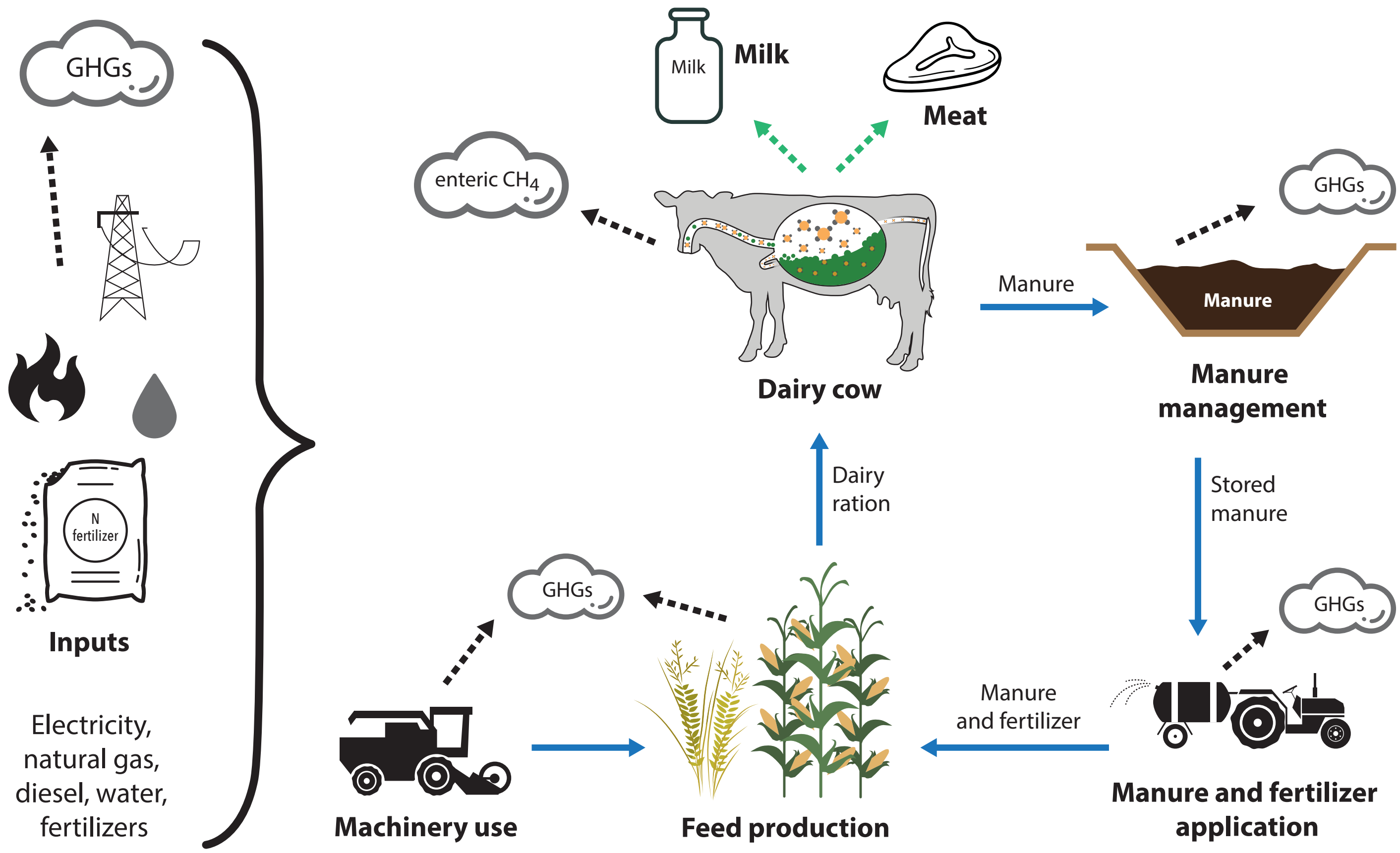


**Figure 3.** Farm components considered within the study system boundaries for the modeled farms (both 150- and 1,500-cow dairies have the same boundaries). Blue solid lines represent material flows within the farm. Black pointed lines represent greenhouse gas (GHG) emissions. Green dashed lines represent products.

cows commonly found in the Great Lakes Region have been modeled to estimate their related GHG emissions using LCA methodology.

The baseline conditions are defined in terms of crop production, crop harvesting, crop storage, feeding, animal housing, milking, and manure handling. Extensive data are needed for all the processes that constitute these categories (e.g., diesel used in machinery, water used for milking and parlor cleaning, etc.). Process-based models with inventory data can be used to gather information on the inputs and outputs of the processes within the system boundaries. These data can then be entered into LCA software to facilitate the construction of the product's life cycle and to model the different scenarios and impacts. The Integrated Farm System Model (IFSM) is a specialized animal agriculture model used in this study to extract inventory data detailing the input and output flows from the system (Rotz et al. 2018). These data were then included in the LCA software SimaPro® to model both farm cases.

The collected data used in LCAs represent different processes and thus have different units. These processes are connected to represent the system and must be scaled to match the system output, which is measured by the functional unit. The functional unit provides a reference relating all the inputs and outputs of the dairy system thus allowing for comparisons to other studies or across farms. Given that the main objective of the dairy farm is to produce milk, the functional unit is often defined as one kilogram (2.2 lbs) of FPCM (4% fat and 3.3% protein), as recommended by the International Dairy Federation (IDF 2010). The reference and characterization factors made to estimate GHG emissions in this study are presented in Table 1.

**Table 1.** Methodological assumptions used to estimate GHG emission results.

| Description | Reference and characterization factors |
|---|---|
| Functional unit | 1 kg of milk corrected to 4% fat and 3.3% protein |
| GWP[1] of methane | 27.8 kg $CO_2$-eq (from biogenic sources); 30.5 kg $CO_2$-eq (from fossil sources) |
| GWP[1] of nitrous oxide | 265 kg $CO_2$-eq |
| Allocation of GHG emissions between milk and meat | Milk is assigned 84.5% of total GHG emissions<br>Meat is assigned 15.5% of total GHG emissions |

[1] Global Warming Potential according to the IPCC GWP 100-year assessment method (Myhre et al. 2013).

**Table 2.** Summary of the baseline characteristics and management practices adopted in both dairy farms.

| Description | 150-cow farm | 1,500-cow farm |
|---|---|---|
| Feed ration composition | 17% crude protein<br>22.9 kg DM[1]/lactating cow/day<br>13.1 kg DM/dry cow/day<br>7.2 kg DM/heifer/day<br>68.0% corn<br>27.4% alfalfa<br>4.6% oatlage | 17% crude protein<br>22.2 kg DM/lactating cow/day<br>12.4 kg DM/dry cow/day<br>7.0 kg DM/heifer/day<br>71.8% corn<br>24.4% alfalfa<br>3.8% grass |
| Herd characteristics | All Holstein cows<br>40% replacement rate | All Holstein cows<br>38% replacement rate |
| Land composition | 46.2% corn<br>43.5% alfalfa<br>10.3% oatlage | 56.2% corn<br>32.1% alfalfa<br>11.7% grass |
| Crop yields | Corn grain: 8,100 kg DM/ha<br>Corn silage: 16,300 kg DM/ha<br>Alfalfa silage: 10,400 kg DM/ha<br>Oatlage: 7,300 kg DM/ha | Corn grain: 7,000 kg DM/ha<br>Corn silage: 15,800 kg DM/ha<br>Alfalfa silage: 13,600 kg DM/ha<br>Grass: 5,800 kg DM/ha |
| Fertilizer application | Corn: 70% of generated manure + 60 kg nitrogen per ha/year<br>Alfalfa: 1,300 kg lime per ha/year<br>Oatlage: 30% of generated manure | Corn: 80% of generated manure + 47 kg nitrogen, 16 kg phosphate, 59 kg potash + 750 kg lime per ha/year<br>Alfalfa: 5% of generated manure + 54 kg potash + 1,300 kg lime per ha/year<br>Grass land: 15% of generated manure + 60 kg nitrogen, 2.1 kg potash + 750 kg lime per ha/year |
| Manure | Slurry at 8–10% TS[2] from milking cows.<br>Land applied two times a year by surface broadcast.<br>Solid at 20% TS[2] from heifers | Slurry at 8–10% TS[2].<br>Land applied two times a year by surface broadcast. |
| Land practices | Conventional tillage<br>Alfalfa harvested in four cuttings<br>Silage stored in bunker silo | Conventional tillage<br>Alfalfa harvested in four cuttings<br>Silage stored in bunker silo |
| Soil characteristics | Silt loam with 22% clay, 45.5% silt, and 32.5% sand | Shallow loam with 22% clay, 54% silt, 24% sand |

[1] Dry matter (DM); [2] Total solids (TS)

Baseline cases for two different dairy farm regions near the Great Lakes were identified based on common farm management practices. Both modeled farms produced milk and meat (in the form of cull cows and calves), requiring a strategy to assign the inputs and outputs to each of these products. The rationale is that if more than one product is produced by a system, then the impacts or benefits (i.e., environmental, social, and economic) should be shared among all the products. A major challenge is determining how to assign impacts. Allocation is an approach used in LCA where different ratios based on physical properties of the products (e.g., mass, volume, etc.), economic indicators (e.g., cost, price, etc.), or other relevant indicators (e.g., nutrients, energy, etc.) are applied to partition the impacts of the complete system among products, which in this case are milk and meat. This study adopts a mass allocation approach for sold crops and co-products exported from the farm (i.e., cull cows and calves for meat production).

<u>150-cow farm</u>

The small dairy farm has 150 lactating and dry cows plus 130 replacement heifers with a daily milk production per cow of 29.1 kg (64 lbs), which is corrected to 27.8 kg FPCM (61 lbs) based on a 4% fat and 3.3% protein correction. Cropland associated with the farm to grow, feed, and apply manure is 130 hectares (ha, 321 acres). The main crops produced are alfalfa silage, corn silage, oatlage, and high-moisture corn grain. In addition to the crops grown on the farm, the dairy ration incorporates soybean meal, expeller soybean meal, and mineral mixtures that are purchased off-farm. The GHG emissions associated with the production of these purchased feeds are included in the boundaries of the system.

Milking cows are housed in naturally ventilated free-stall barns with sand bedding, while heifers are housed in bedded pack barns with straw bedding. Manure from the milking herd is handled as slurry, collected by scraper with a slurry pump, and stored for six months. Manure from the heifers is handled as solid and hauled daily by a scraper with bucket loading. All manure is applied two times a year on cropland as a fertilizer source, with corn fields supplemented with purchased commercial fertilizer and alfalfa supplemented with lime. Table 2 presents a summary of additional characteristics and practices adopted on the modeled farms.

1,500-cow farm

The large farm has 1,500 milking cows and 1,180 replacement heifers with an average daily milk production per cow of 27.4 kg (60 lbs) which is corrected to 26.1 kg FPCM (57 lbs) based on a 4% fat and 3.3% protein correction. Alfalfa and corn are produced on-farm on nearly 1,300 ha (3,212 acres). The main ingredients of the ration include alfalfa silage, corn silage, and dry corn grain. These feedstuffs are supplemented with purchased soybean meal and expeller soybean meal.

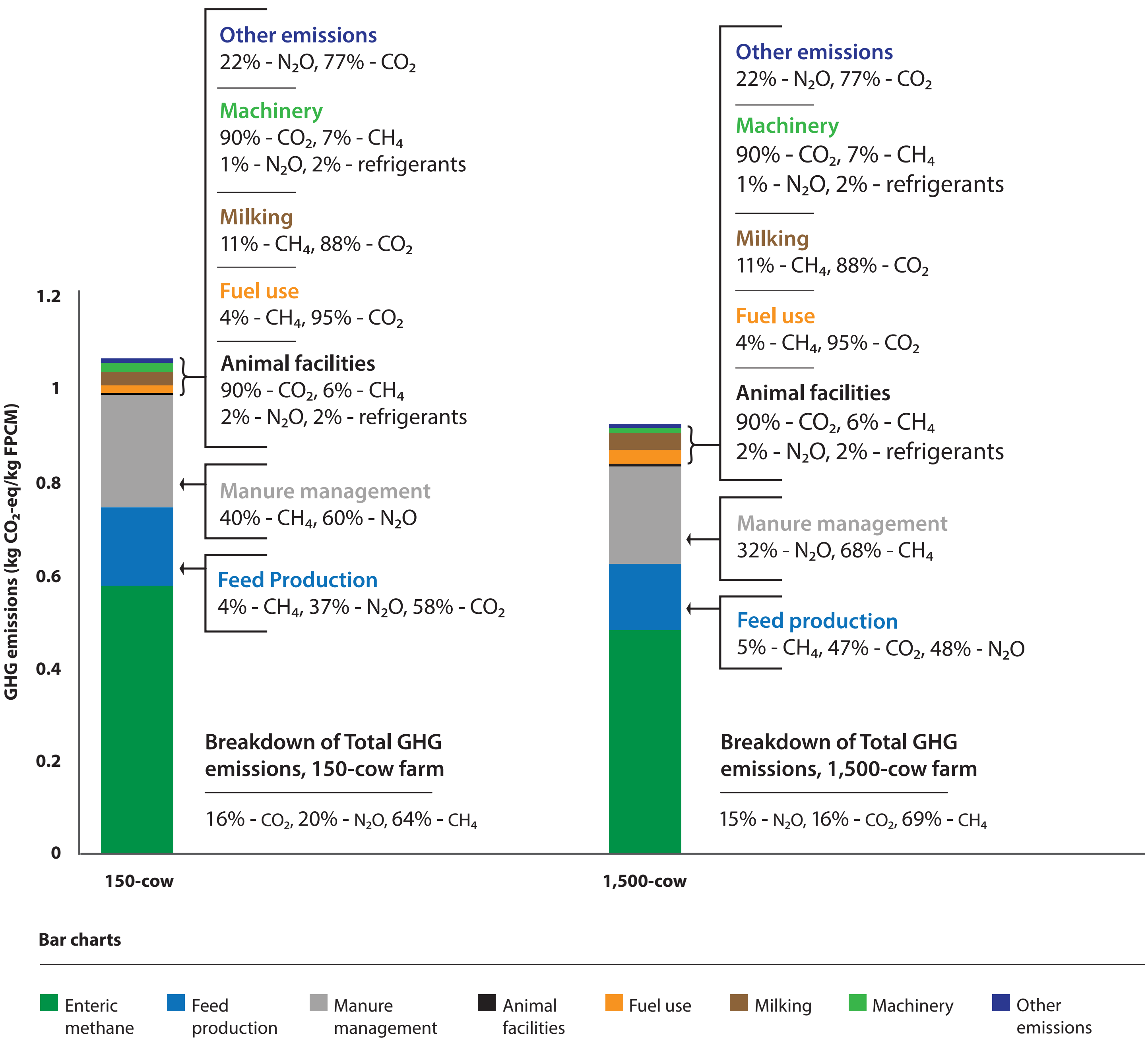


**Figure 4.** Greenhouse gas (GHG) emission results in modeled 150-cow and 1,500-cow dairy farms under common practices used in the Great Lakes Region. Bar graphs show farm GHG emissions per source (from bottom to top: enteric methane, feed production, manure management, animal facilities, fuel use, milking, machinery use, and other emissions). Pie charts show the percentage that each gas type (nitrous oxide: $N_2O$; methane: $CH_4$; and carbon dioxide: $CO_2$) contributes to each source.

The entire herd is housed in mechanically ventilated free-stall barns with straw bedding from which manure is collected daily by a scraper with slurry pump. Manure is stored for six months before 90% is land-applied in spring and fall. The remaining 10% of stored manure is exported to neighboring farms. Corn farmland is supplemented with synthetic nitrogen, phosphorus, and potassium fertilizers, whereas alfalfa land is supplemented with potassium and lime.

## Life cycle GHG emission results

Emissions of GHGs are higher per FPCM for the smaller herd at 1.06 kg $CO_2$-eq when compared to the larger herd that emits 0.92 kg $CO_2$-eq/kg FPCM (Figure 4). Results show higher GHG emissions of milk production from the 150-cow farm due to higher emissions from feed production, enteric methane (a co-product of the fermentation process that takes place as part of the digestive physiology of dairy cows and ruminant animals) emissions, and nitrous oxide associated with the manure bedded pack system.

Overall, feeding rations that increase milk production reduce GHG emissions as the functional unit is defined as one kilogram FPCM produced on the farm. Despite the fact that milk production per cow is 4 lbs higher on the 150-cow farm, due to higher dry matter intake, the increase in milk production does not mitigate the increase in emissions from the production of the additional feed and enteric methane. Also, the conversion ratio from feed to milk in the small herd is lower than the conversion ratio in the large farm, suggesting that the diet ration differences affect GHG emissions.

Ingredients in the dairy feed ration also played an important role in GHG emission results as feeding more silage and high moisture grain by the 150-cow farms increased enteric methane emissions when compared to the 1,500-cow farm that fed dried grain. Finally, nitrous oxide, another GHG which is more potent than methane, is more easily formed in bedded pack systems as the mix of aerobic (promoting nitrification) and anaerobic conditions (promoting denitrification) create the optimal conditions for nitrous

**Table 3.** Summary of the individual factors influencing the difference in GHG emissions between the 150-cow farm and the 1,500-cow farm.

| 150-cow farm | 1,500-cow farm | Individual GHG being influenced | Comparison of influenced GHG per kilogram FPCM between farms | Explanation |
|---|---|---|---|---|
| 27.8 kg FPCM (61 lbs) milk per cow | 26.1 kg FPCM (57 lbs) milk per cow | Overall GHG emissions | 150 < 1,500 | Increased milk production per cow reduces the overall GHG as milk is the functional unit |
| Higher silage and grain diet | Lower forage and higher dried grain diet | Enteric $CH_4$ | 150 > 1,500 | Diets higher in silage and high moisture grain increase activity of methane producing bacteria; whereas diets with dried corn grain and lower forage decrease activity of methane producing bacteria |
| Bedded pack housing | Free-stall housing | $N_2O$ | 150 > 1,500 | Bedded pack housing systems create the ideal conditions for nitrous oxide to form; whereas ventilated free-stall housing systems avoid conditions for nitrous oxide to be emitted |
| Feed production resources | Feed production resources | $CO_2$ | 150 > 1,500 | More resources are needed to produce the feeds constituting the dairy ration for the 150-cow farm than for the 1,500-cow farm per kilogram of milk produced |
| Diesel fuel use | Diesel fuel use | $CO_2$ | 150 < 1,500 | Diesel fuel use is lower for the 150-cow farm than the 1,500-cow farm per kilogram of milk produced |

$CO_2$: carbon dioxide; $CH_4$: methane; $N_2O$: nitrous oxide; FPCM: fat and protein corrected milk.

oxide to be formed. Table 3 presents a summary of the factors driving GHG emissions in both modeled farms.

Both farms modeled follow a similar trend in terms of emission sources (Figure 4). Overall, enteric methane is the greatest contributor to GHG emissions with more than 50% of total farm emissions. In both farms, the second largest source of total farm GHG emissions is manure management (manure collection, transport, and storage). Within manure management, methane from storage is the major contributor to GHG emissions as the anaerobic conditions of slurry during the six-month storage period are ideal for methane formation. Emissions from manure management are higher from the 150-cow farm as the nitrous oxide emissions from the bedded pack housing system are included within this category. Nitrous oxide emissions from manure application are not included with management but are included in the feed production category because they result from the soil nitrogen cycle.

While methane emissions from manure storage are significant, manure storage is critical in reducing potential negative impacts on water quality by increasing the flexibility of when manure is land-applied. It is important to manage these systems to reduce methane emissions. Methane emissions from manure storage could be reduced by covering the storage and flaring the produced methane, or by installing manure processing technologies such as anaerobic digestion and solid–liquid separation.

Feed production contributes nearly 16% of total farm GHG emissions of the two studied farms. Feed production activities include land occupation, fertilizer use, diesel use, and manure application. Most GHG emissions from feed production occur as nitrous oxide from manure application on soil with the next largest contributor being synthetic fertilizer application (ammonium nitrate, diammonium phosphate, and potassium chloride). When comparing individual crops, corn is the major contributor to GHG emissions per kilogram of dry matter intake. Besides the fact that corn is the major feed component, corn production emits more GHGs than other crops because of its greater requirement of nitrogen fertilizer.

On-farm energy consumption is also an important source of GHG emissions. Electricity is used for milking and other activities, but use is similar for both farms per kilogram of FPCM. Emissions from diesel consumption are greater per FPCM on the 1,500-cow farm as the hauling distance is increased with greater animal density. Finally, other sources of emissions come from transport of purchased feed, water use, and other farm maintenance activities (e.g., medication, veterinarian visits, etc.).

A follow-up fact sheet presents GHG emission results from alternative feed, manure, and field management practices that seek to reduce the carbon footprint of milk production (Aguirre-Villegas et al. 2018). In summary, GHG emissions can range from 0.93 to 1.12 kg $CO_2$-eq/kg FPCM in the modeled 150-cow farm and from 0.70 to 0.95 kg $CO_2$-eq/kg FPCM in the modeled 1,500-cow farm based on different management practices.

## Summary

Greenhouse gas emissions were quantified on two dairy farms in the Great Lakes region. The small 150-cow dairy farm emits higher GHG emissions than the large 1,500-cow dairy farm per unit of FPCM. The differences in emissions from these two farms are attributed to different management practices. Specifically, higher GHG emissions in the 150-cow farm come from feed rations higher in forage and high moisture corn grain (vs. low forage and dried grain in the 1,500-cow farm), which result in higher enteric methane emissions; and from the bedded pack barn for animal housing (vs. free-stall barn), which result in higher nitrous oxide emissions. There is potential to reduce these emissions to 0.93 and 0.70 kg $CO_2$-eq/kg FPCM in the modeled 150-cow and 1,500-cow farm, respectively, by adopting different beneficial management practices throughout feed production, manure management, and field practices (Aguirre-Villegas et al. 2018).

## References

Aguirre-Villegas, Horacio A., Daesoo Kim, Greg Thoma, Rebecca A. Larson, and Matthew D. Ruark. 2018. *"Identifying Beneficial Management Practices to Reduce GHG Emissions from Dairy Farms." UWEX A4131-13; GWQ 085.* Madison, WI: University of Wisconsin-Extension.

Aguirre-Villegas, Horacio A., Thais H. Passos-Fonseca, Douglas J. Reinemann, Louis E. Armentano, Michel A. Wattiaux, Victor E. Cabrera, John M. Norman, and Rebecca A. Larson. 2015. "Green Cheese: Partial Life Cycle Assessment of Greenhouse Gas Emissions and Energy Intensity of Integrated Dairy Production and Bioenergy Systems." *Journal of Dairy Science* 98 (3): 1571–92. doi:10.3168/jds.2014-8850.

Belflower, Jeff B., John K. Bernard, David K. Gattie, Dennis W. Hancock, Lawrence M. Risse, and C. Alan Rotz. 2012. "A Case Study of the Potential Environmental Impacts of Different Dairy Production Systems in Georgia." *Agricultural Systems* 108: 84–93. doi:10.1016/j.agsy.2012.01.005.

Cederberg, Christel, and Magnus Stadig. 2003. "System Expansion and Allocation in Life Cycle Assessment of Milk and Beef Production." *International Journal of Life Cycle Assessment* 8 (6): 350–56.

Food and Agriculture Organization of the United Nations (FAO). 2010. "Greenhouse Gas Emissions from the Dairy Sector – A Life Cycle Assessment." http://www.fao.org/agriculture/lead/themes0/climate/emissions/en/.

International Organization for Standardization (ISO). 2006. "ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework." Geneva, Switzerland.

McGeough, Emma J., Shannan M. Little, H. H. Janzen, Tim A. McAllister, Sean M. McGinn, and Karen A. Beauchemin. 2012. "Life-Cycle Assessment of Greenhouse Gas Emissions from Dairy Production in Eastern Canada: A Case Study." *Journal of Dairy Science* 95 (9): 5164–75. doi:10.3168/jds.2011-5229.

Myhre, Gunnar, Drew Shindell, Francois-Marie Bréon, William Collins, Jan Fuglestvedt, Jianping Huang, Dorothy Koch, Jean-François Lamarque, David Lee, Blanca Mendoza, Teruyuki Nakajima, Alan Robock, Graeme Stephens, Toshihiko Takemura, and Hua Zhang. "2013: Anthropogenic and Natural Radiative Forcing Supplementary Material." *In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* edited by Thomas F. Stocker, Dahe Qin, Gian-Kasper Plattner, Melinda M.B. Tignor, Simon K. Allen, Judith Boschung, Alexander Nauels, Yu Xia, Vincent Bex, and Pauline M. Midgley. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2013. http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf

Rotz, Alan C., Felipe Montes, and Dawn S. Chianese. 2010. "The Carbon Footprint of Dairy Production Systems through Partial Life Cycle Assessment." *Journal of Dairy Science* 93 (3): 1266–82. doi:10.3168/jds.2009-2162.

Rotz, C. Alan, Michael S. Corson, Dawn S. Chianese, Sasha D. Hafner, Rosa Jarvis, and Colette U. Coiner. 2018. *The Integrated Farm System Model – Reference Manual – Version 4.4*. https://www.ars.usda.gov/ARSUserFiles/80700500/Reference%20Manual.pdf.

The International Dairy Federation (IDF). 2010. "A Common Carbon Footprint Approach for Dairy. The IDF Guide to Standard Lifecycle Assessment Methodology for the Dairy Sector." *Bulletin of the International Dairy Federation* 445/2010.

Thoma, Greg, Jennie Popp, Darin Nutter, David Shonnard, Richard Ulrich, Marty Matlock, Dae Soo Kim, Zara Neiderman, Nathan Kemper, Cashion East, and Felix Adom. 2013. "Greenhouse Gas Emissions from Milk Production and Consumption in the United States: A Cradle-to-Grave Life Cycle Assessment circa 2008." *International Dairy Journal* 31: S3–14. doi:10.1016/j.idairyj.2012.08.013.

Thoma, Greg, Jennie Popp, David Shonnard, Darin Nutter, Marty Matlock, Richard Ulrich, Wayne Kellogg, Daesoo Kim, Zara Neiderman, Nathan Kemper, Cashion East, and Felix Adom. 2013. "Regional Analysis of Greenhouse Gas Emissions from USA Dairy Farms: A Cradle to Farm-Gate Assessment of the American Dairy Industry circa 2008." *International Dairy Journal* 31: S29–40. doi:10.1016/j.idairyj.2012.09.010.

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