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Greenhouse Gas Emissions from Milk Production in the US

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Greenhouse Gas Emissions from Milk Production in the US

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Abstract

Life cycle assessment is performed to determine the environmental impacts of the life cycle of a product. In this study, the greenhouse gas emissions from milk production in the United States were calculated using a cradle-to-gate analysis. The dairy industry has a noticeable impact on the total greenhouse gas emissions in the US. Performing life cycle assessment provides information about the main emission sources in the life cycle which can spark innovative changes to reduce these emissions. The life cycle assessment was performed using the openLCA software and ReCiPe impact assessment methodology. The results indicated that 1.28 kg of carbon dioxide equivalent (CO_2eq) per kg of fat and protein corrected milk (4% fat, 3.3% protein). Enteric and manure management emissions contribute the largest impact (45% and 24%, respectively) on the total emissions from the life cycle. The results from this study are comparable to other life cycle assessments of milk production. Opportunities to reduce greenhouse gas emissions on the dairy farm are present but further research must be conducted to make sure that there are not environmental burden shifts or trade-offs occurring when changes are made to the system.

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1. Introduction

Sustainability is an important aspect for industries as they become more aware of their environmental footprints. The dairy industry is a considerable contributor to the total US greenhouse gas emissions throughout the life cycle of milk and other dairy products. In 2017, dairy cows were responsible for 1.3% of the total US GHG emissions (Rotz, 2017). The dairy industry has set environmental stewardship goals for 2050 to become carbon neutral or better, optimize water use while maximizing recycling, and improve water quality by optimizing utilization of manure and nutrients (Rotz et al., 2021). There are many factors that affect the sustainability of the dairy industry and understanding emission sources on dairy farms allows for the creation of innovative changes to reduce emissions. This process begins with life cycle assessment (LCA).

LCA is a method to measure environmental impacts of a product or service throughout its entire life cycle. A complete life cycle includes collection of raw materials, production of the product, distribution, its use, and the disposal of the product. LCA involves four main pillars, goal and scope definition, inventory, impact assessment, and interpretation of results which are all interconnected as shown in Figure 1 (Baldini et al., 2017).

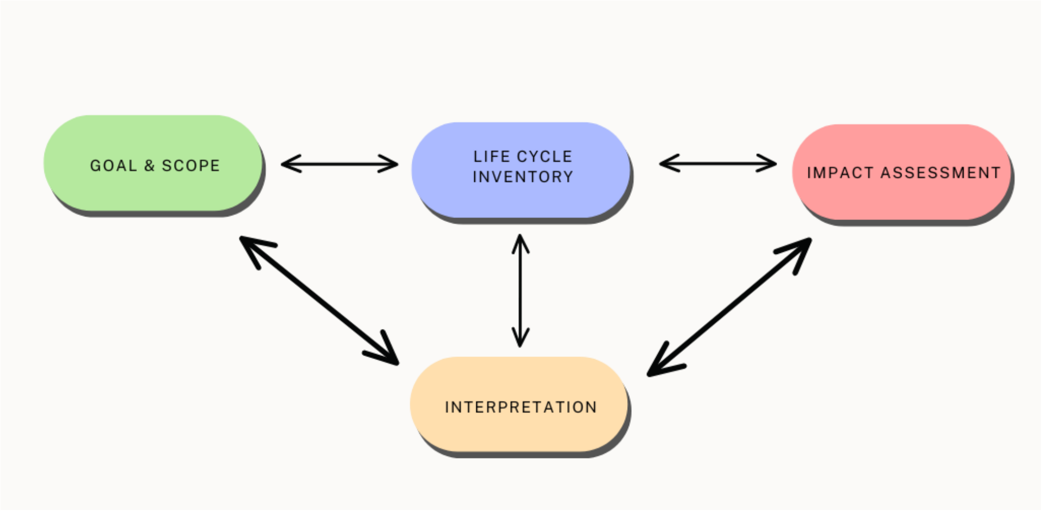

Figure 1. Illustration of the general phases of a life cycle assessment, as described by ISO 14040

The goal and scope of LCA involves the definition of a functional unit to provide a standard basis for analysis, a definition of the system boundaries, and the reasoning behind performing the assessment. Clearly defined system boundaries and functional units allow for easy comparison to other studies. The inputs and outputs across the system boundaries are included in the inventory as well as data and calculations. Impact assessment requires definition of the life cycle impact assessment method used and sensitivity or uncertainty analysis can be performed in the interpretation of results to provide clearer understanding of the results. The ideal LCA is a cradle-to-grave assessment where the system boundaries include the full life cycle of the product. A cradle-to-gate assessment can be performed to focus on individual portions of the product's life cycle.

Many LCAs have been performed focusing on milk production in the dairy industry. An extensive study was conducted to determine the carbon footprint of the entire life cycle of milk in the US. In the cradle-to-grave LCA, it was determined that 72% of the total burden associated with milk consumption occurred before the dairy farm gate (Thoma et al., 2013). The methodology for every LCA is different so no two LCAs can be directly compared. Typical differences stem from the system boundaries and allocation procedures for the impacts of milk and beef. Most studies report greenhouse gas emissions ranging from 0.75-1.5 kg CO_2eq kg^{-1} milk with 85-90% of the burden allocated to milk rather than the beef co-product (Thoma et al., 2012).

1.1 Goal and Scope

While a cradle-to-grave assessment provides an in-depth analysis of the impacts from producing milk, this type of assessment was larger than the scope of this project. A cradle-to-farm gate assessment was performed instead to focus on determining the environmental impacts of the dairy farm itself when producing milk. The system boundary includes feed production, soil, crops, manure management, enteric methane from cows, and fuel use. The functional unit is defined as one kilogram of fat and protein corrected milk (FPCM) produced at the US dairy farm gate. The goal of the study is to estimate greenhouse gas emissions from producing one kilogram of FPCM at the farm gate. The scope of the study is cradle-to-gate analysis. The system boundaries include the greenhouse gas emissions associated with each step of the life cycle from fertilizer production until the milk is produced at the farm gate.

The gases encompassed by greenhouse gases are carbon dioxide (CO_2), methane (CH_4), and dinitrogen monoxide (N_2O). Emission factors are used to create a CO_2 equivalent value for the amount of CH_4 and N_2O produced. This allows for one number to be reported for the carbon footprint of the LCA. The emission factors used were 34 kg CO_2eq per kg of CH_4 and 298 kg CO_2eq per kg of N_2O following the guidance available in the openLCA manual.

2. Methods

Many different software are available to perform LCA. SimaPro is one of the most well-known LCA software and has been used in numerous LCAs for dairy production. A goal of this project was to determine if similar results to these LCAs could be determined using the openLCA software. OpenLCA is an open-source software for life cycle and sustainability assessment and has been developed by GreenDelta since 2006 (Ciroth et al., 2019). OpenLCA Nexus provides databases that can be downloaded and imported into openLCA. The databases contain elementary flows and reference data. The database used in this study is the European reference Life Cycle Database (ELCD) of the Joint Research Center (Ciroth et al., 2019).

2.1 Project Scope

This life cycle assessment is a cradle-to-gate analysis of the greenhouse gas emissions from the production of milk. The system boundaries are shown in Figure 2. The scope of this project includes soil and crops, feed production, enteric methane emissions, manure management, and milk production but does not extend past the milking process.

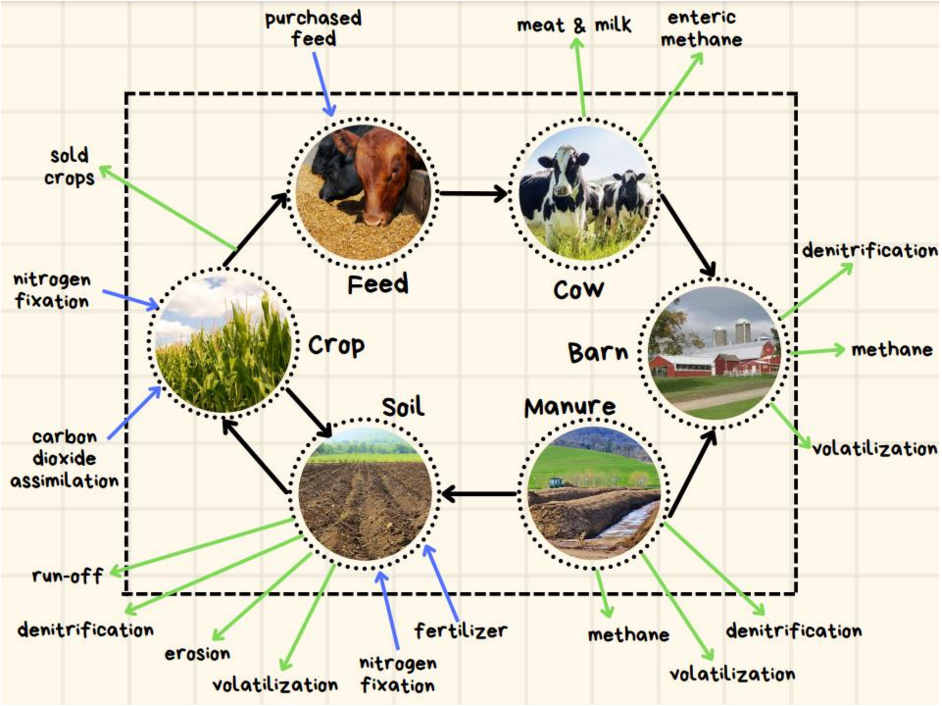

Figure 2. System Boundaries

Since the LCA only focuses on GHG emissions, not every input or output on the system boundaries diagram is analyzed in the study. Volatilization occurs when nitrogen is in the form of urea and converts to ammonia gas and escapes from the soil into the atmosphere. Urea originates from animal manure, urea fertilizers, and may come from the decay of plant materials. Ammonia volatilization is more likely to occur when the soil is moist and warm, and the urea source is on or near the soil surface (Killpack & Buchholz, 2022a). Volatilization occurs from manure and can therefore take place in barns where manure management practices are performed. When analyzing the effects of volatilization, it is important to not account for volatilization effects multiple times. For example, accounting for the effects of volatilization from manure when it is produced, in the barn, and from it being applied to the soil would create an overcalculation of the amount of volatilization that is actually taking place. Denitrification occurs when soil microorganisms need oxygen for fuel and use nitrites (NO_2^-) and nitrates (NO_3^-) to obtain this oxygen. N_2 and N_2O gases are formed and emitted to the atmosphere, creating a net cycle in the soil. Many factors affect the rate at which denitrification occurs including the amount of organic matter, soil water content, oxygen supply, temperate, nitrate levels, and pH (Killpack & Buchholz, 2022b). Nitrates can easily move with water and either soak deeper into the soil contaminating groundwater or flow with the water when run-off occurs. Run-off typically occurs after heavy rains when water carries nutrients and soil along with it. Soil erosion can then take place, removing quality soil from the farmland which takes hundreds of years to regenerate. Run-off can also create water problems when nitrogen rich run-off contaminates water sources such as rivers and lakes. This causes algae blooms, affecting the ecosystems in the water source by blocking sunlight and depleting the oxygen. The algae blooms can also produce harmful toxins and contaminate drinking water.

The functional unit chosen for the study is one kilogram of fat and protein corrected milk. Since not all milk produced has the same fat and protein composition, this unit creates a standard milk with 4% fat and 3.3% protein so that the results can be easily compared to other studies. The calculation involves an energy content ratio of milk to standard milk by using fat and protein concentrations. The conversion is completed using the National Research Council approach with the following equation.

$$FPCM = \frac{0.0929F + 0.05882P + 0.192}{0.0929 \times 4\% + 0.05882 \times 3.3\% + 0.192} = \frac{0.0929F + 0.05882P + 0.192}{0.7576}$$

In the equation, F is the percentage of milk fat in the milk that is produced, and P is the percentage of protein in the produced milk (Thoma et al., 2013). While there is not a large difference in the fat and protein content for milk across the United States, using the FPCM functional unit allows for comparisons to LCAs in European countries.

2.2 OpenLCA

A large portion of this project was centered around learning how to perform life cycle assessment using the openLCA software. The openLCA manual was used to gain an understanding of how the software works and the process of creating systems for the life cycle. A case study for plastic bottle production was practiced to get experience using the software. OpenLCA has flows that are created for each unit in the life cycle. Flows are created by and used in processes to create larger and larger systems. All inputs that are needed to create the next flow are placed as inputs into the process and the outputs from creating the product flow are placed as outputs. A product system is then made using the end product’s process. Life cycle impact assessment (LCIA) is performed on the product system using a LCIA method of choice to calculate the environmental impacts of the product system. This process was practiced using the plastic bottle production case study then replicated for a dairy farm. The larger input categories (feed production, enteric methane, manure management, and milk production) were broken down into smaller categories in order to create the unit flows and processes. For example, feed production was broken down into each individual crop and included the fertilizer and fuel used to grow the crops. A simplified network tree for the openLCA model is shown in Figure 3. Three different dairy farms were used in the model to create a weighted average for the emissions from raw milk production. Each farm had the same structure in openLCA with the enteric methane, pasture, and feed breakdown.

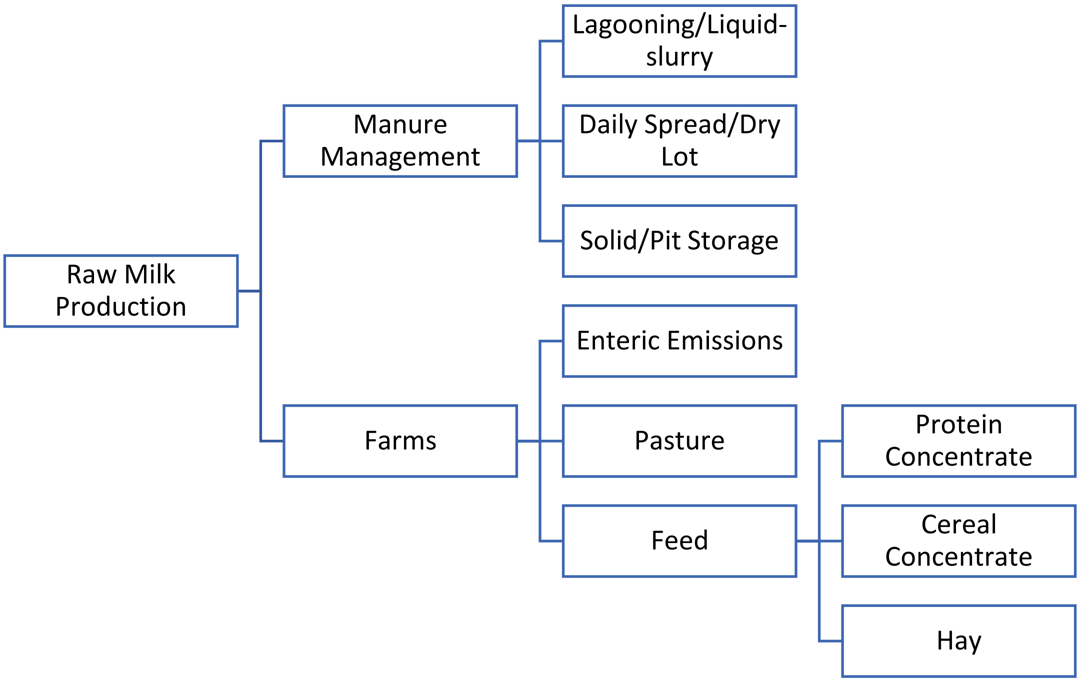

Figure 3. A simplified network tree for the openLCA model

LCIA was performed using the ReCiPe 2016 Midpoint (H) method. Life cycle impact assessment provides an environmental profile indicating the areas in the life cycle where environmental effects score well or poorly and the areas that contribute more to environmental effects. Characterization factors indicate the environmental impact per unit. A characterization factor at the midpoint means that the factor is located along the impact pathway and is typically at the point after the environmental mechanism is identical for all flows in the impact category. Midpoint characterization relates stronger to the environmental flows and has a low uncertainty. The hierarchist (H) perspective is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms and is placed in between the more extreme perspectives of individualist and egalitarian (Hulijbregts et al., 2016).

3. Life Cycle Inventory

The main components of the life cycle that are included in the study are crop and feed production, enteric emissions from cows, manure management, and milk production. The life cycle inventory provides a deeper understanding of what all is included within the system for the life cycle assessment.

3.1 Crop Production

The following crops were used in the LCA: hay, barley grain, maize grain, maize starch, rapeseed, wheat grain, and soybean, etc. Existing processes for the crops in openLCA were used. These processes included direct field emissions for the crops and soil, input of seeds, mineral fertilizers, pesticides, and machine operations with corresponding machine infrastructure. Soil cultivation, sowing, fertilization, weed control, pest and pathogen control, combine-harvest, grain drying, and transport from field to farm were all considered in machine operations.

3.2 Feed Production

In the LCA, the processes for crop production were inputs into the processes for feed production. Feed production includes the production of the raw materials from crop production, the transport of the crops to the feed mill, the processing of the crops, and the transport of the feed mix to the farm. A cereal-based feed was created using barley grain, maize grain, rapeseed, and wheat grains. A protein concentrate feed was also created consisting of maize starch, rapeseed, and soybeans. The cereal-based feed is consumed by lactating cows, dry cows, and heifers while the protein feed is only consumed by lactating cows. Hay is also produced and is consumed by all cows, but the use and consumption of the pasture is only considered for dry cows and heifers. The feed consumption for lactating cows is made up of about 49% hay, 47% protein concentrate feed, and 4% cereal-based feed. Dry cows and heifers consume about 73% hay, 25% pasture, and 2% cereal-based feed.

3.3 Enteric Methane

Methane is produced through fermentation during the digestive process of ruminant animals like cattle, goats, sheep, and buffaloes. Microbes decompose and ferment the feed in the digestive tract and rumen, producing methane as a byproduct. The methane is released as enteric methane emissions with about 95% of these emissions occurring through belching. The amount of methane produced by cows is directly related to the composition of the feed and the amount of feed consumed. Cattle account for about 77% of global enteric methane emissions from ruminants and ruminants are responsible for 30% of global methane emissions (FAO, 2016). An average value of enteric methane emissions was used in the openLCA model for lactating and dry cows and heifers. A study was conducted to determine the average and median enteric ethane emissions from cows using the results of 31 studies in the US and Europe, shown in Figure 4. The results indicated an average emission of 417 grams of methane per animal per day. The following equation can be used to estimate the amount of enteric methane produced per cow per day (Niu et al., 2018).

$$\begin{aligned} CH_4(g\ cow^{-1}day^{-1}) \\ &= -126 + 11.3 \times DMI(kg\ day^{-1}) + 2.30 \times NDF(\%\ of\ DM) \\ &+ 28.8 \times MF(\%) + 0.148 \times BW(kg) \end{aligned}$$

In the equation, DMI is the dry matter intake of the feed, NDF is the neutral detergent fiber in the dry matter, MF is the milk fat, and BW is the body weight of the cows. The amount of enteric methane produced per kg of milk can be determined by multiplying the value by the number of cows and dividing it by the amount of milk produced during the time period. Converting the methane emissions to a per year basis and dividing by the amount of milk produced per year is recommended to create a better average for the emissions. The methane emissions are then converted to a CO_2eq value using an emission factor.

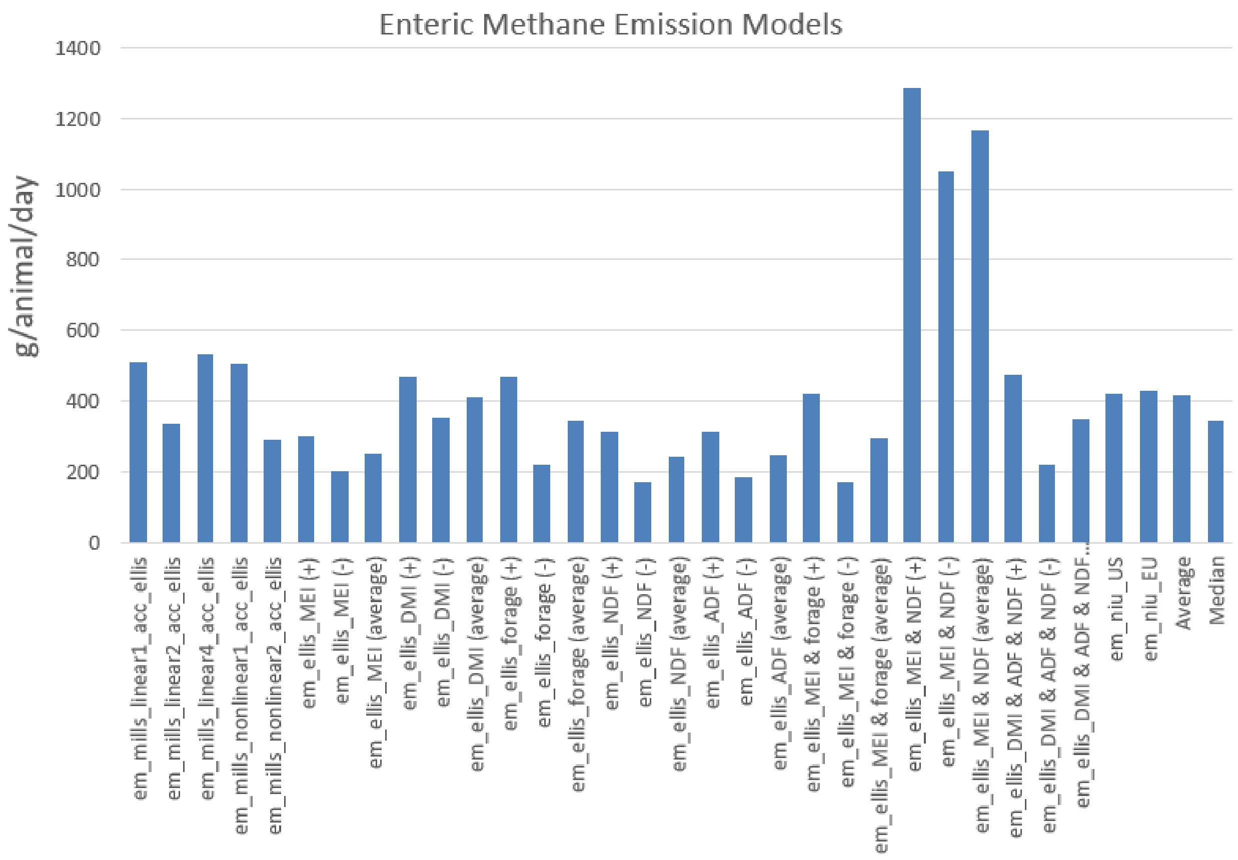

Figure 4. Enteric Methane Emissions Model (Thoma et al., 2013)

3.4 Manure Management

Manure management practices are broken down into the following categories: daily spread, dry lot, lagooning, liquid-slurry, pit storage, and solid storage. These emissions are based on volatile solids which, through simplification, are assumed to be equal to dry matter content. The main three manure management practices are lagooning, liquid-slurry, and solid storage. Lagoon systems handle highly diluted manure which can then be pumped through irrigation systems. This method is preferred by farmers because it has the lowest cost associated with it. Liquid-slurry handles manure with a high moisture content and is stored in tanks on farms to later be applied to soil. Solid storage involves manure which has had the liquids drained or bedding added to make it more solid. The solid manure must then be stored before spreading on fields or transporting the waste. The different manure management practices are broken down by how much of the manure is handled per kilogram of milk. An average value for the amount of manure produced per kilogram of milk produced is used in this calculation. Liquid-slurry accounts for the largest portion of manure management with 30.2%. The breakdown for the remaining manure management used in the model is 29.5% solid storage, 20.6% daily spread, 16.8% lagooning, and 2.9% pit storage.

3.5 Milk Production

Milk production takes into account the energy and auxiliary materials like water, lubricating oil, and cleaning agents that are required throughout the milking process. The energy and auxiliary materials are needed for lighting, operation and cleaning of the milking machine, milking parlor, and milk room. Raw milk production does not include emissions from packaging or transport of the milk to a dairy facility. Since meat is also an output on dairy farms, allocation is important for the life cycle assessment. Allocation allows for a distribution of the environmental burden between the coproducts on the farm. If possible, allocation should be avoided by performing system expansion. Allocation on a bio-physical causality basis was applied to the milk production portion of the model in openLCA. Other methods include economic or mass allocation. Mass allocation only accounts for raw production and economic allocation heavily depends on time and place which makes comparing results more difficult (Baldini et al., 2017). The milking process in openLCA creates an average of different farm types. The three types of farms that are averaged are large scale production non-grazing, medium scale production with grazing, and medium scale production non-grazing. The production of milk is 40% from the large scale farm, 40% from the medium scale non-grazing, and 20% from the medium scale with grazing so a weighted average of greenhouse gas emissions from milk production is calculated.

4. Results

The greenhouse gas emissions from milk production were reported to be 1.28 kg CO_2eq kg^{-1} FPCM. Figure 5 displays the breakdown of the global warming potential results in which the fuel category is comprised of diesel and electricity use on the farm and the other category contains emissions from the rest of the milking process and emissions from construction. The construction emissions are due to construction being embedded in flows from processes that were used in the openLCA model. Enteric fermentation and manure management make up the largest portion of the emissions with 69% of the total emissions coming from these two categories.

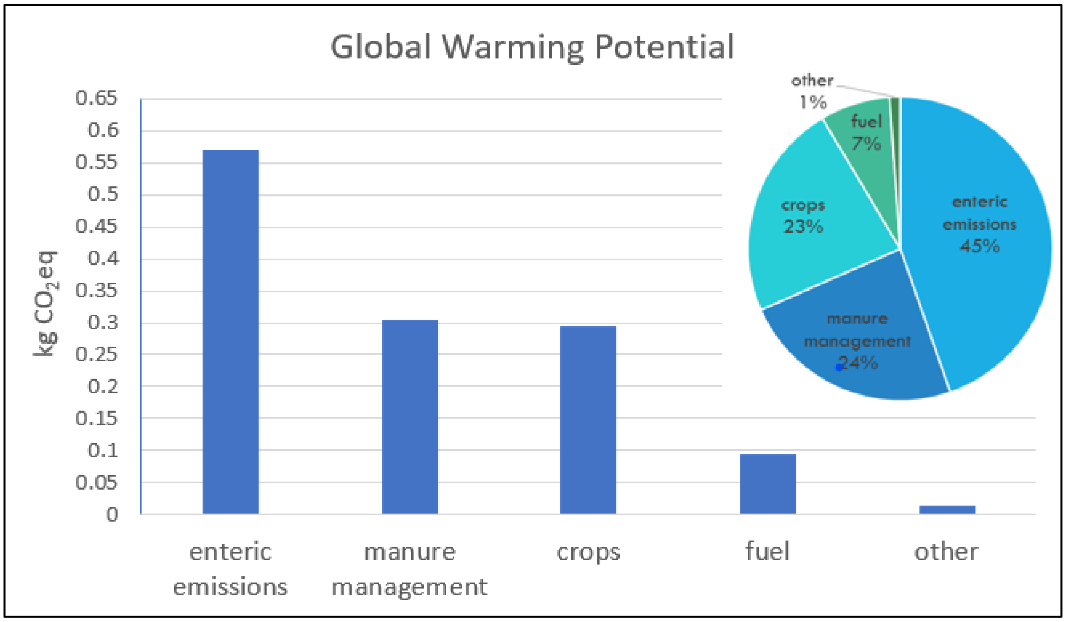

Figure 5. Greenhouse Gas Emissions

Crop production emissions are displayed per crop in Figure 6. Soybeans produce a majority of the total crop emissions.

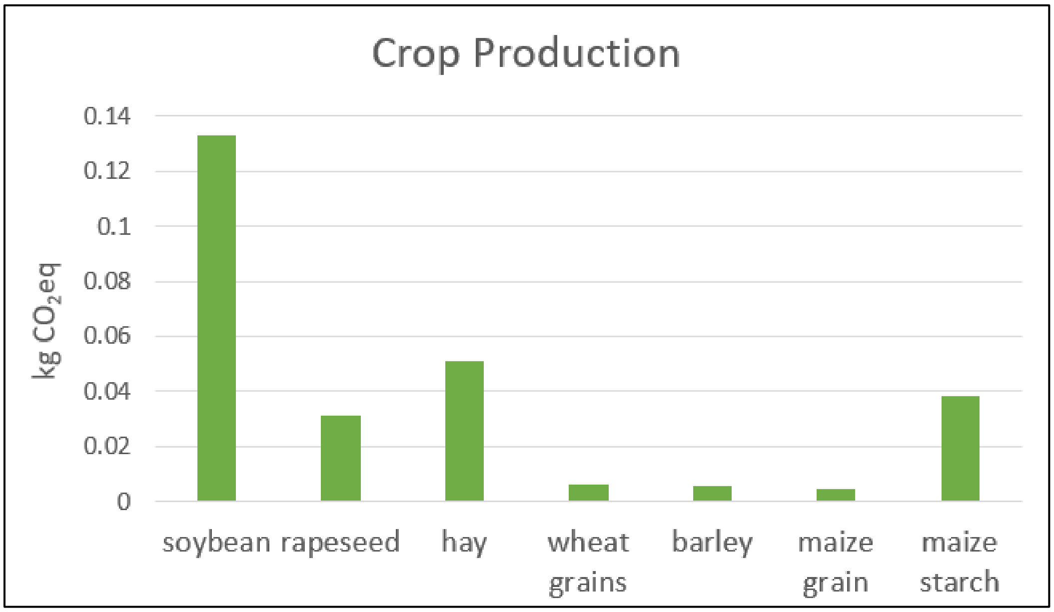

Figure 6. Greenhouse Gas Emissions per Crop

The carbon footprint contribution by each component is shown in Figure 7. Methane has the largest contribution towards the carbon footprint with 0.921 kg CO_2eq kg^{-1} FPCM. These emissions are mainly from the enteric and manure management categories. N_2O accounts for 0.079 kg CO_2eq kg^{-1} FPCM while carbon dioxide contributes 0.278 kg CO_2 kg^{-1} FPCM.

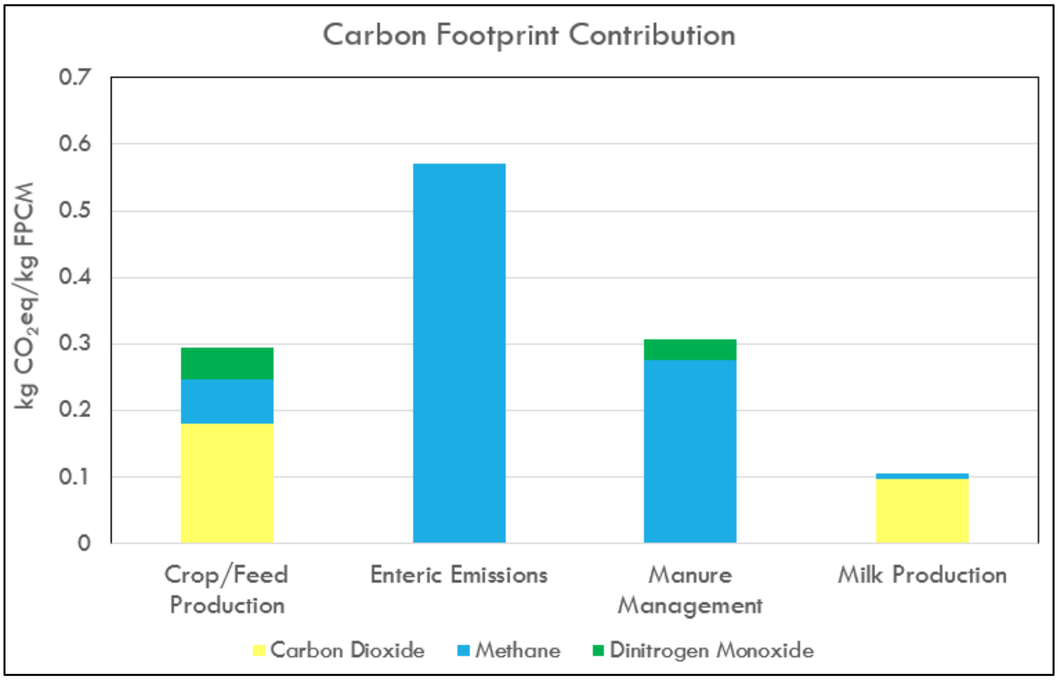

Figure 7. Carbon Footprint Contribution

5. Conclusions

This LCA provides consistent results to other studies that have performed cradle-to-gate assessments for milk production. Table 1 displays results from milk production LCAs. While the studies have the same general scope of cradle-to-gate, the results cannot be directly compared. Each study is performed with a different inventory and may include or exclude things that other studies do not. Assumptions are made throughout life cycle assessments that ultimately affect the results of the study and vary for each assessment. The FAO study reported the intensity for North American dairy production and the Verge study was conducted in eastern Canada. The Capper and Cady study used the more recent values for emission factors, which were the same emission factors used in this study but did not include allocation factors among the farm products. The overall results from using the openLCA software are comparable to those using SimaPro or other LCA software, indicating that openLCA can be used to perform life cycle assessment for milk production.

Table 1. Life Cycle Assessment Results

GWP (kg CO_2eq/kg FPCM)	LCA Study
1.23	Thoma et al., 2012
1.35	Capper et al., 2009
1.3	FAO 2010
0.74-1.13	Rotz et al., 2016
1.26	Verge et al., 2013
1.84	Capper and Cady, 2020

There is a great need to reduce the carbon footprint of the dairy industry. The agriculture sector is responsible for 10% of all greenhouse gas emissions in the US with 43.8% of these emissions coming from livestock (EPA, 2020). The LCA indicates that enteric emissions and manure management have the largest impact on the carbon footprint. The feed composition directly affects the amount of methane produced through digestive fermentation. A supplement like seaweed could be added to the feed composition to reduce the amount of enteric methane emissions. Adding 80 grams of seaweed into the diet caused an 82% reduction in the amount of methane released into the atmosphere by cows (Nelson, 2021). Further research is required to determine the environmental impacts of using seaweed in the feed, how to implement these feed changes, especially for grazing cattle, and how to farm the seaweed to have a large enough supply. Increasing the feed conversion efficiency would also help reduce emissions. Feed conversion efficiency is defined as the ratio of the dry matter intake per day and the daily milk production. Feed is a major farm input and directly impacts enteric emissions and the quantity and quality of manure (Thoma et al., 2012). This is an area in which research could be done to continue improving the feed conversion efficiency as this would help reduce emissions from multiple areas of the life cycle.

Manure management emissions could be reduced by using an anaerobic digestor on the farm. The anaerobic digestor would convert manure and other farm waste, such as wastewater, straw, corn husks, grass, and leaves, into biogas consisting of methane and carbon dioxide. A study at Penn State University indicated that the biogas produced contained about 60% methane, meaning that the gas has 60% of the energy in natural gas. The biogas produced from manure provided enough power to provide 20% of the energy used on the farm (*Biogas from Manure*, 2023). The use of anaerobic digestors would aid in reducing methane emissions from manure and reduce emissions from fuel use on the farm. It would also decrease the amount of manure that is stored on the farm. This would also help prevent deadly fires like the one at South Fork Dairy Farm in Dimmitt, Texas on April 10, 2023 by reducing the amount of flammable methane that is contained on the farm. Further research needs to be conducted to determine if these changes would provide a positive impact on the carbon footprint of the dairy industry and that environmental burden shifting does not occur. Since the LCA focuses only on greenhouse gas emissions, a further study is needed to understand the full range of environmental impacts. Sensitivity analysis could be performed, specifically by choosing different allocation factors for the environmental burden of milk compared to beef co-products, to understand the effects of choosing specific allocation factors.

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