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Farm level environmental assessment of organic dairy systems in the U.S.

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ABSTRACT

A farm scale life cycle assessment (LCA) was conducted to estimate environmental indicators of organic dairy systems in the U.S. and evaluate alternative management practices and methodological decisions. Fourteen farm layouts (including Amish and grass intensive) are evaluated over four U.S. regions. Carbon (C) sequestration from pasture and cropping systems is estimated based on C added to the soil and the crop and grassland management practices. Greenhouse gas (GHG) emissions range from 0.76 to 1.08 kg CO_2-eq/kg fat and protein corrected milk (FPCM) after C sequestration. Methane (CH_4) from enteric fermentation and liquid-slurry manure storage are major sources of GHGs, with the first related to cow feed to milk conversion efficiency. The production and consumption of fossil energy contribute to GHGs depending on the mix of fuels of regional electricity production. NH_3 emissions range from 7.7 to 20.0 g/kg FPCM with differences between regions explained by environmental factors, management practices, and dairy diet composition. Eutrophication potential ranges from 3.4 to 6.6 g PO_4/kg FPCM from phosphorus and nitrogen losses after manure application from on-farm and imported feeds. Electricity and diesel are the major contributors to fossil energy depletion (2.1 to3.7 MJ/kg FPCM), with the embedded energy from imported feeds also contributing significantly. Land use ranges from 0.9 to 2.0 m^2/kg FPCM, influenced by the composition of the diet, crop yields, and milk production. Water use is increased from a range of 5.3 to 13.6 kg/kg FPCM to a range of 173 to234 kg/kg FPCM in irrigated farms. The analysis of 14 alternative management practices measures GHG reductions of 15% and 30% for individual and combined practices, respectively, where manure storage and renewable energy production have the greatest benefits. Land and animals as alternative functional units change trends in GHGs, but trends are maintained when analyzing different enteric CH_4 equations with variations in intensity. The allocation to milk based on nutritional content is greater than an energy-based allocation, while the choice of N_2O emission factor from manure deposited on pasture is more significant for farms with long grazing seasons. Combining the alternative methodological choices increases GHGs by 30%.

1. Introduction

Agricultural systems are challenged to balance feeding a growing population while addressing environmental concerns and providing a high quality of life for farmers and rural communities. Agricultural emissions to air and water contribute to climate change, ecosystem deterioration, and human health issues (Poore and Nemecek, 2018). In the U.S., agriculture is responsible for 10% of total greenhouse gas (GHG) emissions, with soil management, enteric fermentation, and manure accounting for 55%, 28% and 10%, respectively (U.S. EPA, 2021a). Up to 70% of the excreted nitrogen (N) in manure can be emitted as ammonia (NH_3) in livestock operations (Hristov et al., 2002). These losses represent 80–90% of the global anthropogenic NH_3 emissions (Xu et al., 2019) that can redeposit and lead to impaired waterways (U.S. EPA, 2004), or further transform to particulate matter or N_2O. Nutrient losses from manure have the potential to reach ground and surface water contributing to eutrophication.

To improve sustainability, consumers are shifting their preferences towards organic products that require less resources. Organic farm products in the U.S. have a market value of $10 billion, with organic

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milk accounting for 16% of this market (USDA-NASS, 2020). In 2019, 3.6% of cows in the U.S. were managed under certified organic conditions, producing 2.3 billion kg of organic milk, or 2.3% of the national milk production. While the milk produced and the number of cows are increasing, the productivity of organic dairy farms lags conventional systems (Schwendel et al., 2015; Pinedo and Velez, 2019). Some studies suggest the environmental impacts of organic systems can be similar or higher than conventional systems per milk produced (Cederberg and Mattsson, 2000; Thomassen et al., 2008). While all organic farms have certain commonalities in their management, depending on region and size, they can vary in their specific management approaches (USDA-AMS, 2021). As we refine our understanding of both positive and negative environmental impacts of organic dairy systems, the influence of these differences on metrics must be considered.

Thoma et al. (2013) found that more than 70% of GHGs from milk production are emitted at the farm level in the U.S. Life cycle assessment (LCA) has been used to define a variety of dairy farm systems and assess their production processes, compare product footprints, and identify mitigation strategies (FAO, 2010; Flysjö et al., 2011; Mc Geough et al., 2012; O'Brien et al., 2014; Aguirre-Villegas et al., 2017; Veltman et al., 2017; Kim et al., 2019; Ledgard et al., 2020; Naranjo et al., 2020). However, most farm dairy LCAs in the U.S. have focused on GHG emissions from conventional dairy systems. These studies provide great insight on the environmental sustainability of conventional dairy systems, but they do not represent the practices in organic dairies.

Direct extrapolation of results from conventional LCA studies to organic farms are not accurate as farm management practices and milk production vary significantly. Many studies exploring organic production were conducted in Europe and apply to specific regions (Cederberg and Mattsson, 2000; Haas et al., 2001; De Boer, 2003; Olesen et al., 2006; Weiske et al., 2006; Thomassen et al., 2008; Hietala et al., 2015). Rotz et al. (2020a) estimated GHG emissions, loss of reactive N, and fossil energy and blue water consumption for different farm types, including organic. The study estimates regional impacts rather than farm practices, making it difficult to isolate the trade-offs for organic systems. Rotz et al. (2021) conducted a national assessment of dairy farms in the U.S. where organic practices are represented only by two farms in each region and environmental trade-offs of these systems cannot be clearly identified. Therefore, it is crucial to develop a systems approach that evaluates environmental impacts of organic dairy systems and practices in the U.S. In addition, dairy systems are complex, and the processes are heavily linked where changes in one area of the farm can lead to unintended consequences or trade-offs between impact categories. Therefore, assessments of organic systems should be conducted independently with organic specific data.

Carbon (C) sequestration has been explored only by a few LCA dairy studies (Batalla et al., 2015; Salvador et al., 2017; Sabia et al., 2020). The feed intake of organic dairy cows is composed mainly of pasture and forages (Holly et al., 2019) that have more developed root systems that can store more C below ground than other crops included in conventionally managed dairy farms (Griscom et al., 2017). Studies that included C sequestration were based on practice changes (Mogensen et al., 2014) or used fixed factors (Guerci et al., 2013; Rotz et al., 2020b). However, C sequestration depends on other factors that are related to location that need to be considered (Taghizadeh-toosi et al., 2014). In the long-term, not all the C reaching the soil is sequestered. Most of this C will be slowly decomposed and emitted as carbon dioxide (CO_2) until it reaches a new equilibrium, with the remaining C stored in the soil. Field management can also affect C sequestration as certain practices lead to higher and more rapid CO_2 emissions while others promote C additions to the soil (e.g., cover crops) (IPCC, 2006a). Conservation practices are generally implemented by organic dairy systems to sequester C are not captured by most dairy LCA studies.

As the market drivers change to support more sustainable products, it is critical to provide policymakers, farmers, stakeholders, and consumers with the needed information to assess the environmental impacts of production systems. This study uses a farm scale LCA model to quantify GHG emissions (including C sequestration), NH_3 emissions, resource depletion (energy, land, and water use), and eutrophication potential (EP) at organic dairies in the U.S. Furthermore, it evaluates the effect of different practices and LCA methodological choices on GHG emissions.

2. Methods

2.1. Model description and data

The U.S. was divided into eight regions (Figure B1 and Table A1) based on climate categories (IPCC, 2006a) and practices of the organic dairy farms that participated in the study. All farms are members of the Cooperative Regions of Organic Producers Pools (CROPP), marketed as Organic Valley (OV), the largest organic dairy cooperative in the U.S. The membership of CROPP represents more than 50% of the 3100 organic dairy farms in the country (USDA-NASS, 2020). This paper evaluates the Midwest-Great Lakes, New England, California, and the Northwest, where representative individual organic farms and management practices for each region are modeled to estimate GHG emissions (kg CO_2-eq), NH_3 emissions (grams, g), EP (kg PO_4-eq), and use of fossil energy (MJ), water (kg), and land (m^2). Farms were modeled individually, considering the LCA framework provided in Aguirre-Villegas et al. (2015) but modified to capture the practices of the evaluated organic farms. Daily dietary requirements and feed composition for each crop and animal type are considered (NRC, 2001) and key constituents in milk, meat, and manure tracked. All inputs and outputs at the farm level are included in the analysis, where milk and meat are the only products (Fig. 1). Impacts involved in the production of infrastructure and machinery are not included, as they are a small component (1–4% of farm GHG emissions (Samson et al., 2012; Hijazi et al., 2020)) of the environmental impacts in dairy farms (Frischknecht et al., 2007; Flysjö et al., 2011). The functional unit is defined as 1 kg of fat and protein corrected milk (FPCM), adjusted to 4% fat and 3.3% protein and allocation is based on the underlying use of feed energy by the dairy cows and their physiological feed requirements to produce milk and meat (IDF, 2015).

Farm characteristics and data about herd management, milk production, crop production, energy use, manure and cropping management for each farm type and region were provided by OV and compiled through internal surveys, and interviews with farmers, in-house veterinarians, and feed specialists. State level data (Tables A2-A4) was regionalized based on the number of farms in each state (Figure B1) including temperature and precipitation from Regional Climate Centers averaged for the last 30 years (NOAA, 2021), GHG emissions from electricity profiles (U.S. EIA, 2019), energy matrices (U.S. EIA., 2020), crop yields averaged for the years 2015–2019 (USDA - NASS, 2019), and irrigation for crops and pastures (USDA - NASS, 2018). Data from material and energy inputs were taken from SimaPro and built-in databases (Pre-Consultants, 2019).

Evaluated GHGs and characterization factors over 100-years are CH_4 (28), direct and indirect N_2O (265), and CO_2 (1) from fossil sources (Myhre et al., 2013). CO_2 emitted from the decomposition of living organisms and animal respiration is excluded as it has been captured by plants that feed the cows. Other biotic emissions are estimated with the process-based models and emission factors presented in Table A5. NH_3 is emitted from manure on barn floors, manure storage, and from crop and pasture fields after land application. A nutrient balance, after N-emissions, determines the amount of N and phosphorus (P) reaching the soil, and posterior losses to the soil. Water is used for cows consumption (and horses in Amish farms, defined as farms using draft animals for field work in lieu of tractors and that generate electricity on-site with diesel) estimated based on temperature, body weight, and milk production); parlor equipment and cleaning (Rotz et al., 2018); materials production (Pre-Consultants, 2019); and irrigation when applied (USDA - NASS,

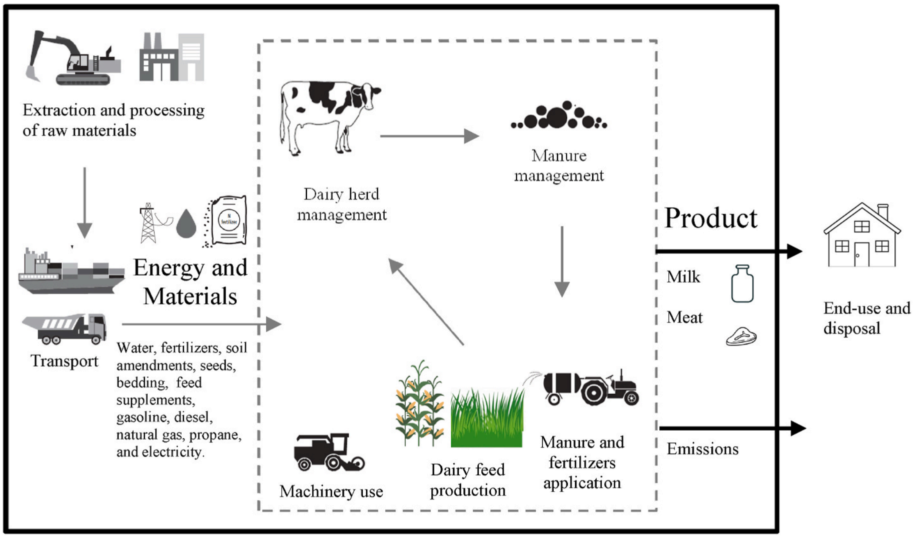

Fig. 1. System boundaries are within the solid black line. Dashed lines show farm-level activities. FPCM: fat and protein corrected milk.

2019). Fossil energy is used directly on farm operations (e.g., harvesting crops, manure application, and milking cows) and indirectly to produce energy and other materials used at the farm. Land is used directly for grazing and growing row crops (directly related to the yields of the crops fed to the herd, Table A6) and indirectly to produce materials off-farm (feed supplements and imported feeds) but used on-farm.

2.2. Carbon sequestration

Carbon sequestration from pasture and row crops is estimated based on: i) the C added to the soil from biomass in above and below ground residues and manure; ii) the change in C above and below ground as a result of crop and grassland management practices, iii) the amount of C from the first steps that will be sequestered long-term.

Carbon is 45% of the total dry biomass from above and below ground residues (U.S. EPA, 2021b). Above ground residue for pasture and row crops is determined with the harvest index (Table A7), that allows for calculating the remaining fraction not harvested nor collected for other purposes (e.g., bedding) (Eq. C1). For crops harvested once a year, above ground biomass is the same as peak biomass. For perennials and grass, above ground biomass is the sum of the biomass collected at each harvesting event and the biomass remaining after each harvesting event (Table A8).

Below ground residue (Eq. C2) is the sum of the biomass in the roots that stay in the soil after the plant decomposes and the yearly turnover for perennials and grasses, (fine roots and hairs that decompose and are again produced yearly). Below ground biomass is estimated based on root:shoot ratios for each crop (biomass in the roots vs biomass in the plant above ground at its peak, Table A7). The turnover is estimated by multiplying the biomass in roots and the turnover rate expressed as an exponential function of temperature.

Carbon from manure is estimated for each animal type based on the nutritional models developed in Aguirre-Villegas et al. (2015) (Eq. C3) and considering that there is 75.5% C in fat and 44.4% C in fat free organic matter (Ensminger et al., 1990).

Land use regime, management, and input of organic matter into the soil are evaluated as activities affecting the C stock (IPCC, 2006b; IPCC, 2006c). For each of these activities, different factors (for both crops and grass) based on the level of activity, temperature, and moisture are applied to the estimation of above and below ground residues for each crop (Table A9). The total C stock change is obtained by multiplying all these factors (Eq. C4).

The outputs from the C-Tool model (Taghizadeh-toosi et al., 2014) estimated in Petersen et al. (2013) are used to determine C sequestration potential factors (Table A10) based on temperature and adjusted for moisture for each modeled region for 100 years. Finally, the C sequestration potential (Eq. C5) is estimated and integrated in the overall farm C accounting as a benefit.

2.3. Description of farms

A scenario analysis of each representative farm is presented. Five farms were modeled in the Midwest-Great Lakes, five in New England, two in California and two in the Northwest based on the most common farm practices within each region. Farm characteristics, practices, and diet compositions are presented in Tables A11-A14 and Figures B2-B5. Farm sizes range from 30 to 350 lactating cows, plus the respective maintenance animals. Two farms in the Midwest-Great Lakes and New England represent intensive rotational grazing and Amish practices. Milk production ranges from 17 to 27 kg/cow with fat and protein contents higher for Jersey cows. Each farm is divided into grazing and non-grazing seasons to capture the effect of climatic conditions and management practices. Farms in the Midwest produce all feeding crops on-farm except for supplements, whereas farms in the Northwest only produce pasture and corn silage on-farm with the remaining feeds imported (Figures B2-B5). For all farms, manure is the main source of nutrients. Only one farm with a flush collection system and a solid-liquid separator (separation efficiencies from Aguirre-Villegas et al. (2019)) handles liquid manure with the rest managing slurry and solid manure. Inventory data presented in Table A15.

2.4. Analysis on GHG emissions

2.4.1. Changes in management practices

The effect of 14 alternative management practices on GHG emissions has been evaluated in two farms per region (Table A16). Improving feed efficiency is evaluated by increasing milk production, milk fat, or reducing DMI. Improving the herd's health is evaluated by reducing the lactating cow replacement and heifer mortality rates. The effect of reduced body weights of organic cows is also explored based on recent survey results from the evaluated organic farms. To capture the effect of the dairy diet and feed efficiency on N-based emissions, the crude protein (CP) content was reduced. High CP in the diet results in more N excreted in manure, with the potential to be emitted to air and water (Aguerre et al., 2010). Changes in manure management include replacing bedded packs with solid storage systems, as the former can promote N-emissions (Rotz, 2018); using a cover (with no flare) or a cap-and-flare system (with 1.5% fugitive emissions of the produced CH_4, Rotz et al. (2018)) in farms with liquid and slurry manure storage as this is the main source of manure CH_4 emissions (Kim et al., 2019); solid-liquid separation as it can reduce CH_4 emissions due to the reduced volatile solids (VS) in the stored liquid manure fraction (Aguirre-Villegas et al., 2019); and injecting manure into the soil (vs. surface application) as it can reduce NH_3 and indirect N_2O emissions (Chadwick et al., 2011). Finally, the adoption of a renewable energy system that provides electricity in the amount consumed by the farm (no electricity sold to the grid) is evaluated.

2.4.2. Changes in methodological choices

Most milk related LCAs define the functional unit as FPCM, but studies argue that alternative units, such as land (hectare) or cows (number), better capture benefits of systems that do not focus on maximizing productivity (O'Brien et al., 2012; Ross et al., 2017). These LCA studies have also adopted the allocation approach recommended by the IDF (Thoma et al., 2013; Ledgard et al., 2020; Naranjo et al., 2020; Rotz et al., 2021). Other studies, however, have adopted different allocation approaches, finding significant differences in results (O'Brien et al., 2014; Ross et al., 2017; March et al., 2021; Romano et al., 2021). Two additional functional units of land and number of animal units (1 AU = 454 kg animal) and allocation based on the fat and protein content of both milk and meat according to Aguirre-Villegas et al. (2015) are evaluated. Enteric CH_4 is the main source of GHG emissions at the dairy farm level, with multiple predictive equations available to be included in models; however, depending on the equation used, a wide range of outcomes in estimations of enteric CH_4 can result (Appuhamy et al., 2016). Four alternative enteric CH_4 prediction equations are evaluated based on structural and nonstructural carbohydrates (Moe and Tyrrell, 1979), energy intake (IPCC, 2006a), fat and digestibility of feed (Nielsen et al., 2013) (Equation (C6)-C9). Organic dairy farms use manure as their main source of N for crop production, thus, manure is the main source of soil N_2O emissions. Based on experimental evidence, this study assumes that 1% of the applied N is emitted as N_2O for both manure land applied and excreted on pastures (Van Groenigen et al., 2005; Galbally et al., 2010; Chadwick et al., 2018; Ledgard et al., 2020). However, different LCA studies apply a 2% factor (IPCC, 2006d) when manure is excreted directly on pastures due to the high concentrations of N in urine and feces in small patches that interact with soil bacteria (O'Brien et al., 2014). To evaluate this effect, the N_2O–N emission factor is changed from 1 to 2% of applied N for manure deposited on pastures.

3. Results and discussion

In general, farms with reduced FPCM production have increased environmental impacts when compared to the rest of farms as results are expressed as a function of milk production. Overall, results are within the range of similar studies for dairy systems with Table A17 presenting a comparison for all evaluated environmental impacts.

3.1. GHG emissions

Average GHG emissions for the modeled farms and regions range from 0.76 to 1.08 kg CO_2-eq/kg FPCM (Fig. 2). Enteric CH_4 represents more than half (47–59% before C sequestration) of total GHGs and is closely related to the efficiency of conversion of feed to milk by the cow (Fig. 3). Farms with Jersey cows (50-J in the Midwest and New England) have improved feed efficiency when using FPCM, as milk is characterized by higher fat and protein content than Holstein cows.

Carbon dioxide from the production and consumption of fossil energy (3–15%) and materials (4–23%) represents 16–28% of total GHGs (Figure B6). Diesel is one of the main sources except for California 150-J that relies more heavily on grazing. Emissions from electricity in New England are lower than the other regions as electricity is produced mostly from renewables whereas the Midwest uses coal and natural gas. In Amish farms, emissions from horse maintenance are small when compared to avoided emissions from using farm machinery. However, Amish farms routinely use diesel-powered generators for electricity, negating the benefits from not using fossil fuel-based farm machinery. Emissions from material inputs in the Midwest and New England regions, that only import feed supplements, are lower than farms in California and the Northwest that import other feed components (e.g., corn

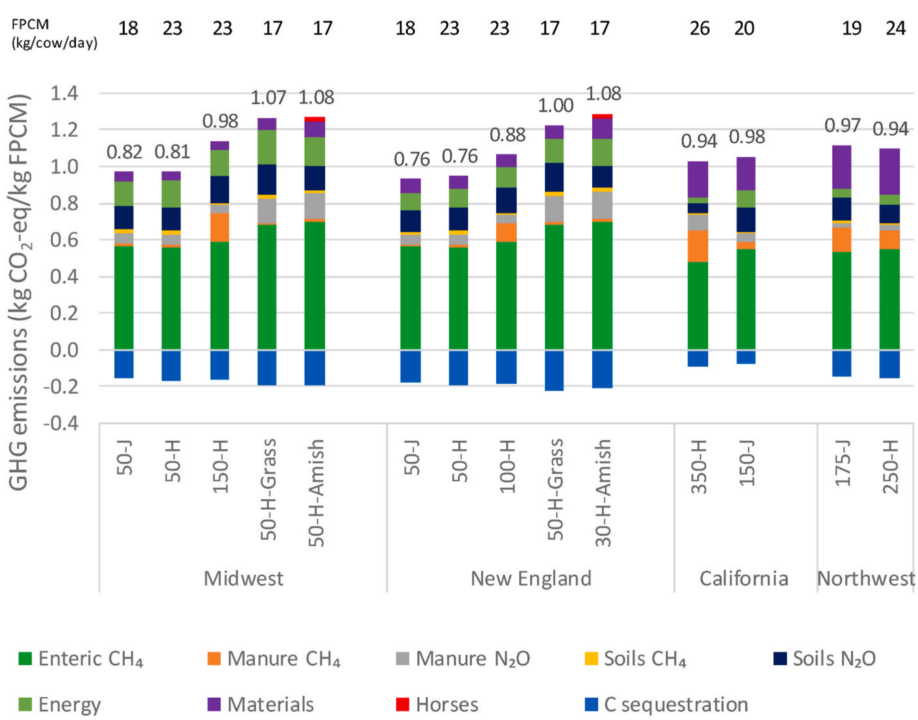

Fig. 2. Net greenhouse gas (GHG) emissions per gas source for each modeled farm and region after accounting for the benefits of carbon C sequestration (negative). Fat and protein corrected milk (FPCM) per farm is shown to relate emissions to milk production.

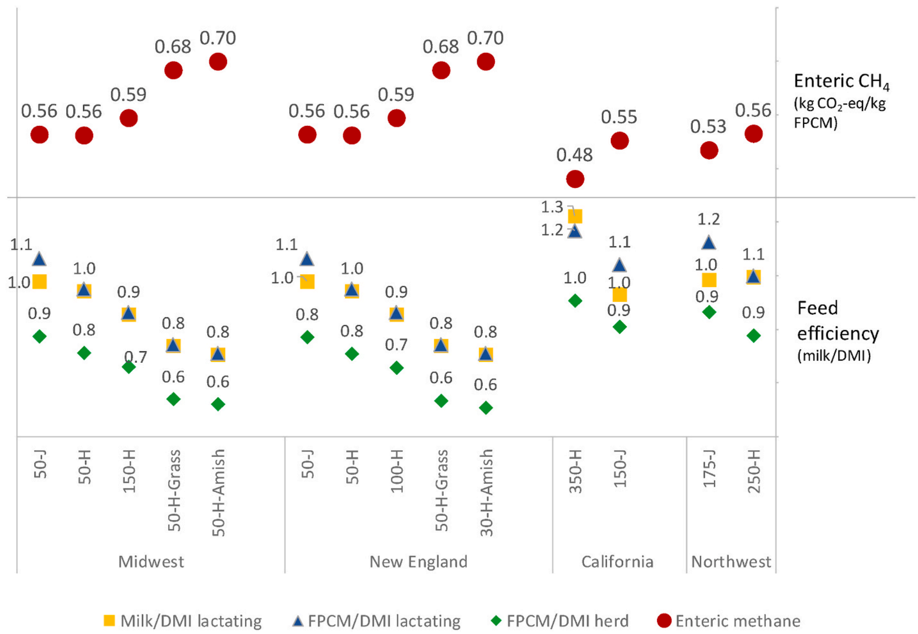

Fig. 3. Enteric methane (CH_4) and feed efficiency ratio (milk production/dry matter intake (DMI)) for: 1) raw milk/lactating cow's DMI, 2) fat and protein corrected milk (FPCM)/lactating cow's DMI and 3) FPCM/herd's DMI for all modeled farms and regions.

grain) from far away countries, with related transportation impacts, lower yields, and higher inputs than those in the U.S. (Pre-Consultants, 2019). Bedded pack systems (high grass and Amish) have increased emissions due to increased amount of bedding materials used and produced outside of the farm boundaries. Using recycled wood chips for bedding in the Northwest reduced GHGs, when compared to other regions and farms that use (and recycle) sand and straw.

Methane from manure contributes 1–17% of total GHGs and is mostly emitted from farms with liquid and slurry manure storage (farms with >100 cows) that promote anaerobic conditions, as opposed to farms handling solid manure (1–2% of total GHGs from manure storage) that store manure in piles, which facilitate aeration and limit CH_4 formation. Farm 350-H in California has longer storage times than other farms, explaining the higher emissions from manure. In general, manure CH_4 is higher during hotter, non-grazing months, despite less manure is stored during these months, highlighting the influence of temperature on CH_4 formation. The 250-H farm in the Northwest separates manure with a screw press where some VS follow the solids fraction, reducing CH_4 emissions from storage (Table A14).

Emissions of N_2O after land applying manure range from 2 to 12% of total GHGs. Overall, N content in excreted manure is higher in farms that rely more heavily on pasture and forages as these feeds have higher CP contents than grains, which also explains the higher N_2O emissions from soils during the grazing season. N_2O emissions are also higher for farms with higher replacement rates that need more maintenance animals. Bedded packs create a mix of aerobic and anaerobic conditions at high temperatures and moisture for long periods of time, resulting in higher N_2O emissions in farms with these systems. These conditions are also created during solid and slurry manure storage with organic crust formation (Aguerre et al., 2012).

Carbon sequestration benefits range from −0.08 to −0.22 kg CO_2-eq/kg FPCM (7–20% reduction). Farms in the Midwest and New England

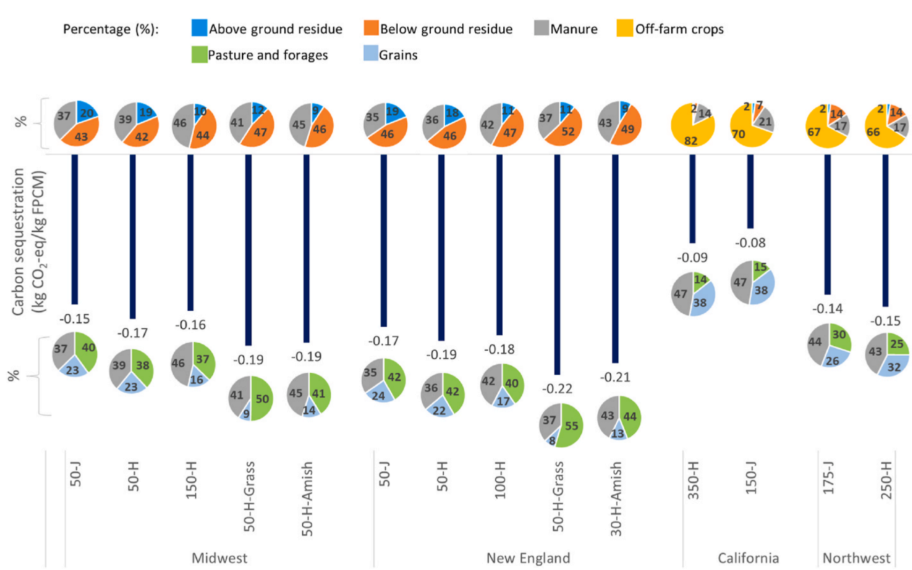

Fig. 4. Breakdown of carbon (C) sequestration benefits and sources per feed component and residue type.

rely heavily on pasture during the grazing season and on grass forages produced on-farm during the non-grazing season, with most of the C sequestered through residue that stays in the soil (Fig. 4). The addition of C in manure is also significant in all farms, especially those relying on imported feeds. The used C sequestration potential is lower as temperature increases, explaining the lower benefits in California where most of the C sequestration comes from the production of imported feeds. Farm 350-H in California relies on annual ryegrass (*Lolium multiforum*), which has a lower root:shoot ratio compared to perennial grasses that are produced on the rest of farms.

3.2. Ammonia emissions

Total NH_3 emissions range from 7.7 to 20.0 g/kg FPCM (Fig. 5). On average, manure storage represents 30% of the total NH_3 emissions in farms handling solid and liquid manure and 50% in farms with bedded packs. The warm temperatures created in bedded packs in the Midwest and New England, added to the greater manure collection rates during non-grazing seasons result in the higher NH_3 emissions in these farms. Also in these regions, farms with <100 generally have diets with a higher content of grass and forages than >100 cow farms, which is reflected in the higher N content in excreted manure and posterior NH_3 emissions. Farm 350-H in California leaves 70% of manure in open lots where 30% of excreted N in manure is emitted as NH_3 (IPCC, 2006e), explaining the higher NH_3 emissions from manure management in this farm. Farm 250-H in the Northwest separates liquid manure with <5% TS, impeding a natural crust formation during storage (that acts as a barrier to wind exposure), which explains the higher NH_3 emissions from manure management than 175-J also in the Northwest. However, NH_3 emissions from 250-H are lower after land application as liquid manure infiltrates and binds more rapidly into the soil. For free-stall and tie-stall farms, up to 90% of total farm NH_3 emissions results from the cropping as manure is not incorporated, leaving N exposed to wind with limited opportunity to bind to soil.

3.3. Eutrophication potential

Total EP ranges from 3.4 to 6.6 g PO_4/kg FPCM (Fig. 6) and is driven by N and P in manure reaching grasslands and row crops on-farm in the Midwest and New England (manure application) or imported feeds in California and the Northwest (materials and energy) (Figure B7). Nutrient loss is directly related to rainfall, which varies from region to region, and which is greater during grazing months. The N content of manure is higher during grazing months and for those farms that rely more heavily on grass and forages for feeding. The extra imported straw bedding (and related fertilizer use for its production) for bedded-pack housing at intense grass and Amish farms in the Midwest and New

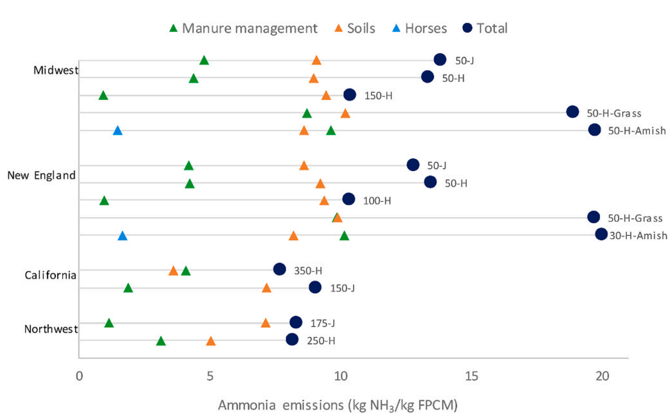

Fig. 5. Ammonia emissions for the modeled dairy farms by region. Manure management includes the barn and manure storage. Crops includes manure land application.

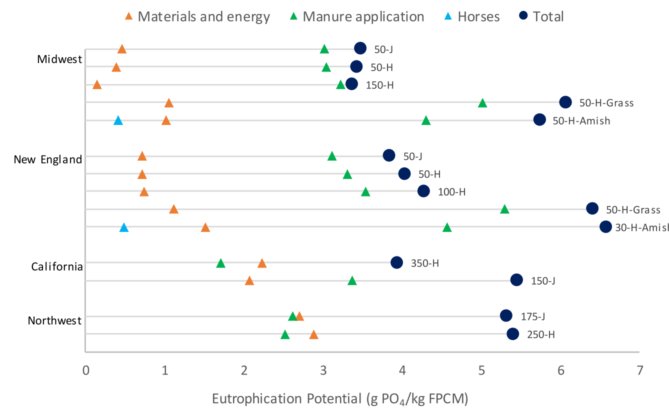

Fig. 6. EP for each of the modeled dairy farms and regions.

England increase the EP from materials and energy in these farms. Additionally, Amish farms need to manage manure from horses. Farm 250-H in the Northwest separates manure, but since both the nutrients from the solids and liquid fractions are land applied to the soil, nutrient levels are similar than the farm without separation.

3.4. Resource depletion

Fossil energy consumption ranges between 2.1 and 3.7 MJ/kg FPCM (Fig. 7a). For the Midwest and New England, 74–87% of the depleted fossil energy comes from the consumption of energy resources on-farm, mostly electricity, diesel, and propane with the electricity mix of New England mostly constituted by renewables and the Midwest by coal and natural gas. The use of horses in Amish farms provide significant fossil energy savings from not using agricultural machinery. However, the use of diesel-generators for electricity increases fossil energy use. Depletion of fossil energy in California and the Northwest comes mostly from the production and transported of imported feeds (e.g., corn grain is imported from Ukraine, Russia, and Turkey). Farm 350-H in California is more energy efficient than farm 150-J that has 47% of its fossil fuel consumption coming from propane and electricity.

Land use is influenced by crop yields and ranges from 0.9 to 2.0 m^2/kg FPCM (Fig. 7b). Farms in the Midwest produce all feed on-farm as opposed to New England, California, and the Northwest where 12–29%, 56–60%, and 68–73% is from off-farm feed production. Amish farms have increased land use from producing feed for horses. Interestingly, land use is lower during the grazing season for all farms in the Midwest and New England due to the high pasture yields. This shows that grazing systems can use land more efficiently than farms combining grass with grains. California and the Northwest show lower land use for Jersey cow farms, highlighting the higher feed efficiency of Jersey cows than Holsteins.

Water consumption ranges from 5.3 to 13.6 kg/kg FPCM when irrigation is not considered. Animal drinking for the herd represents 65–73% of total water use in the Midwest and New England regions. Higher consumption levels are observed in warmer regions as drinking water intake is related to ambient temperature. In California and the Northwest, water consumption rates are higher due to the high percentage of imported feeds requiring water for production. Farm 150-J in California and both farms in the Northwest use irrigation increasing water consumption up to 173–234 kg/kg FPCM.

3.5. Analysis of practices and modeling decisions on GHG emissions

3.5.1. Change in management practices

Practices can mitigate GHG emissions 15% on average, with manure covers and cap-and-flare systems having the biggest effect (Fig. 8). Combining practices can achieve average 30% (and up to 40%)

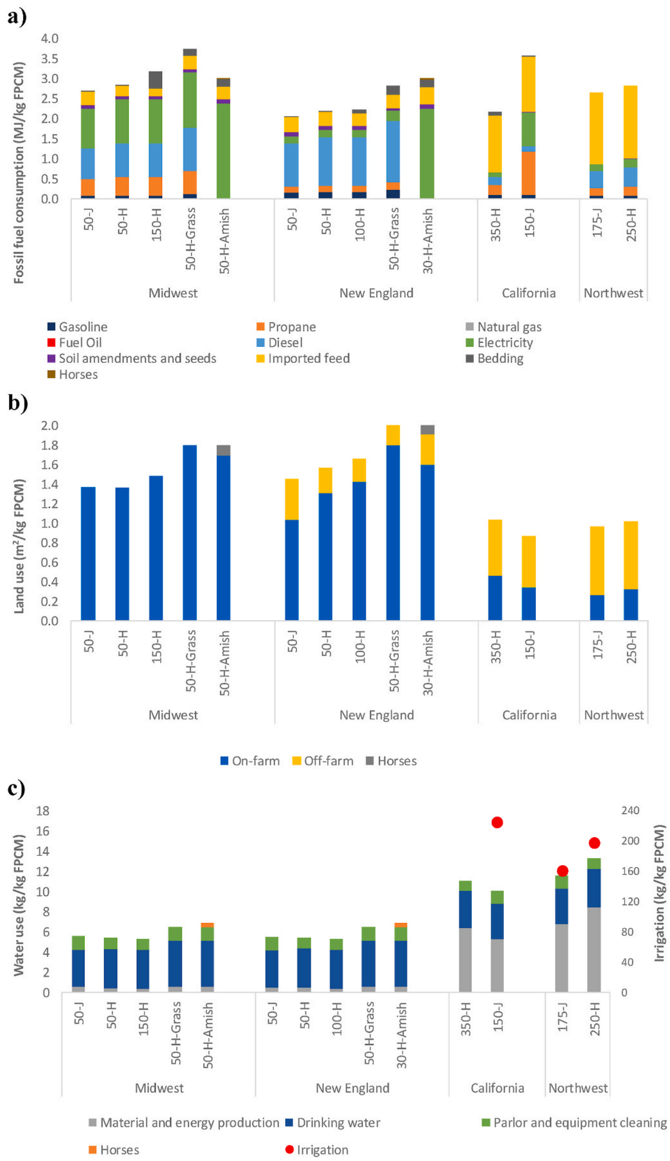

Fig. 7. a) Fossil energy consumption, b) land use, and c) water use for the modeled dairy farms and regions.

reductions. Improving milk yield, feed efficiency, and increasing milk fat show consistent GHG improvements across all farms. Manure separation also reduces GHG emissions from manure storage, while providing nutrient and economic benefits to the farmer. Installing a renewable energy system for electricity shows the highest reduction potential where electricity has a high percentage of fossil-fuels and in Amish farms that produce electricity from diesel. Decreasing the CP content of the diet reduces GHGs by 3–6%, but less N is available for crop production. Improving replacement rates mitigates GHGs but the gain is reduced by its effect on allocation as less meat is produced by the system, highlighting the importance of modeling decisions. Combining practices can achieve up to 40% GHG emission reductions, showing promising results for GHG mitigation goals from dairy farms.

3.5.2. Change in methodological choices

GHGs were assessed using eight alternative methodological decisions (Table 1), with the functional unit significantly affecting trends (Figure B8a). Amish farms go from the highest GHG emissions when expressed per FPCM to the lowest when expressed per AU, showing their low milk production but also low GHGs per cow. GHGs per land are higher for larger farms with increased animal density. Interestingly, FPCM shows lower emissions for California and the Northwest than for the Midwest and New England, whereas both land use and AU show the opposite trend. Land use and AU reflect a different perspective of system efficiency targeting the use of resources of the dairy system (Baldini et al., 2017).

Trends in GHGs after alternative allocation, enteric CH_4 equation, and N_2O emission factor have slight variations for California and the Northwest (Figure B8b). Comparisons with the baseline (under FPCM as functional unit) show that average GHG emissions are increased 2–21% by the evaluated methodological decisions except when using enteric CH_4 equation (C6) (that include nonstructural carbohydrates, hemicellulose, and cellulose as predictive variables) that reduces total farm GHGs (Figure B9). Equation (C8) that relates DMI, fat and NDF to CH_4 results in the highest increase from a single methodological decision. Overall trends are maintained with the different equations, but the intensity varies (Figure B10). This variability reinforces the statement of Hippenstiel et al. (2013) that enteric CH_4 models can produce different results with limited set of diets that are typical to specific regions. Appuhamy et al. (2016) ranked 40 enteric CH_4 predictive equations with equations C9 and C8 ranking first in North America. However, none of the evaluated diets included pasture, which is the main feeding component in this study. The diets of organic farms are more like the diets evaluated for Australia-New Zealand, where equations using only DMI and GEI as predictors (explaining up to 92% of the variability) performed best. Farms 350-H, 150-J, and 175-J in California and the Northwest with 72%, 82%, and 77% pasture and forage content in the diet, respectively achieve closer to the original estimations than the rest of farms with 60–68% pasture-forage contents. Coincidentally, the two farms with the highest pasture-forage contents have Jersey cows, which might indicate that diet composition is related to animal type.

The nutritional-based allocation increases GHGs by 7–15% as it assigns 97–98% of GHGs to milk vs. 84–92% of the original feed energy ratio. Interestingly, the nutritional based allocation shows more consistent ratios among farms. Finally, increasing the N_2O emission factor from manure deposition on pasture has a more significant effect in farms with longer grazing seasons. For example, 150-J in California grazes 9 months and has the highest increase vs. 350-H that grazes 4.5 months and has the lowest increase. Combining methodological choices results in average 30% (21–39%) increase in GHGs among the evaluated farms and regions. This increase is comparable in magnitude by the reduction achieved by the management practices analysis, showing the importance of the methodological choices in milk related LCA studies.

4. Conclusions

GHG emissions (including C sequestration), NH_3 emissions, resource depletion (energy, land, and water use), and EP at organic dairy farms in the U.S. were evaluated. Despite that milk production levels are generally lower than conventional systems, environmental impacts are comparable. Carbon sequestration is largely absent from LCA studies given its complexity but can be important for dairies that rely on pasture and forages. This study presents a procedure that can be implemented in other dairy or agricultural related LCA studies and promote discussion around this topic. Enteric CH_4 remains the most prominent source of GHGs from cradle-to-farm gate, but results show that farms can still improve feeding efficiencies. Impacts from energy consumption are directly related to the regional electricity mix, with the implementation of renewables having the greatest impact on Amish farms that use diesel generators. As NH_3 emissions continue to be an important concern for animal agriculture, baseline estimations will help establish mitigation targets and strategies. Manure management remains an important source of environmental impacts, especially during storage and after land application. Water use is significantly higher on farms that use irrigation and import feed. Alternative management practices can reduce GHGs and can guide on-farm implementation. Variations in

Fig. 8. Effect of alternative management practices on GHG emissions.

Table 1
GHG emissions for the alternative methodological choices evaluated in the selected farms and regions.

Methodological choice	Midwest-Great Lakes		New England		California		Northwest	
	150-H	50-H-Amish	100-H	30-H-Amish	350-H	150-J	175-J	250-H
Original estimations								
kg CO_2-eq/kg FPCM	0.98	1.08	0.88	1.08	0.94	0.98	0.97	0.94
Functional Unit								
kg CO_2-eq/Ha[a]	6612	5997	5314	5256	9079	11,237	10,052	9208
kg CO_2-eq/AU[a]	3764	3088	3373	3059	4213	4575	4437	3773
Fat and protein allocation								
kg CO_2-eq/kg FPCM	1.08	1.24	0.97	1.24	1.01	1.06	1.06	1.03
Enteric CH_4 (kg CO_2-eq/kg FPCM)								
Enteric CH_4–C6[b]	1.02	1.11	0.93	1.12	1.02	0.95	0.95	0.94
Enteric CH_4–C7[b]	1.09	1.19	0.99	1.18	1.00	1.01	1.01	1.03
Enteric CH_4–C8[b]	1.16	1.29	1.07	1.29	1.10	1.10	1.09	1.09
Enteric CH_4–C9[b]	1.11	1.22	1.02	1.22	1.05	1.03	1.02	1.04
N_2O emission factor								
kg CO_2-eq/kg FPCM	1.02	1.14	0.93	1.13	0.96	1.05	1.04	1.00
Combined (allocation, CH_4–C_9, and N_2O factor)								
kg CO_2-eq/kg FPCM	1.28	1.49	1.18	1.50	1.16	1.28	1.18	1.20

[a] Based on annual land use (Ha = hectare) and animal populations (AU = animal units).
[b] Enteric methane (CH_4) emissions based on four different equations, where CH_4–C6 is from (Moe and Tyrrell, 1979), CH_4–C7 is from (IPCC, 2006d), CH_4–C8 and CH_4–C9 are from (Nielsen et al., 2013). See Appendix C.

results by different methodological decisions show these choices remain an unresolved topic in LCA worthy of discussion.

CRediT authorship contribution statement

Horacio A. Aguirre-Villegas: Conceptualization, Methodology, Software, Formal analysis, Writing original draft. **Rebecca A. Larson:** Conceptualization, Writing – Reviewing and editing, Project administration, Supervision, Funding acquisition. **Nicole Rakobitsch:** Resources, Writing – review & editing, Funding acquisition. **Michel A. Wattiaux:** Conceptualization, Validation, Writing – review & editing. **Erin Silva:** Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Erin Silva reports financial support was provided by CROPP Cooperative - Organic Valley.

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Appendix A. Supplementary data

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