International Dairy Journal 31 (2013) S29–S40

Contents lists available at SciVerse ScienceDirect

International Dairy Journal

journal homepage: www.elsevier.com/locate/idairyj

Regional analysis of greenhouse gas emissions from USA dairy farms: A cradle to farm-gate assessment of the American dairy industry circa 2008

Greg Thoma[a,*], Jennie Popp[b], David Shonnard[d], Darin Nutter[c], Marty Matlock[e], Richard Ulrich[a], Wayne Kellogg[f], Dae Soo Kim[a], Zara Neiderman[e], Nathan Kemper[b], Felix Adom[d], Cashion East[a]

[a] Ralph E. Martin Department of Chemical Engineering, 1 University of Arkansas, Fayetteville, AR 72701, USA
[b] Department of Agricultural Economics and Agribusiness, 1 University of Arkansas, Fayetteville, AR 72701, USA
[c] Department of Mechanical Engineering, 1 University of Arkansas, Fayetteville, AR 72701, USA
[d] Department of Chemical Engineering and Sustainable Futures Institute, Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931, USA
[e] Department of Biological and Agricultural Engineering, 1 University of Arkansas, Fayetteville, AR 72701, USA
[f] Department of Animal Sciences, 1 University of Arkansas, Fayetteville, AR 72701, USA

ARTICLE INFO

Article history:
Received 10 November 2011
Received in revised form
5 May 2012
Accepted 18 September 2012

ABSTRACT

Greenhouse gas (GHG) emissions were evaluated from crop production through the on-farm portion of the milk supply chain for five production regions in the USA derived from publicly available data and from 536 surveys of farm operations collected from dairy operations nationwide. The production weighted national average footprint at the farm gate was 1.23 kg carbon dioxide equivalent (CO_2e) per kg of fat and protein corrected milk (fat, 4%; protein 3.3%). Regional differences in GHG emissions per kg milk produced can be primarily traced to differences in production and management practices. Feed-to-milk conversion efficiency is shown to be the single most important explanatory variable, followed by choice of manure management technology. While there is no one-size-fits-all solution, GHG emissions reduction opportunities exist across the spectrum of dairy management options. However, as with all decisions, it is important to weigh potential trade-offs with other environmental and economic impacts.

1. Introduction

In June 2008, American dairy leaders and experts met in Rogers, Arkansas for the inaugural Sustainability Summit: Creating Value through Dairy Innovation. The Summit was an unprecedented gathering of 250 leaders representing producers, processors, non-governmental organizations, university researchers and government agencies. Together, these stakeholders made an industry wide commitment to reduce fluid milk's carbon footprint while increasing business value and developed a roadmap with action steps that impact every step of the value chain, from farm to consumer. As part of its commitment to sustainability and environmental leadership, the Innovation Center commissioned a life cycle assessment (LCA) of the greenhouse gas (GHG) emissions from the fluid milk supply chain. This study is one of the largest of its kind ever conducted; collecting data from 536 farms covering a wide range of management practices, which contrasts with many published studies that frequently are case studies with limited breadth of management practices covered. The results serve as the foundation for the creation of best practices and decision-support tools for producers, processors and others throughout the dairy supply chain, and will be used to foster the long-term viability of the industry.

This LCA was performed in compliance with International Organization for Standardization (ISO) 14040:2006 and 14044:2006 standards for life cycle assessment, with the exception that a single impact assessment method, global warming potential, was adopted while ISO standards call for the application of a wider range of impact assessment categories. Retail businesses are beginning to engage their supply chains in an effort to encourage adoption of best practices and development of innovative solutions to reduce environmental impacts while maintaining value. Approximately 72–75% of the entire fluid milk supply chain GHG emissions occur before the dairy farm gate, thus a thorough understanding of the factors influencing these emissions is an important first step in the

* Corresponding author. Tel.: +1 479 575 4951.
E-mail address: gthoma@uark.edu (G. Thoma).

0958-6946/$ – see front matter
http://dx.doi.org/10.1016/j.idairyj.2012.09.010

identification of the most effective reduction opportunities (Thoma et al., 2012b). Post-farm GHG emissions associated with milk transportation (Ulrich, Thoma, Nutter, & Wilson, 2012), processing, packaging, distribution (Nutter, Ulrich, Kim, & Thoma, 2012), retail, consumption, and disposal (Thoma et al., 2012b) are discussed in other papers in this special issue.

The goal of this work was to determine GHG emissions for the functional unit of 1 kg of fat and protein corrected milk (FPCM; 4% fat, 3.3% protein) by USA dairy farmers and identify regional or farm size effects. The scope was cradle to farm gate, specifically including pre-combustion burdens for primary fuels production and other inputs required for milk production. Thus GHG emissions associated with production and use of fertilizer for crops and other off-farm emissions were included.

The dairy sector has been the subject of many LCA studies (e.g., Basset-Mens, Ledgard, & Boyes, 2009; Capper, Cady, & Bauman, 2009; Cederberg & Flysjö, 2004; Cederberg & Mattsson, 2000; Cederberg, Sonnesson, Henriksson, Sund, & Davis, 2009; de Boer, 2003; Gerber et al., 2010; Thomassen, Dolman, van Calker, & de Boer, 2009). Each of these research teams has made slightly different methodological choices: there are some differences in system boundaries and they typically use a different procedure to allocate impacts to milk and beef. Nevertheless, the majority of the studies report similar GHG emissions at the farm gate, ranging from approximately 0.75–1.5 kg CO_2e kg^{-1} milk and 85–90% allocation of burdens to milk compared with the beef co-product. The Food and Agriculture Organization of the United Nations (FAO) reports the USA average farm-gate GHG emission as 1 kg CO_2e kg^{-1} FPCM (Gerber et al., 2010). Each of the studies identifies enteric fermentation and manure management as major sources of GHG emissions. A number of these studies have been summarized by Thoma et al. (2012b); Guinard, Verones, Loerincik, and Jolliet (2009) present a comprehensive review of dairy related LCA studies.

2. Materials and methods

2.1. Functional unit

The functional unit of this study is one kg of FPCM, or energy corrected milk (ECM) milk at the farm gate. Because much of the energy in dairy feed is converted to milk solids (fat, protein, etc.), and not all farms produce milk with standard fat and protein composition, we have normalized on-farm production to a standard milk (4% fat, 3.3% protein) using the National Research Council (NRC, 2001) approach for fat–protein corrected milk; the calculation is based on the ratio of the energy content, as determined by fat and protein concentrations, of produced milk to standard milk. The following relationship was used to convert farm production to a fat and protein corrected basis:

$$\mathrm{FPCM} = \frac{\mathrm{MP}(0.0929\mathrm{F} + 0.05882\mathrm{P} + 0.192)}{0.0929 \times (4\%) + 0.05882 \times (3.3\%) + 0.192} = \frac{\mathrm{MP}(0.092\mathrm{F} + 0.05882\mathrm{P} + 0.19)}{0} \qquad (1)$$

where FPCM is the fat and protein corrected milk production (kg y^{-1}); MP is the reported milk production (kg y^{-1}); F is the percentage milk fat (as %) in the produced milk and P is the percentage true protein (as %) in the produced milk.

2.2. Data sources

Data were collected from numerous sources including the US Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) and Economic Research Service (ERS), peer reviewed literature related to LCA of milk, other technical literature, consultation with experts in different fields, and an extensive survey of 2008 dairy farm operations by region. A detailed discussion of survey development and distribution is presented by Popp et al. (2012). The survey, designed to assess whether the carbon footprint of dairy farms changes with region or farm/herd size, was distributed to over 5000 producers, of which 536 voluntarily responded. The national demographics of dairy producers from NASS and demographics of the survey responses are shown in Figs. 1 and 2. In general the survey sample had lower representation from smaller operations than the actual population of dairy farms; however, the cumulative milk production curves are similarly shaped suggesting that the results from the survey are an acceptable representation of national farm demographics.

SimaPro 7.1 was used as the primary modeling software; the ecoinvent database version 2.2 was used to model the ‘upstream’ unit processes associated with materials like primary fuels, fertilizer production and refrigerants (Frischknecht & Rebitzer, 2005). Technosphere flows used in the LCA model were characterized with a combination of the inherent variability found during the statistical data aggregation and the pedigree matrix of data quality used by the ecoinvent database (Weidema, 1998). MatLab was used for data reduction to create regional and national averages. Data from the surveys and other USA-specific information was incorporated into the model to the extent that it was available. We have used the Intergovernmental Panel on Climate Change carbon dioxide equivalency factors: 25 for methane and 298 for nitrous oxide (IPCC, 2006).

2.2.1. Dairy rations

In the assessment of GHG emissions associated with production of the principal grains used in animal rations (Adom et al., 2012), two main sources of agricultural data were used: crop production data in terms of annual yield of crop/acre, and agricultural chemical use statistics including annual fertilizer and pesticide totals, both reported at the state level from USDA NASS (2007, 2008). State level data were then organized into the dairy production regions as explained in Popp et al. (2012).

Few data have been collected at aggregate levels for cattle forage. GHG emissions from cattle forage production were estimated through an analysis of crop production budgets which provided estimates for the inputs needed to produce alfalfa and grass hay, silage, and pasture. We extracted average consumption of fuel and electricity, fertilizers and soil amendments (nitrogen,

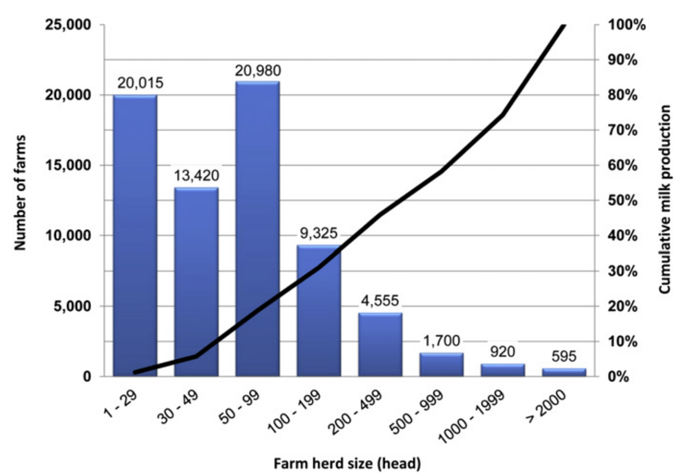

Fig. 1. National Agricultural Statistics Service (NASS) dairy herd demographics in 2007; histogram bars give the number of farms, the black line the cumulative milk production.

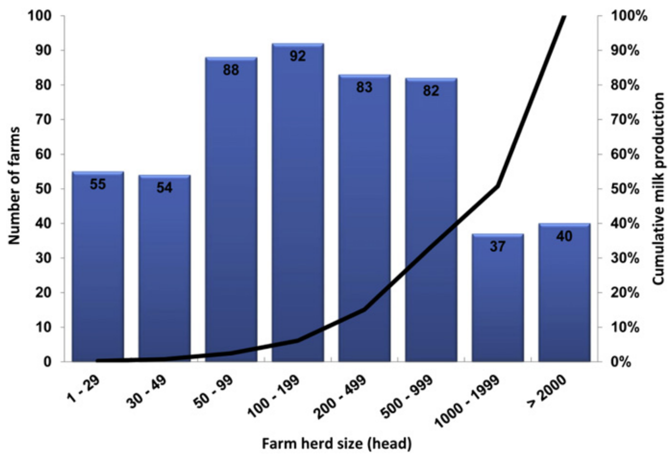

Fig. 2. Producer survey response demographics; histogram bars give the number of farms, the black line the cumulative milk production.

phosphorous, potassium, sulfur, boron and lime), and crop protection chemicals. MacDonald, Ribaudo, Livingston, Beckman, and Huang (2009) reported that 6.9% of hay and pasture land receive manure as fertilizer; we thus estimated the national average manure application rate to hay and pasture to be 6.9% of recommended nitrogen requirements (from production budgets). They reported that 87.5% of dairy cattle manure is spread on corn, and approximately 5% on soybeans (MacDonald et al., 2009).

We aggregated the available budgets by un-weighted averages within a region to estimate a regional average. After compiling inputs for specific crop production, these were entered as inputs to a new unit process, and GHG emissions were estimated using SimaPro 7.1 with the IPCC global warming potential (GWP) 100 year impact assessment methodology (IPCC, 2007).

Somewhat surprisingly, grass has a higher GWP than other forage crops and nearly as high as corn grain. Grass typically requires less maintenance and inputs, but produces lower yields than many other crops. In addition, there is much higher variability and uncertainty in actual yield than for commodity row crops. Region 2, which has the highest GHG emissions for grass and hay production, also has higher fuel, lime, and nitrogen use, based upon the available budget information. For all crops accounted in this study, we followed the IPCC (2006) guidelines for emissions associated with crop residue.

2.2.2. *Enteric fermentation*

Enteric fermentation is known to be dependent on the animal's diet, and a large body of research focuses on the effect of diet on methanogenesis in ruminants. For instance, methane release can vary as much as 50% between low-quality diets, high quality, and concentrate-rich diets (Johnson & Ward, 1996). Diets ranging from silages of maize and grasses, hays, and cereal grain, each have different carbohydrate concentrations, dry/wet matter weight ratios, lipid content, and various other dietary factors which all influence methane production.

Much effort has been expended to model and predict enteric methane emissions from cows fed specific diets, with moderate success (Blaxter & Clapperton, 1965; Ellis et al., 2007; Hindrichsen, Wettstein, Machmüller, Jörg, & Kreuzer, 2005; Mills et al., 2003; Moe & Tyrrell, 1979). It is clear that on-farm methane measurements are not feasible as a general method for estimation of enteric methane production. Thus, we were faced with the task of choosing among published models. We compared the aforementioned published models by evaluating the enteric methane prediction from the model against experimental observations where the diet consumed and enteric methane emissions were both quantified as summarized in Table 1. (Belyea, Marin, & Sedgwick, 1985; Boadi & Wittenberg, 2002; Johnson, Franzluebbers, Weyers, & Reicosky, 2007; Kinsman, Sauer, Jackson, & Wolynetz, 1995; Westberg, Lamb, Johnson, & Huyler, 2001). The characteristics of the experimental rations necessary for each model were used as the model input, and the model prediction of enteric methane emissions were compared with the experimentally reported values. The model proposed by Ellis et al. (2007) had the lowest average root-mean-square-error (0.12) and was used for prediction of enteric methane emissions in this study (Fig. 3).

2.2.3. *GHG emissions from manure management*

The American Society of Agricultural Engineers manual (ASAE, 2005) on manure characteristics was used to predict the quantity of manure generated; this approach was adopted for all farms in the survey. An algorithm to apportion manure into the reported manure management systems (MMS) was developed. In the farm survey, each respondent indicated what fraction of time each animal class spent on pasture; this information was used to determine the fraction of manure that was actively managed in the manure management system compared with that passively managed by direct deposition to the pasture. When available, the reported manure quantities were used as estimators for the relative frequency of use of an MMS to distribute manure to semi-solid or liquid MMS. When this information was not provided, the produced manure was distributed equally between liquid/slurry and semi-solid MMS. Manure was distributed according to the reported fractions for each MMS being used at the facility. Temperature is an important parameter in the estimation of methane release associated with each of the manure management techniques. We extracted monthly average temperature data from the National Climatic Data Center US global summary of day dataset for 2008 (NOAA, 2008). A MatLab program was written to find all the weather stations within an approximately 100 mile radius from each USA county's centroid; temperatures recorded at each of these stations were averaged to determine the monthly average temperature for the county. After determining the local average temperature and the quantity of volatile solids handled by each MMS, IPCC (2006) emission factors for methane were applied to calculate the total manure management methane emissions for each farm in the survey.

Table 1
Rations used for evaluation of enteric methane models.

Diet	Reference	Diet	Reference
Control ration	Johnson et al. (2007)	Chopped alfalfa (ad libitum)	Belyea et al. (1985)
Medium fat ration	Johnson et al. (2007)	Long alfalfa (ad libitum)	Belyea et al. (1985)
High fat ration	Johnson et al. (2007)	High quality legume/grass (ad libitum)	Boadi and Wittenberg (2002)
Total mixed ration	Kinsman et al. (1995)	High quality legume/grass (restricted)	Boadi and Wittenberg (2002)
Alfalfa silage-based	Westberg et al. (2001)	Medium quality grass (ad libitum)	Boadi and Wittenberg (2002)
Corn silage-based	Westberg et al. (2001)	Medium quality grass (restricted)	Boadi and Wittenberg (2002)
Chopped alfalfa	Belyea et al. (1985)	Low-quality grass (ad libitum)	Boadi and Wittenberg (2002)
Long alfalfa (maintenance level)	Belyea et al. (1985)	Low-quality grass (restricted)	Boadi and Wittenberg (2002)

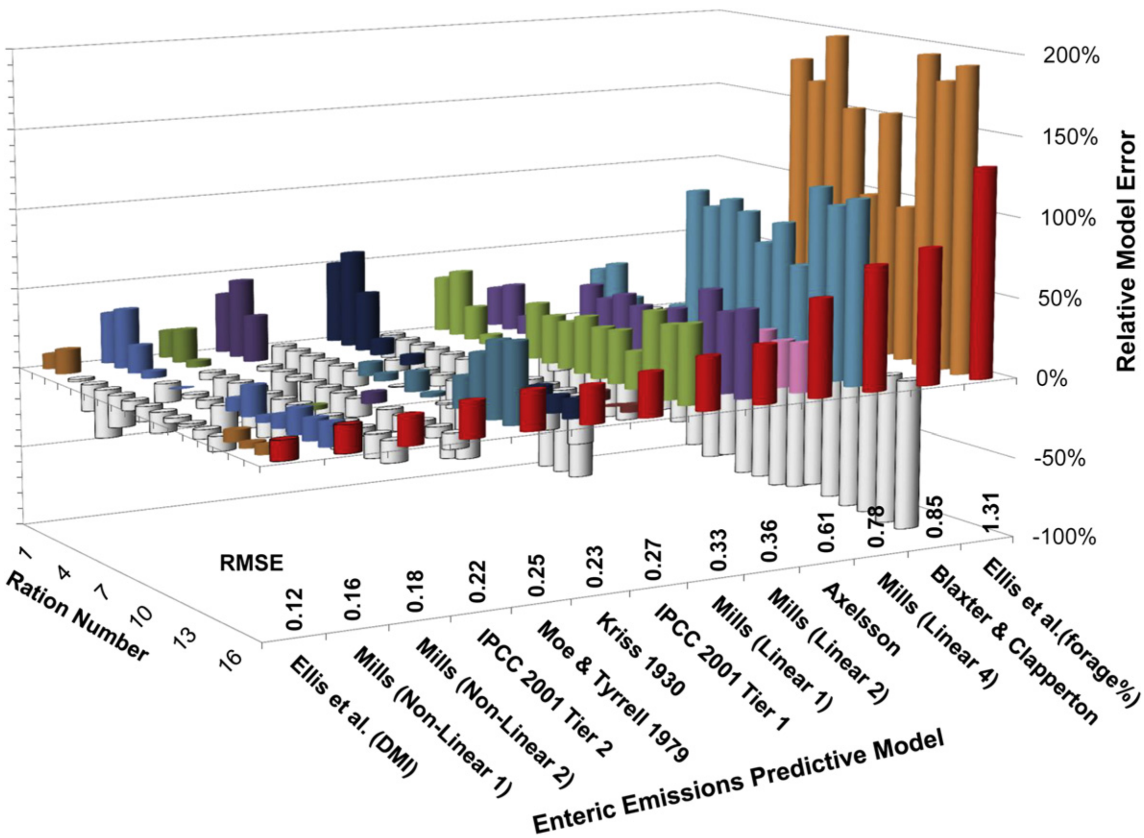

Fig. 3. Root-mean-square-error (RMSE) for different enteric methane model predictions for 16 different diets. The red column is the RMSE for the model, and the data label is the RMSE value.

Nitrogen excreted in manure and urine can be converted through nitrification–denitrification to N_2O. Manure characteristics from the different dairy animal types has been extensively studied and modeled by the American Society of Agriculture Engineers (ASAE, 2005). The predicted nitrogen excretion rates (N_E) per animal types were used along with the herd demographics to estimate the total N produced per farm per year. Using the individual farm ration information coupled with the data provided in the NRC handbook (NRC, 2001), an estimate of the actual crude protein consumption by each animal class on each farm was made. Supplementary material is available with average animal rations for each of the five production regions. This farm specific value for crude protein was used in the following calculations to estimate a farm specific nitrogen balance. The following are Eqs. (5.14), (5.17) and (5.19) (ASAE, 2005):

$$N_{E_{Lac}} = 2.303 \cdot MP + 0.159 \cdot DIM + 70.138 \cdot DMI \cdot C_{CP} + 0.193 \cdot BW - 56.632 \quad (2)$$

$$N_{E_{Dry}} = 12.747 \cdot DMI + 1606.29 \cdot C_{CP} - 117.5 \quad (3)$$

$$N_{E_{Heifer}} = 78.390 \cdot DMI \cdot C_{CP} + 51.35 \quad (4)$$

where N_E is the nitrogen excretion, g animal^{-1} day^{-1}; MP is the milk production, kg animal^{-1} day^{-1}; DIM is the number of days in milk (days since calving); estimated as: (average calving interval − 60)/2; DMI is the dry matter intake for an animal class, kg day^{-1}; BW is live body weight, kg; C_{CP} is concentration of crude protein in the ration, g protein g^{-1} DMI.

Based on the reported rations, the daily nitrogen excretion calculated ranged from approximately 0.2 kg day^{-1} for open heifers up to 0.43 kg day^{-1} for multiparous lactating cows. These estimates were combined with Tier 2 emission factors as a function of manure management practice (IPCC, 2006), accounting for direct deposition on pasture, to estimate the on-farm N_2O emissions associated with manure management. These emissions included direct nitrous oxide emissions as well as indirect emissions resulting from both ammonia volatilization and nitrate leaching followed by transformation to nitrous oxide. An interesting system boundary issue for the LCA arises in manure handling: if manure fertilizer is included in the crop growth life cycle stage (as done here), then the system boundary for the dairy farm, in terms of N cycling, should NOT include land application of manure and associated emissions from the land application (Nemecek, Kägi, & Blaser, 2007). If these emissions are counted, then there will be a de facto double counting of nitrous oxide emissions from land applied manure. In this study, we chose to assign the manure N related emissions to the crop as an input to the farm.

2.2.4. Biogenic carbon and sequestration

For the purpose of this study, we have assumed most crop land under cultivation in support of the dairy industry has seen stable production practices in recent history, thus there is relatively little change in soil carbon content, and therefore sequestration of carbon dioxide by growing plants has not been counted. This simplifies the modeling of the system because it is not necessary to account for respiration or other delayed emissions. It is well documented that when tillage practices change from conventional to conservation or to no till then there can be measurable increases in the carbon content of the soil (Christopher & Lal, 2007; Johnson et al., 2007; West & Marland, 2002; West & Six, 2007). Thus, for site-specific conditions where tillage practices have changed, it would be appropriate to include sequestration of below ground biomass to the extent that it can be documented; however, at the scale of this analysis, inclusion of site-specific tillage practice was not feasible. Because of the difference in global warming potential of methane and carbon dioxide it is clear that the methane cannot be treated as a carbon-neutral emission; therefore biogenic methane is counted, both as enteric methane and methane released during manure management. Methane eventually degrades to CO_2 in the atmosphere; the radiative forcing of this CO_2 is not counted in the GWP of methane emissions, and therefore for biogenic methane balances the carbon removed from the atmosphere during plant growth.

2.2.5. Co-product allocation

Where multiple products, in this case milk and beef, are produced in combination from a single operation, LCA requires that the environmental burdens from the overall operation be allocated between the multiple products. Briefly, the approach represents an effort to follow the ISO hierarchy for allocation decisions in which a biophysical basis is preferred over mass or economic based allocation. For this study, the algorithm used has been recommended by the International Dairy Federation (IDF, 2010) and is conceptually similar to the biological allocation presented in Cederberg and Stadig (2003) where an estimate of the feed energy deposited in the beef and milk products is made, and the ratio of those input feed energies is used to allocate the unattributed environmental burdens. Thoma, Jolliet, and Wang (2012a) describe the basis for this allocation procedure which has been adopted as a practical method by the IDF (2010). In brief, the dairy ration is the single largest input to the production of milk, and the conversion efficiency to milk and meat is not the same. Sufficient nutritional information exists to link milk and meat production to the necessary ration for this production. It is then the ratio of feed consumed for milk versus that consumed for meat which is used to define the allocation of whole farm GHG emissions between the milk and meat produced.

2.2.6. Statistical averaging of inventory data

Given that the survey represents a population sample, it is important to determine the most appropriate statistical analysis for determining the representative average values for the whole population of dairies in each region and nationally. It is clear that production weighted statistics are appropriate. For this study, calculation of the regional and national average inputs of electricity, feed, etc. for production of fat and protein corrected milk was performed assuming a delta-log normal distribution for the input data. In situations where data are expected to be log-normally distributed, which is often the case when negative values are not allowed, but where zero consumption is possible, the delta-log normal distribution is appropriate (Zou, Taleban, & Huo, 2009). In this case, the non-zero data are treated as a log normal distribution, and the mean is corrected by multiplying by the probability that a value is non-zero.

$$\bar{x} = \Pr(x > 0)\exp\left(\mu + \sigma^2\right) \quad (5)$$

Where $\bar{x}$is the mean value of the back-transformed, original data; μ is the FPCM production-weighted mean of the log-transformed data Eq. (6); σ^2 is the variance of the log-transformed data Eq. (7).

The mean and variance of the transformed data is calculated as an FPCM production weighted mean.

$$\mu = \sum_{i=1}^{N} \ln(x_i) w_i \quad (6)$$

$$\sigma^2 = \left(\frac{1}{N}\right)\sum_{i=1}^{N}(x_i - \mu)^2 \quad (7)$$

Where w_i is the weighting factor for farm i defined as the fraction of all milk production reported by survey respondents that was produced on that farm, and x_i is the parameter under statistical analysis.

The mean value of the parameter, calculated in this manner, is not artificially biased to larger values than are representative of the population, and provides statistical moments that can be used for confidence band estimation, which is not possible if a simple arithmetic weighted average, or normal statistics are employed. We adopted the approach of Fletcher (2008) for calculation of the confidence bands for the mean based on the delta-log normal distribution.

3. Results and discussion

3.1. Weighted-mean and median GHG emissions

In this study, the production-weighted national average GHG emission per kg FPCM at the farm gate was 1.23 kg CO_2e. Figs. 4–8 present box-whisker plots showing the range of carbon footprint observed in each region; on the right hand axis, information from the survey on the feed conversion efficiency and milk allocation are presented. Feed conversion efficiency is defined, for purpose of this study, as the ratio of the dry matter intake (kg day^{-1}) with the daily production of FPCM (kg day^{-1}), and thus smaller values indicate more efficient conversion of the feed-to-milk. The milk allocation ratio, calculated according to the IDF (2010), is the fraction of the whole farm emissions that are attributed to milk production; the national average is approximately 87% of the cradle to farm gate GHG emissions are assigned to the milk. The box bounds the 25th and 75th percentiles of the calculated carbon footprint. The median or 50th percentile is marked by the black horizontal line. The narrow gray boxes show the 10th and 90th percentiles, and individual markers are given for the outliers. The red line is plotted at the calculated weighted mean value of the population following the method described above. The box plots do not differentiate among farms regardless of herd size or annual milk production. The position of the production weighted means (red line) on the box plot provides insight into the effect of larger farms, because the production weighted mean value is necessarily shifted in the direction of greater annual production – generally larger milking herds. In cases where the weighted mean is above (sometimes well above) the mean value, as for manure in all Regions, it indicates that the farms with more production tend to use manure management systems that emit larger quantities of GHG. Similarly, the plots for feed conversion efficiency show that the larger farms generally perform better (lower quantity of feed needed per kg of milk produced) than the median farm. This suggests an opportunity for technology transfer across scales. There is relatively low variation in the fraction of whole farm GHG emissions allocated to milk, with the exception of a few outliers, which were correlated to higher cull rates.

The influence of farm size, across regions, was examined. In Regions 4 and 5, larger farms tended to have both higher manure emissions and higher GHG emissions than the median emissions in the same region. However in Regions 1, 2, and 3, while larger farms had greater manure emissions than other farms they generally had slightly smaller than median GHG emissions. However, the significant variability in manure GHG emissions indicates that an opportunity exists to reduce emissions through changes in management; similarly the wide variability in feed conversion points to opportunities for reduced GHG emissions through feed

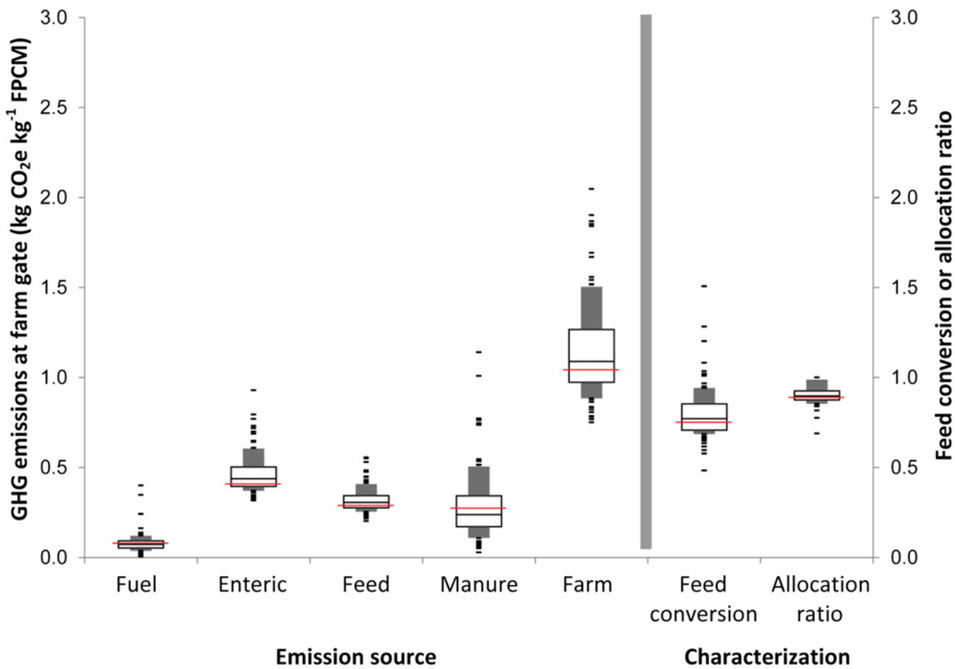

Fig. 4. Contributions to the farm-gate greenhouse gas (GHG) emissions in Region 1.

management, which could include both breed and genetics changes to take advantage of specific animal physiologies. As shown in Fig. 6, the conversion efficiency of larger farms in Region 3 translates into a production weighted enteric methane emission that is near the 25th percentile.

Considering the data presented for Region 4 in Fig. 7, it is clear that larger farms perform near the 25th percentile for fuel, enteric and feed GHG emissions as well as the 25th percentile in feed conversion efficiency. The shift of the weighted mean for manure management in this region seems to correlate with the reported higher frequency of adoption for anaerobic lagoons compared to other regions. One result is that larger farms have higher than median GHG emissions in this region; a similar observation can be made for Region 5 (Fig. 8). Manure management in this region, on a production weighted basis, contributes more GHG emissions than feed or enteric fermentation. Enteric fermentation is the largest single contributor in all the other regions. This strongly suggests that implementation of methane capture technologies should be considered as a priority in this region. In general, variability in a system is a strong indication that there exist opportunities for

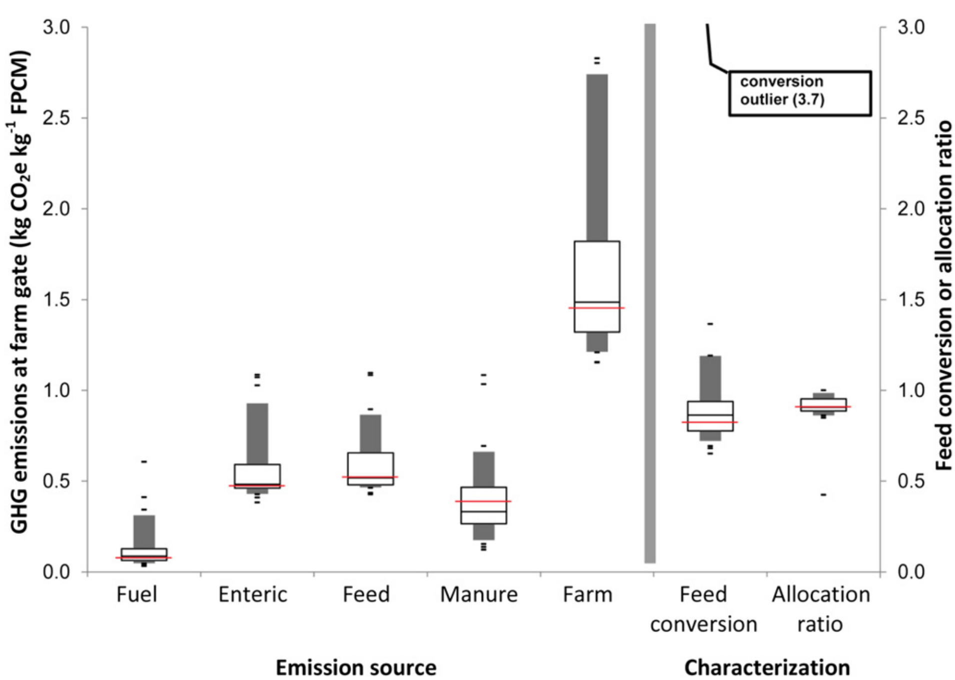

Fig. 5. Contributions to the farm-gate greenhouse gas (GHG) emissions in Region 2. While relatively few responses were received from Region 2, there is still significant variability in GHG emissions.

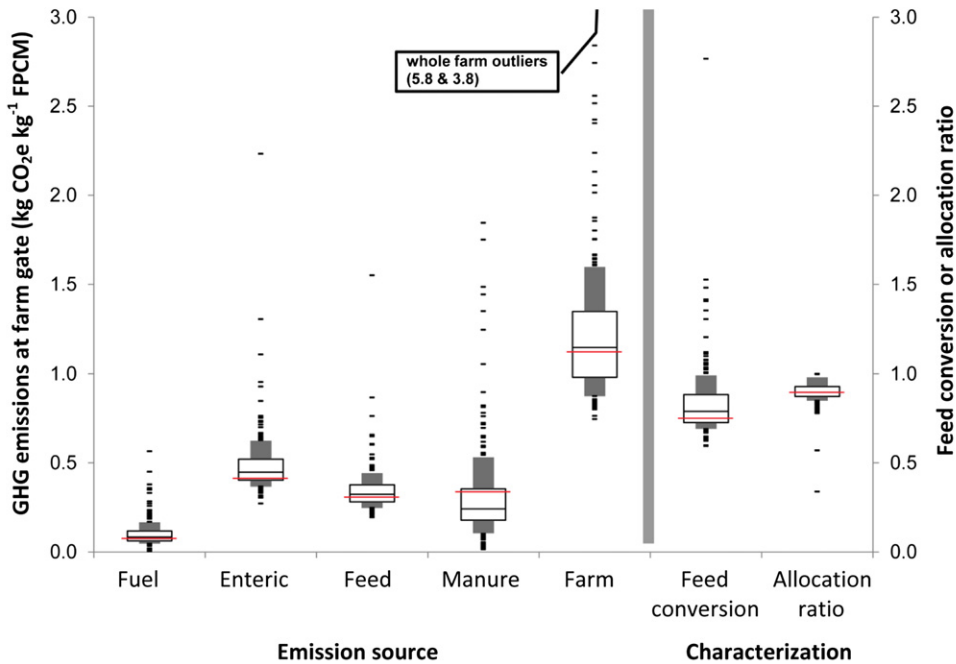

Fig. 6. Contributions to the farm-gate greenhouse gas (GHG) emissions in Region 3.

industry scale GHG emissions reductions through identification of practices at the more efficient operations that can then be adapted for export to other operations.

With the exception of manure management, the weighted mean GHG emission value is closely approximated by the median; for manure management the mean value is closer to the 75th percentile. The reason for this is that the statistics used to create the mean value are weighted by each farm's milk production, and larger farms tended to have manure management practices which emit more methane than practices more common on smaller farms. It is not clear that this currently represents an opportunity for reduction, because the economics of manure management may dictate the practice as a function of size; as digesters become more cost effective, there will be significant opportunity for GHG reduction on these farms. Other comparisons of the weighted mean with the median farm for other categories from the box plots, the feed conversion data suggest that larger farms have approximately 14% better feed conversion efficiency (0.77 versus 0.88 kg feed kg^{-1} FPCM) and somewhat lower enteric methane emissions per kg milk produced (also the result of better feed conversion efficiency).

Fig. 9 presents an alternate view of the farm survey respondent results. The respondents were grouped by the fraction of lactating

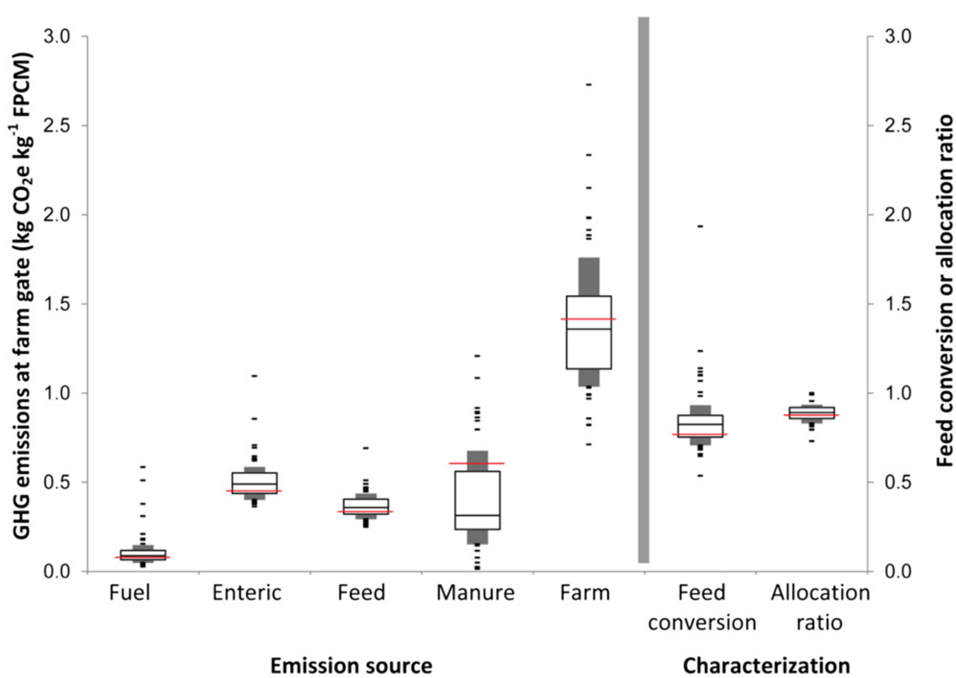

Fig. 7. Contributions to the farm-gate greenhouse gas (GHG) emissions in Region 4.

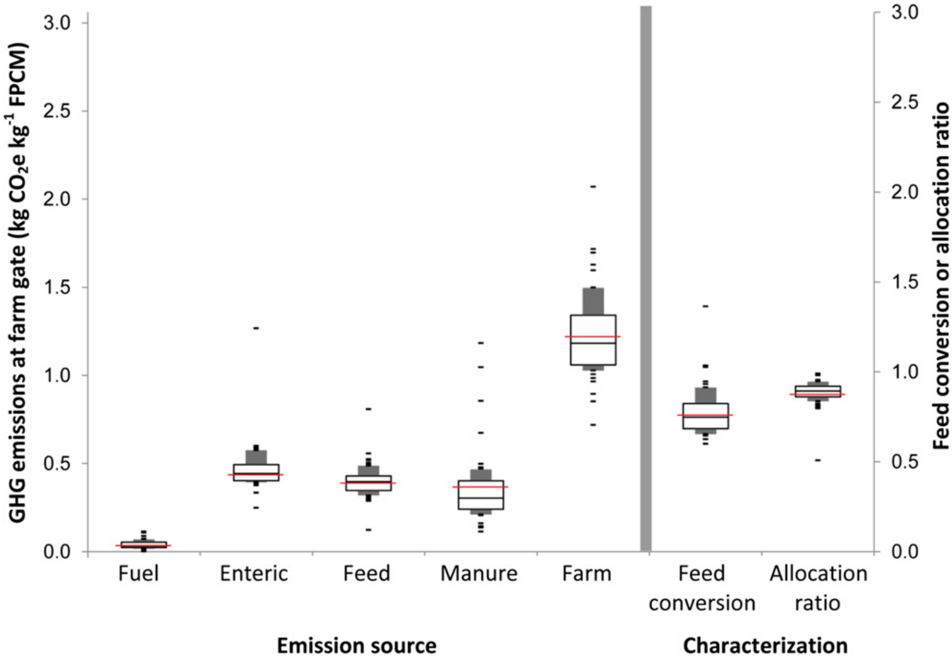

Fig. 8. Contributions to the farm-gate greenhouse gas (GHG) emissions in Region 5.

animal diet reported to come from grazing, and rank-ordered within the group. Two interesting results are apparent from this presentation of the data. First, the GHG emissions from farms with significant grazing are not a strong function of the fraction of forage obtained through grazing. Second, the range in overall farm GHG emissions for grazing systems significantly overlaps the range for confined animal feeding operations (CAFO). This observation suggests that there are other management decisions that are more significant drivers for GHG emissions than pasture versus CAFO. Finally, the most apparent driver for CAFO GHG emissions appears to be manure management as the manure emissions contribution increases steadily with the overall GHG emissions across the CAFO.

3.1.1. *On-farm fuel consumption*

Fig. 10 presents the information collected from the farm survey regarding on-farm energy consumption. The technosphere flows for fuel reported here do not include fuel consumed for crop production, as this was separately accounted in crop production. Large variation in energy efficiency (per kg FPCM at the farm gate) among the regions is apparent. The origin of these differences is not clear from the survey data; however, the existence of large variation in efficiency suggests that further investigation may yield opportunities for transfer of farm practices from farms with higher efficiency to other farms.

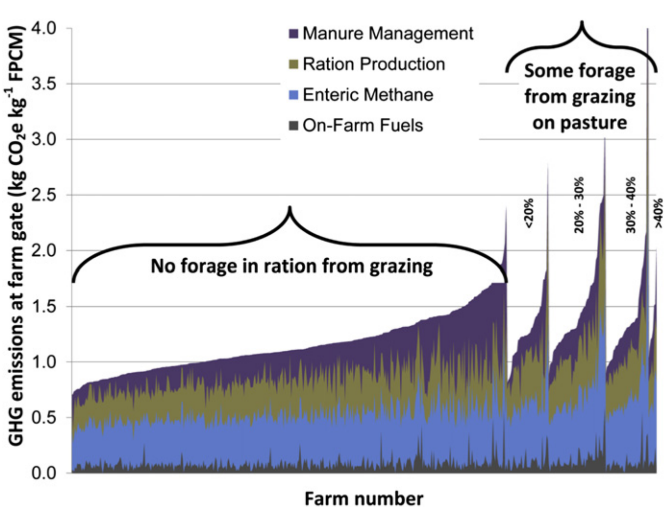

Fig. 9. Ranked farm-gate GHG emissions as a function of the fraction of annual dry matter intake from pasture grazing.

3.1.2. *Enteric and manure management greenhouse gas emissions*

Fig. 11 presents the regional production-weighted elementary flow emissions of methane and nitrous oxide from enteric fermentation and manure management. The information is presented in terms of kg of GHG emitted per kg of FPCM at the farm gate; the average enteric methane emissions for the dairy herd, including replacements, was 95 kg CH_4 head^{-1} y^{-1}, with a standard deviation of 9.5 kg CH_4 head^{-1} y^{-1}. This does not include manure deposited on pasture, which, because the quantities were small, was aggregated into CO_2e. Note that the pasture emissions do not include daily spread of manure as a management system, but only manure deposited directly during the time animals are on pasture. Survey responses distinguished between grazing time and time on pasture – thus manure deposited on the field in winter months when the animals were not grazing is accounted for in the pasture emissions. The major points of interest from these data are methane emission from manure management in Region 4, and pasture emissions from Region 2. The first is a consequence of the relatively large fraction of reporting farms which used anaerobic lagoons for manure management – this technology is one of the highest producers of methane, and suggests opportunities for reduction of emissions through installation of methane capture technology. The higher pasture emissions from Region 2 are due to a somewhat higher proportion of time on pasture; likely related to a combination of climate and farm size. Another factor that influences the pasture emissions estimate is the IPCC emissions factor of 2% of deposited N is released as nitrous oxide; some work in New Zeeland suggests that the emission factor may be lower, and on the order of 1%

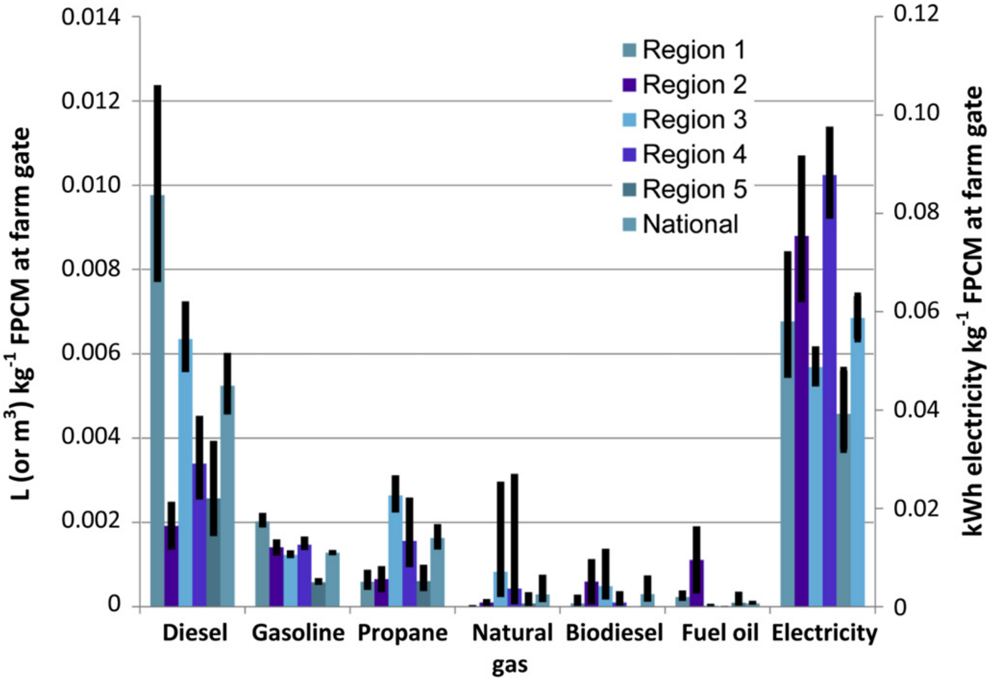

Fig. 10. Components of the farm footprint associated with on farm fuel consumption. 95% confidence intervals are shown with the error bars. Electricity consumption should be read from the right hand axis.

(de Klein, Sherlock, Cameron, & van der Weerden, 2001; Kelliher, de Klein, Li, & Sherlock, 2005).

A full statistical analysis of the farm survey responses is presented elsewhere (Asselin- Balençon et al., 2012). Feed conversion efficiency was shown to be the single most important explanatory factor for differences between farms. The importance of feed conversion is not a particularly surprising result: feed is a major farm input and, in combination with the specific animal genetics and physiology, directly affects both enteric emissions and the quantity and quality of manure excreted. The second most important factor differentiating farms is the choice of manure management technology; opportunities with some of the larger farms in Region 4, where anaerobic lagoons were a commonly reported management system, may be significant.

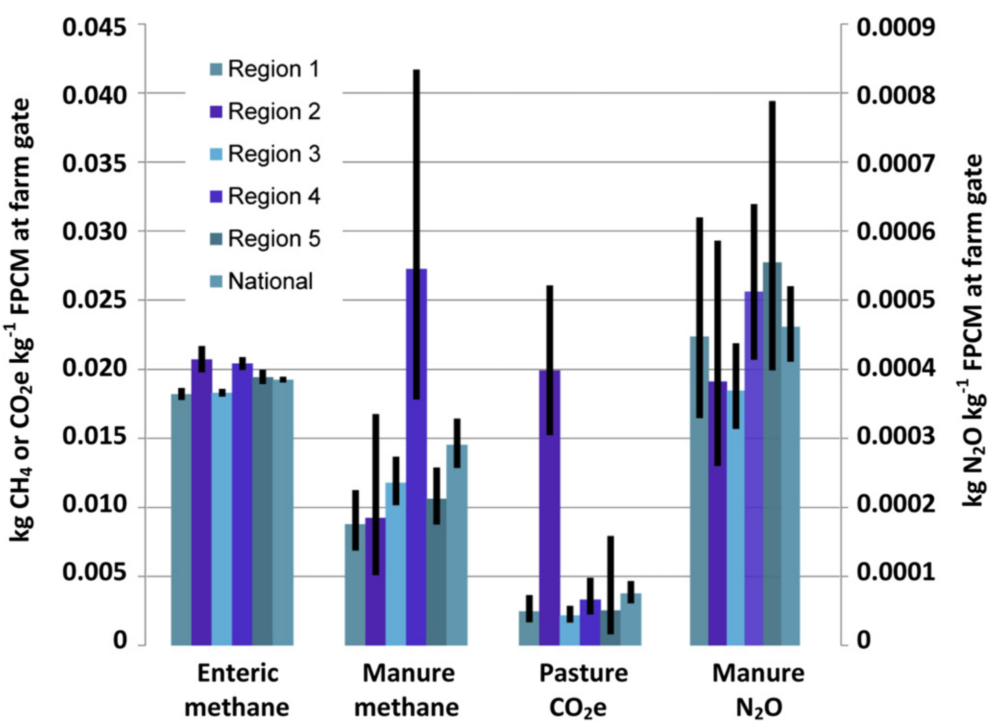

Fig. 11. Manure management greenhouse gas (GHG) emissions. Manure emissions from pasture are reported as CO_2e because the emissions of CH_4 and N_2O were too small to plot on the axes.

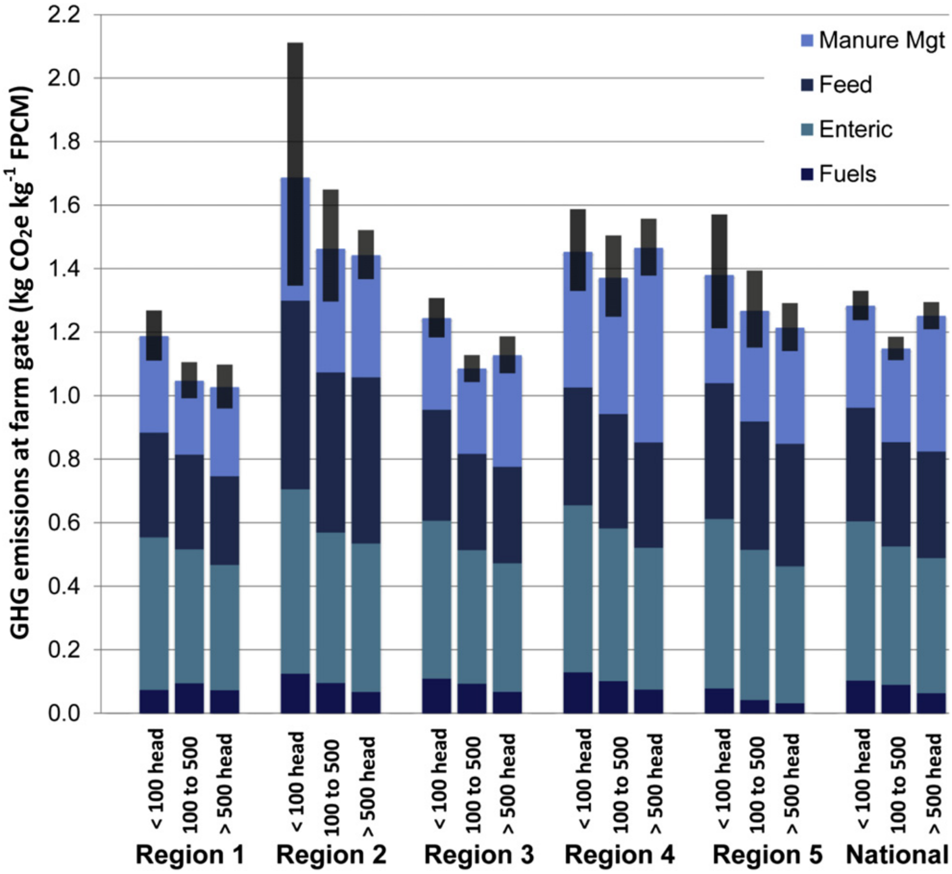

Fig. 12. Comparison of greenhouse gas (GHG) emissions with region and farm size.

3.2. Analysis of farm size and region

One of the original questions prompting this research project was whether there are differences in GHG emissions associated with either farm size or region. While the survey responses were not fully representative of the national farm or regional demographics, there were sufficient responses to evaluate potential differences. The selection of regions was, ultimately, a compromise between creating representative areas (of production practice, size, and climate), the number of responses needed for statistical purposes, and available manpower. The regions were agreed through a series of stakeholder engagements as described by Popp et al. (2012). Fig. 12 presents this comparison for the 5 production regions and 3 farm size classes. There is a general trend showing that smaller farms have slightly larger carbon footprint, which is correlated with slightly lower feed conversion efficiency. The error bars in this figure report only the variability from the survey data and do not include additional uncertainty arising from uncertain input parameters in the LCA model, and therefore, drawing strong conclusions from this data is not supported. Nevertheless, there are trends that support some analyses: there is a general trend of lower fossil fuel contribution associated with increasing farm size, which results from expected economies of scale. There is also an observable trend in reduced enteric methane and to a lesser extent the feed contribution. This trend is reflective of the observed increase in feed conversion efficiency with larger farms, which may correlate to a higher fraction of concentrate feeds in the ration. Finally, and most obvious for Region 4, is the increased contribution from manure management on the larger farms. This is associated with the more prevalent use of anaerobic lagoons previously discussed.

3.3. Variability and uncertainty

The confidence intervals presented in the figures in this paper represent the 90% confidence interval (CI) that the true mean of the variable falls in the range; for this study the mean GHG emissions at the farm gate were 1.23 kg CO_2e kg^{-1} FPCM with a 90% CI range from 1.2 to 1.25 kg CO_2e kg^{-1} FPCM. In the LCA context, this represents the inherent variability in the measurements and not the total uncertainty in the estimate that would include an additional assessment of data quality via an approach such as the pedigree matrix (Weidema, 1998). There is a tendency to over-value point estimators like mean or median. More appropriate interpretation of LCA estimates are as distributions about a mean, rather than discrete points supporting explicit comparisons of GHG sources. The degree of characteristic variability indicates opportunities for improved performance of the whole sector. For example, the wide range of manure GHG emissions in Region 4 (Fig. 7) suggests that the high emitters might be able to adopt practices employed by the low emitters, and thus reduce GHG emission across the industry. A Monte Carlo simulation for propagation of uncertain input information from the entire upstream supply chain to define the uncertainty range for the farm gate GHG emissions was conducted using SimaPro software (Pre Consultants, The Netherlands). The results of this analysis demonstrate additional uncertainty in the farm gate estimate: the 90% CI ranges from 1.1 to 1.5 kg CO_2e kg^{-1} FPCM.

4. Conclusions

This work is a cradle to farm gate agricultural life cycle assessment for USA dairy production, and establishes the current best estimate of baseline GHG emissions associated with production of fluid milk in the USA in 2007. Future progress by the industry can be assessed against this baseline level; of course, the same underlying methodology used in this study must be followed to enable comparison against the benchmark. The process has been open and transparent, and the work has been reviewed by an international panel. Unit process data will be submitted to databases that will allow public access to this information so that others can base LCA of products containing dairy products on the best available life cycle inventory data.

A number of studies for dairy production report similar GHG emissions at the farm gate (Bassett-Mens et al., 2009; Capper et al., 2009; Cederberg & Flysjö, 2004; Cederberg & Mattsson, 2000; Cederberg et al., 2009; Eide, 2002; Gerber et al., 2010; Guinard et al., 2009; Haas, Wetterich, & Köpke, 2001; Thomassen et al., 2009). The recent FAO report gives an average farm-gate GHG emission of 1.0 kg CO_2e kg^{-1} FPCM (Gerber et al., 2010), which is approximately 20% lower than that found in this study: 1.23 kg CO_2e kg^{-1} FPCM (90% CI: 1.1–1.5 kg CO_2e kg^{-1} FPCM). The study highlights manure management, feed production, and enteric methane as three areas for innovation research.

The LCA results give insight into the innovation opportunities for dairy production; however, these opportunities should be carefully evaluated to guard against burden shifting and economic considerations. The on-farm performance showed significant variability (Figs. 4–8); identification and recognition of this variability suggests that opportunities exist for improvement for the lower performers. It is not surprising that the three largest GHG contributors are feed, enteric methane, and manure management.

Nutrient management strategies on the dairy farm that link inorganic fertilizer use with application of manure for crop production should be integral to any GHG reduction approach. Approximately 450,000 tons of nitrogen from manure (all livestock sources, not only dairy) used as fertilizer is currently applied annually to corn; however there are some barriers to further utilization of manure as discussed by MacDonald et al. (2009)·

Feed represents a large part of the GHG footprint of dairy, and improving the conversion of feed into milk represents a significant opportunity for the reduction of CO_2e emissions. Economic considerations also support this conclusion, as methane produced from enteric fermentation is essentially loss of feed energy that could otherwise be converted to milk.

This study indicates that large dairy operations tend to have a lower footprint because of more efficient feed conversion; this study does not provide an explanation for the observed feed conversion difference. Further experimentation to continue increasing feed conversion efficiency is also important, as this variable alone explains over half of the observed variability in the feed and enteric methane contribution to the farm-gate footprint. Interestingly, grass production has a relatively high GHG footprint, due to the ratio of inputs to yield. This could be improved through the use of grass/legume (e.g., clover) mixes to reduce the need for inorganic fertilizers. Because this study only considers GHG emissions, there is need for further study in order to understand the full range of environmental impacts before making decisions.

Manure management practices are one area that did not reward the larger farms which tend to have slightly better feed conversion efficiency. Anaerobic lagoons on larger farms and deep bedding on smaller operations management systems are predominantly used by the larger farms possibly for economic reasons, and the methane emissions from these systems are significantly higher than other systems, such as dry lot and solid storage. On the surface, this seems to indicate that a shift in practices could result in emission reductions; however, both the economic and environmental cost of changing to a different system must be considered. Methane digesters have great potential as a way to capture and potentially utilize methane that is otherwise lost to the atmosphere, and should be considered a high priority for these larger systems.

Acknowledgments

This work was funded by the Innovation Center for US Dairy. The quality and thoroughness of the ISO review panel was invaluable to the project team. The review panel consisted of: Olivier Jolliet from the University of Michigan, Robert Anex from the University of Wisconsin, and Pascal Lesage from Interuniversity Research Center for the Life cycle of Products, Processes and Services (CIRAIG), École Polytechnique de Montréal. Quantis International provided valuable copyediting assistance in the preparation of the final manuscript.

The Innovation Center played an instrumental role in collection of the on-farm data, as well as the information gathered from the processing facilities and dairy cooperatives. Without the strong industry commitment to collect high quality data across the supply chain, this study would not have been possible. The Innovation Center also assisted with testing of the survey instrument for the on-farm data collection, to help provide wording to the questions enabling collection of relevant data. Finally, the Innovation Center has worked with the publisher in the establishment of this special issue.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.idairyj.2012.09.010.

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