A Case Study of Enteric Methane Emission and Nutritional Management of Intensive Dairy Production Systems of California and Wisconsin

Case Study Highlights

Methane (CH_4) emission from enteric fermentation of dairy cows contributes to climate change. Mitigation of enteric CH_4 emission through dietary strategies is an opportunity not only to reduce environmental concerns but also to improve feed efficiency by decreasing the loss of methane energy. In this case study the distinct feeding strategies of California and Wisconsin, the top two dairy state of the United States, were evaluated for their impact on enteric CH_4 emission and milk carbon footprint. Although California dairies rely more heavily on purchased feed (forages and byproduct feeds), Wisconsin dairies have a greater reliance on homegrown forage and in particular corn silage. Production performances of the lactating cows and enteric CH_4 emission did not differ substantially between the two systems despite the differences in dietary strategies. However, the emission associated with the production of the feed was 30% greater for California compared to Wisconsin. Overall, farm-gate carbon footprint of California milk was 9% greater than Wisconsin milk (1.22 vs. 1.12 kg of CO_2-eq/kg of FPCM). Current literature suggested that the potential to reduce enteric CH_4 emission through nutrition is relatively modest (2.5 to 15%). Genetic selection and appropriate herd management practices including, health, reproduction, and housing facility design that contribute to greater feed conversion efficiencies will contribute also to a sustained mitigation of milk carbon footprint. Although enteric CH_4 is the single largest component of the carbon footprint, the contribution of other sources of greenhouse gases should not be ignored. The case study highlighted the importance of feed efficiency as a tool to mitigate greenhouse gases emissions from intensive dairy systems. However future research will likely focus on whole-farm carbon balance because of the positive effects that the enhancement of carbon sequestration (soil organic matter) and carbon credit (bio-digestion) may have on milk carbon footprint.

Background. Gases that trap heat in the atmosphere are referred to as greenhouse gases (GHG). Human activities have contributed to substantial release of carbon dioxide (CO_2) in the atmosphere in particular since the industrial revolution and fossil fuel combustion. Agricultural practices have also contributed substantially to the release of methane (CH_4) and nitrous oxide (N_2O), which are the other two main heat-trapping gases resulting from human activities. The global warming potential of CO_2, CH_4 an N_2O is 1, 25 and 280. In other words, one gram of CH_4 and N_2O are 25 and 280 times more potent than CO_2 to trap heat in the atmosphere. Thus these factors are used to convert an amount of gas into CO_2-equivalent (CO_2-eq) in order to quantify their respective impact on climate change. Enteric fermentation, which is critical to the digestion strategy of ruminants is an important source of CH_4. In the United states, CH_4 emissions from enteric fermentation by dairy cows were 0.61% and 7.30% of national GHG inventory and total agricultural GHG inventory, respectively (EPA, 2016). In addition to climate change concerns, enteric CH_4 represents a significant loss of dietary energy, which is approximately 6% of gross energy intake in dairy cows (Johnson and Johnson, 1995).

Methane is a by-product of the anaerobic breakdown of carbohydrates by the rumen microorganisms and its production serves as the principal electron sink within the rumen (Beauchemin et al., 2008). Methane production depends on types and dietary proportions of different carbohydrates such as starch, cellulose, and sugars (Hindrichsen et al., 2005). Thus alteration of the amounts and the sources of dietary carbohydrates may have an impact on enteric CH_4 emission. Knapp et al. (2014) noted that nutritional strategies to mitigate enteric CH_4 are based on 3 basic approaches: 1) ingredient selection to alter volatile fatty acids production patterns to enhance the propionate:acetate ratio from fermentation; 2) increased rate of passage, which alters microbial populations and volatile fatty acid production pattern, and shift some digestion to the intestines; and 3) feeding better-quality diets to increase milk production per cow, which will “dilute” the CH_4 associated with maintenance energy requirements. Feeding strategies such as feeding lipids and high-starch diets, replacing roughages with concentrate, feeding corn and cereal silages, inclusion of legumes, grain processing, increased dry matter intake (DMI), use of ionophore, exogenous enzymes, and direct fed microbials impact enteric CH_4 emission with variable effectiveness (Beauchemin et al., 2008; Grainger and Beauchemin, 2011; Knapp et al., 2014).

California and Wisconsin are the top two leading milk-producing states in the United States of America. In 2015, California produced 18.6 billion kg of milk that amounted to 19.6% of the total US milk supply whereas Wisconsin contributed 13.9% of the US milk supply by producing 13.2 billion kg of milk (ERS-USDA, 2016). The California and Wisconsin-based dairy production and feeding systems are substantially different from each other. The California Production Systems (CPS) are characterized by fewer dairy farms but large herd size (1,438 dairy farms with 1,215 dairy cows/farm in 2015) and feeding strategies that rely heavily on purchased feed and by-products feeds. In contrast, the Wisconsin Production Systems (WPS) are characterized by a greater number of dairy farms with smaller herd size (9,898 dairy farms with 129 dairy cows/farm in 2015) and feeding strategies that rely more on home-grown feed (Short, 2004; CDFA, 2015; NASS-USDA, 2016).

Evaluating the effects of high-performing milk production systems on the environment is vital for their long-term environmental sustainability. From life cycle analysis we know that the three major contributors to milk carbon footprint include enteric CH_4 emission (35%) followed by CH_4 and N_2O emission from manure management (33%) and N_2O emissions associated with the cropping system that produced the feed for the cows (26%; Thoma et al., 2013a). There were no direct studies found in the literature to evaluate the impact of feeding strategies on enteric CH_4 emission and carbon footprint of milk produced on intensive dairy systems of California and Wisconsin. Thus in this case study we hypothesized that there are no difference in enteric CH_4 and carbon footprint of milk produced in California and Wisconsin. The objective of the case study was to gather relevant and most up-to-date scientific evidence to address the question of whether feeding strategies such as found in California and Wisconsin influenced enteric CH_4 emission and the carbon footprint of milk.

Methodology. A literature review was conducted to identify peer-reviewed life cycle analysis articles that described dietary strategies and associated milk production performance of the lactating dairy cows in California and Wisconsin. The intensive dairy production systems characterized with confined feeding operations where animals are housed in barns year-round and receive a high intake of nutrient dense concentrates or supplements were considered in the study. Comparisons were based on the reported diets fed to lactating dairy cows, the performance of lactating dairy cows, and estimates of enteric CH_4 emission and the carbon footprints. Fat and protein-corrected milk (FPCM) was considered as the functional unit. Thus emissions were expressed as kg of CO_2-eq/kg of FPCM (assuming global warming potential of 25 and 280 for CH_4 and N_2O, respectively as indicated above). The study of Thoma et al. (2013b) was used as main source of information for this case study. In their publications, the authors compared 5 regions of the United States for GHG emissions from dairy farms. California was included in “region 5” along with the states of Washington and Alaska. In contrast Wisconsin was included in “region 3” along with the states of Minnesota, Iowa, Illinois, Michigan, Missouri, and Ohio. Given the overwhelming contribution of California and Wisconsin in characterizing regions 5 and 3 of the study, we used the data from these two regions assuming that they are representative of the CPS and the WPS, respectively. Feed ingredient were listed, but nutrient composition of a typical diet used in each region was not given in Thoma et al. (2013b), but it was calculated with the feed composition tables of NRC (2001). Feed efficiency (FPCM/DMI) was calculated as the inverse of feed conversion ratio (DMI/ FPCM) where both DMI and FPCM were expressed as kg/d. Fecal dry matter (DM) excretion was calculated using the equation by Nennich et al. (2005): Fecal DM excretion (kg/d) = (DMI × 0.356) + 0.80, where DMI is expressed as kg/d.

Results and Discussion

Feeding strategies used and diets fed to dairy cows. Feeding strategies used and diets fed to lactating dairy cows were notably different (Table 1). The CPS and WPS used different feed ingredients and different inclusion levels in dairy cow diets. Diets in the CPS included a greater proportion of concentrate (57 vs. 49%), greater inclusion levels of fat sources (0.83 vs. 0.16%), by-products (33 vs. 18%), and corn-based by-products (11 vs. 7%), but lower inclusion levels of corn silage (20 vs. 30%), corn grain (13 vs. 19%), and soybean by-products (1 vs. 6%) when compared with the diets fed to lactating dairy cows in the WPS. There was no difference in the alfalfa concentration in the diets (19%). However, CPS relied predominately on alfalfa hay rather than alfalfa silage (17 vs. 3%) whereas the WPS used alfalfa silage as the predominant alfalfa source compared with alfalfa hay (2 vs. 17%). Nutrient composition was a reflection of the differences in the ingredients used and their proportions in the diets. Diets fed in the CPS included greater DM (73 vs. 59%), crude protein (16.1 vs. 15.5%), and crude fat (4.98 vs. 4.30%) concentrations, but less forage neutral detergent fiber (NDF; 19 vs. 23%), and starch (23 vs. 29%) concentrations compared with the diets fed in the WPS. However, total (32%) concentration of the diets was not different between the two systems.

Differences in the feed ingredients used in the diets reflect the local availability and cost. Feeding strategies in CPS is dependent in part on long-distance transportation of dietary ingredients such as alfalfa hay, corn grain, and soybean meal (Newton, 2015), and agricultural by-products such as almond hulls, corn by-products (distillers grains, gluten feed, and hominy), canola meal, and cotton seeds (Thoma et al. 2013b). Feeding a greater proportion of dry, fibrous, and low-starch by-products may result in greater DM, concentrate, and non-forage NDF concentrations in the diets as observed in the CPS. The inclusion of greater concentration of fat sources in CPS diets indicated most likely insufficient energy supply from all other dietary ingredients together. On contrast, the inclusion of greater concentrations of energy-dense corn silage and corn grain, and high-CP soybean by-products in the WPS diets resulted in less DM and crude fat concentrations but greater starch concentration.

Performance of the dairy cows. According to Thoma et al. (2013b), dairy cows in CPS consumed less feed on DM basis (22 vs. 25 kg/d) and produced less FPCM (28 vs. 34 kg/d) compared with WPS. However, cows from both production systems had a similar feed efficiencies (1.32), diet DM digestibility (61%), and fecal DM excretion (0.30 kg of fecal DM per kg of FPCM; Table 1).

*Enteric CH_4 emission***.** As a single source, enteric CH_4 emission was the greatest contributor to milk carbon footprint both in CPS and WPS (36 and 37%, respectively). The CO_2-eq from enteric CH_4 emission were not much different between the two dairy production systems despite the notable differences in feeding strategies, dietary ingredients, and nutrient composition of the diets (Table 1). However, the contribution of dietary ingredients to either enhancing or reducing CH_4 emission was distinct between the two dairy production systems. As characteristic of the CPS, feeding lipids, and replacing roughages with concentrate, are dietary factors known to reduce enteric CH_4 emission. In contrast, high starch and corn silage diets were characteristics of the WPS that most likely contributed to reducing emissions.

Various feeding and nutritional strategies may help reduce enteric CH_4 emission per kilo of milk but gains will be mostly achieved with improvement in feed efficiency (Knapp et al., 2014). Reducing the ruminal pH <5.5 may reduce enteric CH_4 emission substantially (15-20%) but would not be a practical solution in dairy cattle because of the negative association between low rumen pH on milk fat depression. Each kilogram increase in DMI could reduce the enteric CH_4 emission per kilo of milk by 2-6%, and a 1% increase in non-fiber carbohydrate concentration in the diet would reduce enteric CH_4 emission by 2% (up to a maximum of 15%). Similarly, a 1% increase in dietary lipid would reduce enteric CH_4 emission by 5%. Many of the biological effects of the feeding strategies described here are interrelated and interdependent, thus, the changes in enteric CH_4 emissions are not likely to be additive (Knapp et al., 2014). After reviewing the literature, Knapp et al. (2014) concluded that the potential for reducing enteric CH_4 emission through feeding strategies is modest and range from 0 to 15%. Also, Cottle et al., (2011) claimed that nutritional management strategies may have an important role to play in the near future, but other longer-term, sustainable mitigating strategies must be considered to reduce the overall carbon footprint of milk.

Carbon footprint. Thoma et al. (2013b) observed that carbon footprint of the crop production in CPS was 30% greater than that of the WPS (Table 1). Adom et al. (2012) suggested that the carbon footprint of the major feeds used in the dairy industry, alfalfa (hay and silage), corn (grain and silage), grass (hay, silage), and soybean meal in the Western United States (corresponding to region 5 of Thoma et al., 2013b) was greater compared with the Midwest of the United States (corresponding to region 3 of Thoma et al., 2013b). Their analysis included GHG emissions from fuel, agro-chemicals, fertilizers, and electricity used during land preparation, cultivation, and harvesting. However, they did not include the GHG emissions associated with the transportation of feed ingredients. The CPS is dependent on imported feed ingredients from adjacent states (Newton, 2015); thus, GHG emission during transportation of feed ingredients should be considered when calculating the carbon footprint. Feeding agricultural by-products tended to increase milk carbon footprint compared to their agricultural raw materials because of GHG emission associated with processing and transportation. For example, the average carbon footprint of corn dried distillers grains in the United States is more than twice that of corn grain (910 vs. 402 g CO_2-eq/kg dry feed; Adom et al., 2012). Thus, the high proportion of by-products in the CPS contributed to a higher carbon footprint. The validity of this assertion may be questioned because the proper approach to allocate GHG emissions to a by-product feed has not been entirely resolved. Similarly the allocation of GHG emissions to meat as a by-product of milk production on specialized dairy farms, which was assumed to be 89.3% in both systems (Table 1) has not been entirely resolved either.

The data of Thoma et al. (2013b) suggested similar emissions from manure management in California and Wisconsin (Table 1). However, Rotz et al. (2010) simulated emissions from managed manure and found 25% greater emission for the confined dairy production systems of California compared to Pennsylvania (which is similar the WPS). There are large variations in GHG emissions associated with the type of manure storage systems. The highest emissions have been reported for uncovered anaerobic lagoon (Asselin-Balençon et al., 2013), which are more prevalent in California compared to Wisconsin. The main difference in emission between the CPS and the WPS appeared to be associated with the production of feed for the herd. Ultimately, when emissions from crop production, enteric fermentation, manure management, and other sources (fuel combustion) were summed up, the milk carbon footprint of CPS was 9% greater than for the WPS (1.22 vs. 1.12 kg of CO_2-eq/kg of FPCM, Table 1). These estimated were in relative agreement with those reported in Phetteplace et al. (2001) and Capper et al. (2009).

Mitigation of enteric methane vs. other GHG mitigation strategies. Although enteric emission was the single most important source of emission in both dairy systems, the contribution of the other primary sources for GHG emissions was 62 and 57% for the CDPS and WDPS, respectively. These observations indicated that, in the long term, substantial mitigation of GHG will be achieved only if novel dietary strategies are developed in concert with other strategies such as genetic selection and appropriate herd management practices including, health, reproduction, and housing facility design that contribute to greater feed conversion efficiencies (Knapp et al., 2014). Interestingly, the work of O'Brien et al. (2014) has demonstrated the importance of soil carbon sequestration in the calculation of milk carbon footprint. Emissions vary substantially among crop rotation systems used to produce feed for dairy cows. In general, more complex (diverse) and increasingly perennial crop systems are associated with increased potential for soil carbon sequestration (Osterholz et al., 2014). Also, the work of Aguirre-Villegas et al., 2015 suggested that bio-digestion for electricity generation may contribute to the displacement of emissions from power plants. Thus another avenue for future research is to focus on whole-farm carbon balance because of the positive effects that the enhancement of carbon sequestration (soil organic matter) and carbon credits (bio-digestion) may have on managing milk carbon footprint.

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Table 5. Comparison of California and Wisconsin intensive dairy systems.

Item[1]	California-based dairy production systems[1]	Wisconsin-based dairy production systems[2]
Diets fed to dairy cows-Ingredient (% of DM)		
Forage:concentrate ratio	43:57	51:49
Alfalfa	19.2	19.2
Corn silage	19.8	29.9
Corn grain	13.3	18.8
Fat sources	0.83	0.16
By-products	32.5	17.5
Corn by-products[3]	11.2	6.96
Soybean protein by-products[3]	1.38	5.73
Other by-products[3]	19.9	4.81
Diets fed to dairy cows-Nutrient (% of DM unless noted)		
Dry Matter (% of diet)	72.4	59.1
Crude Protein	16.1	15.5
Neutral Detergent Fiber (NDF)	32.0	31.8
NDF from forage	19.1	23.6
Starch	22.5	28.6
Crude fat	4.97	4.18
Performance of dairy cows		
Dry Matter Intake (DMI), kg/d	21.7	25.2
Fat-and-Protein Corrected Milk (FPCM), kg/d	28.2	33.5
Diet digestibility, %	60.7	61.2
Fecal DM excretion[4], kg/d	8.54	9.75
Fecal DM excretion, kg/kg of milk	0.30	0.29
Feed efficiency, FPCM/DMI	1.30	1.33
Carbon footprint, GHG[5], kg of CO_2-eq/kg of FPCM		
Enteric emission	0.43 (35.6%)	0.41 (36.5%)
Crop production	0.39 (31.8%)	0.30 (27.1%)
Manure management	0.36 (29.9%)	0.34 (29.8%)
Other emissions (fuels)	0.03 (2.7%)	0.07 (6.5%)
Carbon footprint at farm level	1.22	1.12

[1]Data on diets fed to dairy cows (ingredients and chemical composition), performance of dairy cows, and carbon footprint for the both dairy production systems were created using the data from Thoma et al., 2013b.

[2]Comparison is based on Region 5 (California-based) and Region 3 (Wisconsin-based) dairy production systems of United States as classified by Thoma et al., 2013b. Region 5 included Alaska, California, and Washington and Region 3 included Minnesota, Iowa, Illinois, Michigan, Missouri, Ohio, and Wisconsin.

[3]Corn by-products = distillers grains (dry and wet), gluten feed (dry and wet), hominy; soybean protein by-products = soybean meal, roasted soybean; other by-products = almond hulls, canola meal, cottonseeds, whey, wheat middlings, citrus pulp, beet pulp.

[4]Fecal DM excretion = (DMI × 0.356) + 0.80; DMI = dry matter intake: Nennich et al., 2005.

[5]GHG = greenhouse gasses; Numbers within the parenthesis indicate the percentage contribution of each sources of GHG at farm level.