Whole Farm Decision-Making, Dairy Farms Profitability and Greenhouse Gas Emission

By

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Abstract

The dairy industry has been under the spotlight for the greenhouse gas (GHG) emission. Methane and Nitrous oxide are the two major GHG in a dairy farm. As a ruminant, dairy cows produce methane from the rumen microbial activities. Manure management is another major emission source of methane and nitrous oxide on a dairy farm. Feed production on-farm and off-farm are associated with nitrous oxide and methane emission. Previous research has studied many GHG mitigation options through nutritional management, grazing management, genetic selection, however, not much research has been conducted on herd management. The dissertation estimates the effect of different management strategies and the interaction between strategies on dairy farms GHG emission intensity (kg CO_2 eq. per unit of milk) and profitability simultaneously with farm-level life cycle assessment models.

Results confirmed previous research suggesting that increasing milk production is the ultimate approach to reducing dairy farm GHG emission intensity. Higher replacement rate increases farm-level GHG emission due to the greater number of replacement animal needed. However, the higher meat production due to higher replacement rate also reduces the farm-level GHG emission allocation to milk production. Greater milk productivity improvement may counterbalance the effect from higher replacement rate on enteric methane emission in a long-term. Feeding strategies and diet formulation (i.e. extensive grazing, higher concentrate feed, etc.) influenced on all the 3 major emission sources (enteric fermentation, manure management, and feed production). Mitigation strategies that focus on enteric methane emission (such as diet formulation changes) may have a carryover effect on manure GHG emission and crop production emission. Selection of the functional units in the LCA also changes the evaluation of different strategies.

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Growing up as an urban girl in a small city in China, I never thought I would pursue a Ph.D. in Dairy Science. Although this path is a bit different than the 10-year old Di's imagination of being an engineer, I found my interests in dairy farm management, especially estimating the management strategies impacts through modeling techniques. Doing a Ph.D. is not an easy thing, I truly appreciate the guidance, help, and support from the people below.

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Chapter 1

Introduction

1.1 Background

Greenhouse gas emission from the agricultural industry is a primary source of the non-CO_2 emission in the US. The dairy farm has three primary GHG emission sources:1. Enteric fermentation (CH_4); 2. Manure management (CH_4 and N_2O); 3. Feed production (N_2O and CH_4). The dairy industry has been under the spotlight for GHG emission and committed to reducing the emission by 25% before 2010 in the US. Reducing the GHG emission for a dairy farm is more than improving the environmental performance because GHG emission also decreases the farm's energy and nutrient efficiency.

As a business property, the bottom line of a dairy farm is always the profit. All the potential management strategies changes on a dairy farm need to be beneficial to the animal performance or the profitability. Given these impacts, dairy cattle farming faces a major challenge: to reduce GHG emissions while maintaining or increasing profitability. The abatement cost of GHG emission needs to be considered. Some mitigation options (i.e. rumen protozoa defaunation) are effective in the GHG reduction but also expensive to conduct as a practical routine. Previous research has been studying many dairy farms GHG mitigation options through the nutritional management (i.e. diet formulation, grazing practices) and manure management (i.e. system type, treatment, crust), however, not much research has been done on the herd management (i.e. reproduction, culling). Herd management influences on the GHG emission and profitability indirectly through changing the productivity, treatment and labor cost, and herd structure. The ideal mitigation approach leads to a win-win solution of GHG emission and profitability. As dairy farms are continuously improving the herd performance, evaluating the effects of management strategies on GHG emission and profitability could assist the farm to reach the win-win solution.

Whole-farm level evaluation of mitigation options is necessary. On the cow-level, nutritional mitigation strategies towards reducing enteric CH_4 emission by changing diet formulation may have a carryover effect to manure emission because the diet formulation changes the manure composition. On the farm-level, management strategies often influence on multiple aspects on a dairy farm. For example, a higher culling rate may modify the herd structure, the genetic selection progress, reproduction at the same time. The evaluation of management strategies has to consider the impacts on all the aspects, as well as the interactions between different aspects on a farm.

This dissertation aims to study the whole farm decision-making in dairy farm profitability and GHG emission. The primary objective is to estimate the effects of common management strategies on the farm GHG emission and profitability simultaneously. The secondary objective is to assess the trade-off between farm GHG emission and profitability on the farm-level. Hence, a literature review discusses the available mitigation strategies through farm management and their feasibilities. Life cycle assessment approach is employed to evaluate mitigation options and management strategies on the farm-level GHG emission. A nonlinear optimization model is developed to estimate the trade-off effects between farm-level GHG emission and profitability.

1.2 Thesis Outline

Chapter 2 is a comprehensive review of GHG emission in dairy farms and the associated mitigation options through farm management. Most of the mitigation options are studied in the following chapters, including feeding strategies, culling rate, genetic selection, manure management system.

Chapter 3 estimates how productivity and culling rate influence on the farm GHG emission and profitability using the Integrated Farm Simulation Model.

Chapter 4 extends Chapter 3 and takes the milk productivity improvement (through genetic selection and management) into consideration. This chapter uses a Markov chain model to simulate the herd structure and predict the herd-level milk production, income over feed cost, and enteric CH4 emission in a long-term.

Chapter 5 compares four types of certified Wisconsin organic dairy farms in the farm-level GHG emission using the life cycle assessment approach. Farm types differentiate in the feeding strategies, including DMI, grazing length, concentrate supplement amount, etc. Results are expressed as kg CO_2 eq. per kg of ECM,

Chapter 6 is a follow-up study of chapter 5 that compares 3 functional units (kg CO_2 eq. per kg of ECM, per cow, and per ha of land) in the farm-level GHG emission. Choosing another functional unit changes the rankings of four types of organic dairy farms.

Chapter 2

Literature Review

Greenhouse gases in the atmosphere change the balance of incoming solar radiation and outgoing infrared radiation, which enhances heat trapping inside of the atmosphere and contributes to global warming and climate change (Knapp et al., 2014; Lashof and Ahuja, 1990; Lowe and Zealand, 2007). Global warming potential (**GWP**) is a widely-accepted metric that evaluates gases heat-trapping capacity over a time horizon. As a baseline, CO_2 has the GWP of 1 (Myhre et al., 2013). Methane (**CH_4**) has the GWP of 34 in 100 years and Nitrous Oxide (**N_2O**) has the GWP of 296, which indicates that emitting one unit CH_4 or N_2O could add 34 times or 296 times more energy to the climate system in 100 years than the same amount of CO_2 (Myhre et al., 2013).

Greenhouse gas emission from livestock enteric fermentation (164.5 MMT CO_2 eq. in total and 41.6 MMT CO_2 eq. from dairy cattle) and livestock manure management (61.4 MMT CO_2 Eq. in total and 31.8 MMT CO_2 Eq. from dairy cattle) are an important portion of the anthropological GHG emission (EPA, 2014). Livestock enteric fermentation CH_4 emission was the greatest proportion (24.9%), and manure management CH_4 emission was the 5th highest proportion (9.3%) in the U.S. anthropogenic CH_4 emission; manure management N_2O emission was the 3rd highest emission source (4.3%) in the U.S. anthropogenic N_2O emission (EPA, 2014). Agricultural soil management (fertilizer application and other activities), which dairy farm is contributing to, was the highest proportion (74.8%) in U.S. anthropogenic N2O emission (EPA, 2014).

Effective greenhouse gas (**GHG**) mitigation strategies may lead to win-win situations of reducing GHG emissions while improving productivity and likely farm profit (Hristov et al., 2013). This chapter discusses four aspects of dairy farm management strategies, which have the potential to reduce the dairy farm GHG emission. These include: 1) nutrition (diet formulation, feed efficiency, feed additives, and grazing management), 2) manure management, 3) genetics and culling, and 4) reproduction and health. This chapter also reviews several modeling techniques (life cycle assessment, Integrated Farm System Model, and Markov Chain model) used in this dissertation.

2.1 Nutrition

Forage-to-concentrate ratio. Both forage and concentrate have high carbohydrate content but of different types. Forage has higher neutral detergent fiber (**NDF**) whereas concentrate has higher non-fiber carbohydrate (**NFC**) content. Carbohydrate type in the ration influences enteric CH_4 emission by changing fermentation pattern, rumen pH, and microbial population. Non-fiber carbohydrates and NDF have different fermentation patterns in the rumen, which affect the profile of volatile fatty acid (**VFA**) produced as end products of fermentation (Moe and Tyrrell, 1979; Knapp et al., 2014; Johnson and Johnson, 1995b). A feed ingredient will promote CH_4 emission if it ferments more into acetate or butyrate than in propionate. Greater acetate and butyrate synthesis promote enteric CH_4 emission whereas greater propionate decreases CH_4 emission by influencing production and disposal of hydrogen equivalent. Acetate and butyrate formation from hexose produces hydrogen (**H**) that promotes methanogenesis. In contrast, propionate formation consumes H and thus reduce methanogenesis (Hungate, 1966). Neutral detergent fiber is composed of cellulose, hemicellulose, and lignin. Hemicellulose has higher digestibility than cellulose in ruminant animals (Keys et al., 1969). One unit of hemicellulose produces much less CH_4 compared with one unit of cellulose because it ferments into more propionate (Moe and Tyrrell, 1979; Murphy et al., 1982). The impact of cellulose was greater than hemicellulose (1.39 vs. 0.51 MCal per kg DM) on enteric CH_4 emission (MCal per d) regarding regression coefficients (Moe and Tyrrell, 1979). Non-fiber carbohydrates are majorly starch, sugar, organic acids, pectin, and other reserve carbohydrates (NRC, 2001). Non-fiber carbohydrates favor propionate-genesis microbes during rumen fermentation (Martin et al., 2010; Knapp et al., 2014). In general, lower NDF: NFC (forage-to-concentrate ratio) diet decreases CH_4-energy loss as a proportion of gross energy intake (**GEI**; MCal per cow per d), Beauchemin et al., 2008; Martin et al., 2010; Knapp et al., 2014).

A high forage-to-concentrate ratio diet normally leads to greater enteric CH_4 emission (Murphy et al., 1982). Aguerre et al., (2011) tested the effect of forage-to-concentrate ratio on enteric CH_4 emission. Results showed that increasing forage proportion increased CH_4 emission, increased rumen pH linearly, and increased butyrate concentrate quadratically. Substituting forage with concentrate in the diet tends to increase protein and energy intake, which positively correlates with milk production (Knapp et al., 2014; Yang and Beauchemin, 2007). The lower forage-to-concentrate ratio can increase milk production and reduce total rumen enteric CH_4 emission (L); both of the effects contribute to the lower GHG emission intensity (**GHG-EI**), which is the GHG emission per kg of milk production. Farms that rely heavily on forage intakes, such as grazing or organic farms, can increase the productivity of cows fed in these systems and decrease the cows' enteric GHG-EI by providing supplemental concentrate to lactating cows, which increases GEI and reduces forage-to-concentrate in the diet. Using a whole-farm simulation model, Soder and Rotz (2001) compared the farm profitability with four levels of concentrate supplement in dairy farms. Results showed that higher level of concentrate supplement (6 kg or 9 kg concentrate DM intake vs. no concentrate DM intake) increased cows' productivity. In spite of the greater feed cost due to a greater amount of concentrate supplement, farm profit was higher with the higher level of concentrate supplement. Changes in forage-to-concentrate ratio also influence on milk composition. Milk of cows fed on high forage-to-concentrate ratio diet (70:30, DM basis) had higher milk fat concentration and lower true protein concentration, compared with the milk of cows fed with the low forage-to-concentrate ratio (30:70, DM basis; Benchaar et al., 2014). The total yield of milk fat was not significantly different between cows fed high and low forage-to-concentrate. Meanwhile, the total yield of true protein and lactose was higher when cows were fed the high forage-to-concentrate diets, compared with low forage-to-concentrate diets.

Low forage-to-concentrate diet also changes the rumen microbial and rumen pH. Hook et al. (2011) analyzed the rumen microbial population of dry cows with different forage-to-concentrate ratio levels (from all hay diet to 65% grain and 35% hay diet) using real-time PCR technique. During 6 weeks of the experiment, the high concentrate diet had no significant influence on the rumen methanogens density. However, it changed the methanogens diversity and community structure and the protozoal density. The same study also observed rumen pH drop with higher concentrate content diet ($P<0.001$). Russell (1998) found that high concentrate diet led to lower rumen pH, higher VFA content, and are lower in acetate: propionate ratio than an all forage diet in vitro. Methane emission decreased when pH was in the range of 5.5 to 6.5. When pH drops below 5.5, H_2 started to accumulate, which further suggested an inhibition of methanogenesis in spite of abundant H availability (Russell, 1998; Hook et al., 2011).

Pasture and grazing management. Pasture and grazing management includes selecting forage species and ensuring its optimal quality (maturity), which affects CH_4 emission by changing the concentration and digestibility of plant NDF. Species of forage used in dairy cattle diet vary in different regions, depending on the climate condition. The C4 photorespiration metabolic pathways are more common in tropical grasses whereas C3 pathways are more common in temperate grasses for carbon fixation (Archimède et al., 2011). The C4 grasses has a higher content of lignin in the cell wall, which reduces the digestibility and voluntary intake (Jung and Allen, 1995; Wilson, 1995). Archimède et al. (2011) compared the CH_4 emission per kg dry matter intake (**DMI**) of C3 grasses, C4 grasses, and legumes and found that C4 grasses led to the greatest CH_4 emission (33.7 L CH_4/kg DMI) and warm climate legume emitted the least CH_4 (25.9 L CH_4/kg DMI). The C3 grasses (30.0 L CH_4/kg DMI) and cold climate legume (30.1 L CH_4/kg DMI) did not differ in emission. Forage maturity influences CH_4 emission because more mature forage has greater lignin content, and consequently lower NDF digestibility (Moss et al., 2000; Boadi et al., 2004b). Jung and Allen (1995) found that C4 grasses (with higher lignin content) produce more CH_4 during fermentation than C3 grass (low lignin content). Lignification in C4 grass provides for greater resistance to physical and microbial digestion process and increase the retention time in the rumen. Thus CH_4 emission per kg of DMI and CH_4 emission per kg of organic matter (**OM**) intake is expected to increase for both reasons (Archimède et al., 2011). Robertson and Waghorn (2002) reported that CH_4 emission of grazing cows increased by 11.1% (361g to 401 g CH_4/cow/d) as pasture matured from September (Spring) to December (Summer) in New Zealand. Choosing appropriate forage feed ingredient and monitoring the maturity (during harvesting or grazing management) may help reduce forage lignin and CH_4 emission per cow per d.

Corn silage and grass silage are the two common types of silage used for feeding dairy cows. Compared with corn silage, grass silage favors enteric CH_4 emission (g/DMI, g/MCal digestible energy, $P<0.05$) because of its higher fiber digestibility and lower starch content, which leads to a higher rumen pH, greater ruminal protozoa density, and higher acetate: propionate ratio (Hassanat et al., 2013). However, Arndt et al. (2015) found that replacing corn silage with alfalfa silage had no significant effects ($P>0.05$) on CH_4 emission (per kg DMI and per MCal GEI). The results showed a linear decreasing of CH_4 emission (g) per kg digested NDF (*P*<0.05), a linear increasing of NDF intake (% of body weight) and total-tract NDF digestibility (%) (*P*<0.05), and a quadratic trend of CH_4 emission (per kg NDF intake) (*P*>0.05) with the increasing alfalfa silage to corn silage ratio in the diet. Instead of ensiled forage type (corn silage or alfalfa silage), rumen pH, the carbohydrates type, and fermented amount (both starch and NDF) may be the influencing factors in ruminal CH_4 emission (Arndt et al., 2015b; Guyader et al., 2016).

Increasing DMI. Several decades ago, research demonstrated that enteric CH_4 emission (g/d) is positively related to feed intake level, including DMI or GEI level (Blaxter and Clapperton, 1965; Moe and Tyrrell, 1979; Murphy et al., 1982). Greater DMI has been associated with larger rumen capacity that enables longer feed retention time in the rumen and increases the extent of digestion, which leads to a greater daily enteric CH_4 emission (Pinares-Patio et al., 2003). A meta-analysis conducted by Ramin and Huhtanen (2013) and Moraes et al. (2014) agreed that dietary intake level (DMI or GEI) is the most important factor influencing enteric CH_4 emission prediction (L per d or MJ per d). Dry matter intake explains 85% of the variation in CH_4 emission (L per d, Ramin and Huhtanen, 2013). Daily CH_4 emission increases as DMI increases, however, the ratio of CH_4-energy to GEI decreases as the intake level increases (Jentsch et al., 2007). For every multiple of intake above the maintenance energy intake level, CH_4-energy loss decreases approximately 10% (Ramin and Huhtanen, 2013). Dry matter intake level is also positively related to milk production (NRC, 2001). Assuming the cow's body weight, lactation stage, and feed efficiency are the same, greater DMI (or GEI) increases milk production linearly and decreases enteric CH_4 emission per kg of milk nonlinearly (Figure 2.1) using the prediction models from NRC (2001) and Ramin and Huhtanen (2013). The reduction of enteric CH_4 emission (L) per kg FCM was greater when the daily milk production was low. Hence, higher DMI has the advantage to increase production and reduce CH_4 emission per unit of feed intake or milk production (Pinares-Patino et al., 2009; Johnson and Johnson, 1995b).

Increasing intake elevates milk productivity and decreases the proportion of enteric CH_4-energy to GEI and further reduces CH_4 emission per kg of energy-corrected milk (**ECM**) produced (Johnson and Johnson, 1995b; Capper et al., 2009; Yan et al., 2010). Therefore, high-producing cows are preferred if the goal is to lower CH_4 emission per unit of milk production. In addition to the high milk production, fewer cows are needed to produce a given amount of milk, which further reduces CH_4 emission per kg of milk. Defined as the ratio of ECM over DMI, a higher feed efficiency signifies a higher milk production for the same amount of feed resource. Thus, greater feed efficiency converts into decreasing feed expenditure and land demand. In turn, reduces land demand reduces GHG emissions from sources associated with feed production (energy use and fertilizer production for example; Bell et al., 2011).

Digestibility affects manure volatile solid (**VS**) content, which determines potential maximum CH_4 yield (**B_0**) during manure storage. Volatile solid is the same as the OM in total manure solid, which oxidizes and gasifies at 600 °C (Jun et al., 2000). It has a negative relationship with dietary digestibility and ash content; the manure VS content also has a positive relationship with dietary GEI and DMI (IPCC, 2006). As discussed above, the changes in NDF digestibility has opposite effects on ruminal CH_4 emission and manure CH_4 emission.

Dietary crude protein level. Dietary crude protein (**CP**) is a measure of nitrogen (**N**) content of a diet. Dietary CP determines in part manure N content. Increasing dietary N content increases N_2O emission from manure storage, especially in an aerobic storage system (Aguerre et al., 2012a; Montes et al., 2013a). On percentage decrease in dietary CP content reduced the manure total N content by 3.5% according to a meta-analysis result (*P*<0.05, Hou et al., 2015). Kuelling et al. (2001) found that increasing dietary CP content increased N_2O emission from manure storage, decrease CH_4 emission during 5 weeks of the experiment from urine-rich slurry manure storage (90% urine), and had no effect on CH_4 emission from other manure storage type (slurry or solid storage).

Dietary CP content also changes manure VFA concentrate (g per kg DM or g per kg VS), greater manure VFA concentrate may be an inhibitor of CH_4 emission (m^3 CH_4 per livestock unit (**LU**)) from manure (Hansen et al., 1998; Møller et al., 2004; Le et al., 2005). One study (Aguerre et al., 2012a) showed CH_4 emission increasing from storage while manure VFA concentrate decreasing. However, experiments to demonstrate the causality between manure VFA concentrate and CH_4 emission from manure are lacking. Increasing dietary CP content to reduce manure CH_4 emission may not be an efficient option to reduce the farm-level GHG-EI because it potentially causes greater N_2O emission from manure storage. Evaluation of increasing dietary CP content on manure management GHG-EI needs to consider the trade-off between CH_4 and N_2O emission and adjust for their GWP. Kuelling et al. (2001) estimated the trade-off between the effects of the dietary CP on N_2O and CH_4 emission from manure storage. Although the overall GHG emission (kg CO_2 eq., including both N_2O and CH_4) during storage did not differ between low or high dietary CP in a 7-week period, manure management type (slurry, urine-rich slurry, dry lot, or deep litter) had a significantly impact ($P<0.01$) on CO_2 eq. emission (Gerber et al., 2013; Aguirre-Villegas and Larson, 2016).

In addition to reducing N_2O emission from manure, decreasing dietary CP level may be the most effective mitigation option of manure ammonia (NH_3) emission (Hristov et al., 2011;

Hou et al., 2015), which contributes to indirect N_2O emission (IPCC, 2006). Hou et al., (2015) summarized 87 previous published studies and found lowering dietary CP by 2% reduced the manure NH3 emission by 45% compared with the reference scenario (14.4% CP, slurry-based system).

Dietary lipid level. Greater dietary lipid content reduces CH_4 emission. The following three mechanisms have been proposed to explain this effect: 1) decrease the acetate: propionate ratio in the ruminal VFA profile; 2) suppression of rumen methanogens population in vivo and ciliate protozoa in vitro; and 3) reduce H availability due to bio-hydration process of unsaturated fat (Hook et al., 2010; Beauchemin et al., 2008b; Knapp et al., 2014). Fatty acids (**FA**) have direct toxicity on methanogens, cellulolytic bacteria, and protozoa; however, the mechanism remains unclear (McAllister et al., 1996; Giger-reverdin et al., 2003; Martin et al., 2010).

Different FA profile in feed ingredients may impact enteric CH_4 emission differently. Beauchemin et al. (2009) found that crushed flax seed and sunflower seed decreased CH_4 emission by reducing DMI and digestibility to some extent; meanwhile crushed canola seed reduce CH_4 not affecting DMI. Palm kernel oil, coconut oil, and one type of canola oil reduced the density of methanogens, ciliates, and CH_4 emissions (Dohme et al., 2000). Dohme et al. (2001) found that some median-chain saturated FA (C12:0 and C14:0) have a negative effect on daily enteric CH_4 emission (g per d). In addition, unsaturated long-chain FA (C18:1 from rapeseed, C18:2 from soybean and sunflower oil, and C18:3 from linseed) also depress daily CH_4 emission (g per d, Dohme et al., 2001; Martin et al., 2010). According to Martin et al. (2010), increasing 1% of C18:1, C18:2 and C18:3 in the diet, decrease CH_4 emission (g CH_4 per kg DMI) by 2.5%, 4.1%, and 4.5%, respectively; CH_4 emission (g CH_4 per kg DMI) decreased by 3.5% by increasing 1 additional percent of C16 or C18 saturated FA (from tallow). The bio-hydrogenation of unsaturated FA in the rumen reduces the availability of H and thus reduces the potential for methanogenesis. This bio-hydrogenation process, however, has a minor quantitative effect in reducing H amount comparing to the mechanism of reducing the acetate: propionate ratio. Increasing 1 mol of C18:1 (linoleic acid) reduced 1 mol of CH_4 meanwhile increasing 1 mol of propionate in the rumen fermentation reduced the CH_4 by 2 mol (Ramin and Huhtanen, 2013; Knapp et al., 2014). Polyunsaturated FA has a negative effect on protozoa and cellulolytic bacteria, therefore increasing their dietary concentration would shift rumen fermentation toward more propionate (Doreau and Ferlay, 1995; Martin et al., 2010).

Beauchemin et al. (2008) conducted a meta-analysis and reported 1% additional supplement fat decreased CH_4 (g/kg DMI) by 5.6%. Martin et al. (2010) fit a regression model between dietary lipid content and the enteric CH_4 emission (g per kg DMI) from 28 publications. The result suggested that increasing 1% of dietary lipid content led to an average 3.8% depressing on the enteric CH_4 emission (g per kg DMI). Mitigating enteric CH_4 emission through increasing dietary lipid content is promising, but there are some concerns about its long-term effectiveness and its carryover effect on manure GHG emission. Current research has demonstrated a short-term CH_4 reduction effect of increasing dietary lipid content. However, it has failed to demonstrate the long-term effect (Woodward et al., 2006; Grainger and Beauchemin, 2011). When rumen microbes adapted to the high lipid feed, the effect of adding dietary lipid to reduce enteric CH_4 emission subsided. High dietary lipid content also decreases total DMI, NDF digestibility, which counteracts benefits of more intensive dietary energy content brought by the greater lipid content (Knapp et al., 2014; Beauchemin et al., 2008; Martin et al., 2010). A reasonable maximum of dietary lipid content should be no greater than 6-7% of total DMI (normally no more than 2-3%, Beauchemin et al., 2008a; NRC, 2001). Increasing dietary lipid content also has a carryover effect on manure GHG-EI (Gerber et al., 2013). The high dietary lipid content may reduce feed digestibility and result in more OM excreted in manure, thus increased CH_4 emission during storage. If the lipid supplement is from cotton seed that has high CP content, increasing the dietary lipid content may also increase the manure N content, which results in higher N_2O emission from manure management (Gerber et al., 2013; Hristov et al., 2013a). A study found that ruminal CH_4 reduction by adding lauric acid (C12) to the diet might be compensated by the greater CH_4 emission from manure with long-term manure storage (Külling et al., 2002). The effect of dietary lipid level on dairy farm GHG-EI needs to be on a farm level than only focusing on rumen.

Feed additives. Monensin is a typical feed additive, which is a biologically active compound produced by a strain of *Streptomyces cinnamonensis* (Richardson et al., 1976). Monensin is commonly used to increase feed efficiency. Incidentally, it also decreases enteric CH_4 emission (L per cow per d and L per kg of milk, Boadi et al., 2004). Monensin pushes the fermentation towards propionate and lower hydrogen supply in the rumen, thus increasing feed efficiency and reducing CH_4 emission. Richardson et al. (1976) reported that monensin decreased CH_4 emission by reducing acetate: propionate ratio in rumen VFA both in vitro and in vivo. Monensin decreased rumen microbial growth rate without affecting the amount of fermented substrates (Van Nevel and Demeyer, 1977). However, use of monensin to reduce enteric CH_4 is not practical. Beauchemin et al. (2008) indicated that high doses of monensin (24-35 ppm per d) reduced enteric CH_4 emission by 4-10% (g per d) and 3-8% (g per kg DMI), whereas lower dose (<20 ppm per d) were not effective. The nearly double-concentration necessary to observe an effect on CH_4 emission would increase feed costs substantially. Incidentally, Europe prohibits using monensin as feed additive as it is a natural antibiotic.

New technologies in feed additives show the high potential of reducing enteric CH_4 emission. A recent study (Hristov et al., 2015) conducted in Pennsylvania found that a methanogen inhibitor, 3-nitrooxypropanol (3NOP) reduces CH_4 without reducing milk production during the 12-week experiment. 3NOP inhibits the methyl Coenzyme-M, which is the enzyme that catalyzes the last step of methanogenesis. The results showed approximately a 30% reduction in rumen CH_4 emission (per unit of DMI and per unit of ECM). Without a doubt, 3NOP could be an excellent approach to reduce GHG-EI. Nonetheless, more research is needed on this new product to confirm the results and to ascertain no negative effects on herd health and well-being. Partial budgeting will be important before using these new products commercially.

Other. Recombinant bovine somatotropin (**rbST**) has been demonstrated to be an effective approach to increase milk production and feed efficiency, which dilutes enteric CH_4 emission per unit of milk production, meanwhile maintain dairy cows health and well-being. Johnson et al. (1992) reported 19% milk production (kg per cow per d) increase and 9% enteric CH_4 emission (kg per yr) reduction by using rBST. Capper et al. (2008) estimated the environmental effects of utilizing rbST industry-wide with a mathematical model. Using rbST on one-million dairy cows could reduce dairy farm GHG emission (kg CO_2 eq. per yr, including enteric fermentation, manure management, and crop production) by 8.8% while maintaining the same milk production (Capper et al., 2008). In addition to the GHG emission reduction (kg CO_2 eq. per yr), using rBST would simultaneously reduce approximately 8% of farm resources demand (including feed, land, crop fertilizer, fuel, etc.) to produce the same amount of milk production, compared with not using rbST. Recombinant bST shows a potential to reduce dairy farm GHG-EI while maintaining the profit. However several countries and regions (Canada, Europe Union, Australia, New Zealand, etc.) have banned the rbST usage on dairy cattle. In the United States, the use of rbST has been increasingly discontinued under consumer demand.

2.2 Manure management

Manure management is a large contributor to dairy farm GHG emission (kg CO_2 eq. per unit of milk and kg CO_2 eq. per year). In the United States, GHG emission from dairy cattle manure management was 31.8 MMT CO_2 eq., which was 6.2% of total agricultural GHG emissions and 0.48% of total U.S. GHG emissions in 2014 (EPA, 2014). Microbes utilize the CO_2, H, N, and water from manure and produce CH_4 and N_2O (Chadwick et al., 2011). Manure storage type (earthen basin, covered lagoon, solid pile, etc.), manure storage form (liquid, slurry, or solid), and other aspects (location, weather, etc.) determine the manure management characteristics, including temperature, moisture, and oxygen availability in storage. Those factors are critical in determining the GHG emission (kg CO_2 eq. per d and kg CO_2 eq. per m^3) from manure management. For example, CH_4 formation requires anaerobic environment whereas N_2O emission from nitrification process requires an aerobic environment. Accordingly, oxygen availability will shift the environment to favor CH_4 or N_2O. Typically, GHG emissions associated with manure management are from the collection phase in animal housing, the manure storage phase, and the field application phase. Some farms may have manure treatment after storage and before field application, such as liquid-solid separation, aeration, anaerobic digester, composting (Sommer et al., 2004). Nitrous oxide is the major GHG from manure stored in piles (solid) whereas CH_4 is the major GHG from the slurry-based system (liquid; Masse et al., 2008; Chadwick et al., 2011; Montes et al., 2013a). Nitrification process (aerobic) was the dominant mechanism of the slurry storage N2O emission. Meanwhile denitrification process (anaerobic) might contribute a small proportion to the N2O emission (Willers et al., 1996; Sommer et al., 2000). Total emission of CH_4 and N_2O (kg CO_2 eq.) should be considered as the main indicator of manure GHG mitigation options, rather than emission of individual gases.

Housing system and grazing management determine the proportion of manure that can be collected, Manure collection is significantly higher ($P<0.05$) in free-stall (89%) than tie-stall farms (66%) (Powell et al., 2005). When cows are on pasture or a dry lot, manure is typically not collected for storage and/or processing. Shorter storage duration reduces the manure nutrient decomposing time, which further decreases the CH_4 and N_2O emission (kg CO_2 eq. per unit of milk, Hou et al., 2015). Research showed that aged manure have an inoculum effect on fresh manure, which changes the manure storage CH_4 emission after loading fresh manure CH_4 into storage (Husted, 1994; Masse et al., 2008; VanderZaag et al., 2010). Reducing the residual manure height from 60 cm to 30 cm before loading fresh manure from decreased the manure CH4 emission (g CH_4 per kg milk) by 26.4% (VanderZaag et al., 2010). Decreasing manure storage time could reduce the CH_4 emission and potentially N_2O emission (Philippe et al., 2007). Aguerre et al. (2012) measured CH_4 and N_2O emissions from manure stored in barrels. Results showed that CH_4 emissions rate (mg/h per m^2) peaked at d 7 and gradually decreased until the end of the measuring period (d 77). Air-dried crust formed around 1 month on the top of manure surface as observed and indirectly reduced CH_4 emission rate by blocking oxygen from outside. Nitrous oxide emission rate (mg/h per m^2) was minimal in the first 2 weeks of storage, but started to increase after crust formation, peaked at day 35 of storage, and gradually declined after that. Adjusting for the GWP values, the GHG emission rate (CO_2 eq., mg/h per m2) peaked on day 7 and again on day 35 of the storage period. The proportion of CH_4 to the total GHG emission (mg CO_2 eq.) was greater than N_2O before d-28; whereas the proportion of N_2O was much greater when the N_2O emission sharply increased on d-28. In spite of the benefits in GHG emission reduction, shortened manure storage time may not be realistic. Manure storage duration most likely depends on season and farm cropping practices. Manure is normally applied to the land no more than twice a year: after harvest in the fall and/or before tillage in the spring. Manure is stored until the application time.

Hou et al. (2015) conducted a meta-analysis to review and compare different management practices on CH_4 and N_2O emission from manure storage. Acidification and artificial film cover showed the potential of reducing the total GHG emission (kg CO_2 eq. per d) from manure storage, including CH_4 emission, direct N_2O emission, and indirect N_2O emission from nitrate leaching. The reduction was 50% and 24% through acidification and artificial film cover compared with the baseline (slurry-based system without crust cover), respectively.

Acidification reduces manure pH in slurry storage and thus inhibits CH_4 emissions. Methanogens in manure storage are sensitive to the environmental pH value. The methanogenesis optimal pH is slightly alkaline (7.0-7.5), depending on manure storage type and temperature (Liu et al., 2008). Using sulfuric acid to reduce manure pH to 5.5, Petersen et al. (2012) and Petersen et al. (2014) observed more than two-thirds reduction in CH_4 and NH_3 emission from slurry storage. Acidification reduced CH_4 emission (g CH_4 per d) by 94% to 99% in pig slurry and the mitigation effect last for the entire storage period (83 days) (Petersen et al., 2014). Effects of acidification on N_2O emission from manure storage have not been studied yet. Acidified manure raised the concern of lowering land pH after manure application. Chan and Parkin (2001) observed that low manure pH ($pH < 4.5$) had potential inhibiting effects on soil methanogen activities, which may further reduce the soil CH_4 emission. Controlling acidified manure final pH between 5.5 to 6.5, which is optimal for many crops (corn and cereal crops), would not be harmful for crop production (Montes et al., 2013b; Dai and Blanes-Vidal, 2013).

Limestone has been widely used for increasing soil pH in general, and it may need to be applied more frequently if acidified manure pH is applied more frequently. Acidification is an effective CH_4 mitigation option based on current research. Long-term research is needed to evaluate the impacts of acidified manure on soil quality, crop production, and GHG emission (GHG-EI and kg CO_2 eq. per year). In addition to CH_4 mitigating effects, acidification shifts the N equilibrium towards the ammonium (NH_4^+) form and away from NH_3 form, which is volatile (Ndegwa et al., 2008). Although NH_3 is not GHG, the NH_3 emission is an indirect source of N_2O emission and indicates N loss from manure, which lower manure N content after land application.

Covers on top of the storage hold the gases under it; gases may eventually release to the atmosphere when the cover cracks or degrades (Bicudo et al., 2002). Gasification (the releases of gases, including CO_2 and CH_4) enhanced the crust formation by rising the fibers to the storage surface with gas bubbles (Smith et al., 2007; Misselbrook et al., 2005). As a result, storage time influences the crust formation (Hou et al., 2015). In Aguerre et al. (2012b), an air-dried crust formed around 1 month of storage. Covering manure effectively reduces NH_3 emission and eliminates odors (Hou et al., 2015; Petersen et al., 2013). Effect of putting a cover above slurry storage on slurry CH_4 emission depended on the cover's permeability, thickness, and composition (Vanderzaag et al., 2008). Covers (natural, artificial, or formed crust) have an inconsistent effect on CH_4 emission from slurry storage. Husted (1994) also observed CH_4 emission decreased significantly after crust formed on the top of liquid manure storage. Methane emission (g CH_4 per m^2 per h) from uncovered slurry storage was 38% higher than covered storage, with both artificial and natural crust (Sommer et al., 2000). However, Petersen et al., (2013) failed to find a reduction in CH4 emission (g/m^3) by adding extra straw to form a crust during winter and summer. Berg et al. (2006) also found no difference in CH_4 emission from slurry storage with or without covers (both artificial cover and straw crust). The seasonal changes in temperature may explain the inconsistent effect of covers on slurry manure storage CH_4 emission (Petersen et al., 2013; Hou et al., 2015). Straw crust shows a promoting effect on N_2O emission (g N_2O per m^2 per h) during slurry manure storage when water balance is decreasing (evaporation greater than precipitation, Sommer et al., 2000). The aerobic condition occurs in the surface cover and increases the N_2O emission when the cover surface is drying and under a negative water balance.

2.3 Genetic selection and culling

Genetic selection to improve feed efficiency is a long-term mitigation strategy at both the cow level (CH_4 emission per unit DMI) and the farm level (kg CO_2 eq. per year, Berry, 2013). A closely related measure of feed efficiency, the residual feed intake (**RFI**) is the difference between predicted DMI and actual DMI. Genetic selection for low RFI should result in cows with higher feed efficiency (Waghorn and Hegarty, 2011). Enteric CH4 emission represents a source of energy loss and inefficiency in energy use (Berry and Crowley, 2013). Hegarty et al. (2007) found a positive relationship between daily CH_4 emission and RFI ($P = 0.002$). In their study, daily CH_4 emission for low RFI steer was 25% lower than high RFI steer with the same rate of average daily gain. Animal experiments to examine GHG (or only CH_4) of dairy cattle with different RFI may be completed shortly. Heritability for RFI in dairy cattle is 0.15±0.03 for all DIM in the US (Tempelman et al., 2015), with a range from 0.0 to 0.4 (Waghorn and Hegarty, 2011). Uncertain results of genetic selection towards lower RFI weaken the investment into it (Hristov et al., 2013b). The moderate heritability of RFI makes genetic selection towards RFI a relatively long-term mitigation strategy, which may show the effectiveness after implementing for a long period (Berry, 2013). Direct selection for lower CH_4 emission is another breeding-based mitigation option. Selection for reduced enteric CH_4 emission would improve feed efficiency simultaneously. Manipulating ruminal microbial flora, especially methanogens, through breeding approach has been proposed as a mitigation option (Cottle et al., 2011; McSweeney and Mackie, 2012). Zhou et al. (2009) and Arndt et al. (2015a) investigated the difference in rumen methanogen populations between high and low feed efficiency cattle using 16S rRNA gene clone libraries approach. Both of the studies found that the population of *Methanobrevibacter* spp. Strain AbM4 (as a percentage of total methanogens) was greater in the rumen of lower feed efficiency cattle ($P<0.05$), which also had the higher CH_4 emission (per kg DMI, per kg digested NDF, and per kg of milk). Although Zhou et al. (2009) suspected that acetate might be the substrate in the *Methanobrevibacter* spp. Strain AbM4 methanogenesis pathway, more future research is needed to better understand its mechanism and the corresponding genetic selecting approach.

Holstein and Jerseys are the two most common dairy cattle breeds in the US. Jersey had a lower CH4 emission (g/d) compared with Holstein across the entire lactation (309 vs. 394 g/d). However, no difference observed in CH_4 emission per kg DMI or CH_4 emission per kg ECM because Jersey had lower DMI and ECM production (Münger and Kreuzer, 2006). Research has found that Jersey cows may have the advantage of greater feed efficiency than Holstein breed. Jersey’s feed efficiency varied from 18.7% higher to 7.1% lower than Holstein cows in 11 previous studies, in which Jersey showed a higher feed efficiency in 8 studies, a lower feed efficiency in 2 studies, and no difference in 1 study (Goddardb, 2003). The reason maybe that Jersey has lower body weight than Holstein, which is an important factor influencing enteric CH_4 emission (Ellis et al., 2007; Moraes et al., 2014). Halachmi et al. (2011) observed partially contradicting results that feed to milk efficiency (DMI to milk yield ratio) was higher for Jersey than Holstein; feed to milk fat efficiency (DMI to milk fat yield ratio) was higher for Holstein than Jersey. The higher milk fat content compensated for the low production to some extent in the feed efficiency calculation. In another study, the higher milk fat and protein content in Jersey milk reduced the milk amount required by 19% and GHG emission (t of CO_2 eq.) by 20% to produce the same amount of Cheddar cheese (Capper and Cady, 2012). Admittedly, Holstein is the dominating dairy breed, and switching to another breed may not be a feasible mitigation option.

Interaction between culling rate and genetic selection. Whole farm models research found that higher culling rate (40% vs. 30% culling rate, Weiske et al., 2006 and 27% vs. 12%, Garnsworthy, 2004) increases farm-level GHG-EI and decreases with farm profit (Garnsworthy, 2004; Weiske et al., 2006; Bell et al., 2011). Reducing replacement rate by 10% decreases predicted farm-level GHG-EI by 2.3% to 3.9% depending on the production system (Weiske et al., 2006). Raising fewer replacements on-farm and selling surplus heifer calves is a potential option to reduce predicted farm-level GHG-EI. Weiske et al. (2006) found 4.9-6.7% decreasing in whole farm GHG-EI prediction when selling surplus heifer as newborn, compared with raising them until first calving. Genomic testing newborn calves allow predicting future milk production performance. Thus assuming a good reliability of genomic testing, replacement heifer culling decision can be made early in lifespan (Schefers and Weigel, 2012), which may be put to use for reducing GHG emission (kg CO_2 eq. per year) from replacement heifers.

Comparing to a herd with 20% culling rate, a herd with 40% culling rate herd would increase GHG emission (kg CO_2 per year) from replacement heifers and may reduce the average milk productivity (kg milk per cow per year) because of fewer adult cows, it is possible to turn the aggressive culling into a long-term mitigation option. Milk production per cow per year in the US increased from 2,074 to 9,193 kg (443%) between1944 to 2007 (Capper et al., 2014). From 2009 to 2015, Holstein milk productivity (kg per cow per year) improved from 1.0% to 1.5% annually in the U.S. (Council of Dairy Cattle Breeding, Trend in Milk BV for Holstein or Red & White, Bowie MD). Genetic selection contributes 55% to the milk productivity improvement (Shook 2006). Higher culling rate (40%) accelerates the herd turnover, which improves milk productivity faster than a 20% culling rate herd. In the long term, 40% culling rate herd with 1.5% milk productivity rate may have greater milk productivity (kg milk per cow per year) comparing with a 20% culling rate herd with 1% milk productivity rate. The greater milk production (kg milk per year) may dilute the greater farm-level GHG emission (kg CO_2 eq. per year) amount from a larger number of replacement heifers in the 40% culling rate herd and result in a lower GHG-EI. Future research is needed to evaluate the effect of the interaction between culling rate and genetic selection on dairy farm GHG-EI.

2.4 Reproduction and health

Reproduction and health influence GHG-EI indirectly through changing milk productivity (kg milk per cow per year) (Bell et al., 2011; Knapp et al., 2014; Garnsworthy, 2004). Good reproduction and health ensure cows can fully express their genetic potential for productivity. As discussed above, increasing milk productivity reduces the GHG-EI. Herds with good reproduction and health (10% involuntary culling due to sickness or breeding failure) have a lower demand of replacement heifer comparing with a herd with 20% involuntary culling. Fewer replacement heifers decreases the GHG emission (kg CO_2 eq. per year) from raising heifers before 1st lactation (Garnsworthy, 2004; Bell et al., 2011). Shorter productive life may reduce the herd average milk productivity (kg milk per cow) by reducing manure cow number.

Disease and reproductive failure have detrimental effects on milk production, conception time, calving interval, and productive life, all of which lead to greater GHG-EI.

Poor reproduction translates into extended calving interval due to insemination failure, abortion, etc. Bell et al. (2011) found that prolonged calving interval and greater culling rate increase GHG-EI from these emission sources: enteric fermentation, manure and soil, energy use, fertilizer production, and concentration production. Garnsworthy (2004) found that delaying the age at first calving from 24 months (ideal situation) to 27 months would increase herd level CH_4 emission (t per year) by 6%. Late age at first calving (27 months) retained more heifers in the herd, which produces CH_4 without producing milk and eventually increase CH_4 (t per year) on herd level (Garnsworthy, 2004).

Improvement of reproductive performance will reduce GHG-EI indirectly. Choosing appropriate methods depends on farm's current performance. Synchronization programs and timed AI are common strategies to increase service rate and conception rate. Giordano et al. (2012) summarized that the results of synchronization programs and timed AI varied according to current conception rate. These strategies improved reproductive performance and farm profit if the current conception rate is relatively low; however, the effects were smaller in the well managed herd. In recent years, advanced technologies have been commercialized to help detect estrus, such as embryo transfer, gender selected semen (sexed semen). The accuracy of heat detection technologies is not consistent across different technologies (Saint-Dizier and Chastant-Maillard, 2012). In the financial aspect, advanced heat detection tool is usually costly. Implementation of advanced heat detection technologies needs a careful investigation to make sure whether it is suitable for the herd and how much effort the heat detection technology can provide to avoid the reduction in reproductive performance. Partial budget on the heat detection monitoring technology is necessary before a decision is made to adopt the advanced heat detection technology. Sexed semen is used to produce more heifer calves and accelerate genetic selection. Future research is needed to quantify the effects of advanced reproductive technologies on GHG-EI.

Health is another factor affecting farm-level GHG-EI indirectly through productivity, longevity, and fertility. Health status, especially transition cow health, influences productive and reproductive performance. Immune function reduction for cows during the transition period leads to greater risk of uterus infection, which associates with retained placenta, metritis, and endometritis (LeBlanc, 2010). Specific disease (i.e., metritis, retained placenta, dystocia, stillbirth, etc.) may delay conception (Fourichon et al., 2000). Diseases have detrimental effects on milk production (Fourichon et al., 1999; Wilson et al., 2004). For some diseases (mastitis, metritis, lameness, etc.) treated with antibiotics, milk withdrawal further decreases the sellable milk production (Pol and Ruegg, 2007) and further reduce the farm-level GHG-EI. Diseases also increase mortality and involuntary culling rate (Rajala-Schultz and Gröhn, 1999a, b,c), which increase the requirement for more replacement heifers and thus elevate the farm-level GHG-EI. Health status may have potential direct influences on GHG-EI. No research has been conducted on the direct influence of disease on GHG-EI yet, but theoretically, it may occur. Subacute acidosis, which is characterized by a ruminal pH decline ($pH < 5.6$ for 3-5 hours in a day), may reduce enteric CH_4 emission (L CH_4 per h) by inhibiting the methanogen activity temporarily (Hook et al., 2011).

Poor health status decreases the herd productivity and feed efficiency, which indirectly leads to greater GHG-EI. Improving health management could help reduce GHG-EI (Knapp et al., 2014; Hristov et al., 2013b). Cows fed appropriately are also healthier and have stronger immune systems, which lowers the risks of metabolic diseases (VandeHaar and St-Pierre, 2006). Quantitative estimates of health status on farm-level GHG-EI is currently lacking. Combination of disease model and whole-farm environment model may be a useful tool for such studies.

2.5 Greenhouse gas emission and other environmental issues

Leaching and volatilization of N from manure are major concerns for dairy farm nutrient management. Leaching implies nitrate (NO_3^-) loss to water bodies, and volatilization involves ammonia (NH_3) release into the atmosphere. Both leaching and volatilization result in manure nutrient loss as fertilizer and may have harmful environmental and human health consequences (Jarvis, 1993). Mitigation options on GHG emission sometimes are consistent with reducing NH_3 and NO_3^- losses. Brink (2001) estimated that if the dairy farmers in the European Union implemented systematic NH_3 abatement strategies, the reduction would be 11%, 12%, and 15% for NH_3, N_2O, and CH_4, respectively. Results showed that abatement through manure injection to soil and housing changes (frequent removal of slurry or manure, reduce waste exposure time to oxygen) were major mechanisms responsible for the simultaneous decrease in N_2O and NH_3 emissions (Brink, 2001; Brink et al., 2001). Nitrogen use efficiency (the ratio of milk N over the feed N intake) is always below 30% on dairy cows, which indicates that over 70% of dietary N excreted in manure or urine (VandeHaar and St-Pierre, 2006). Increasing N use efficiency in cows by reducing dietary N content could reduce N_2O and NH_3 emission per kg DM (VandeHaar and St-Pierre, 2006; Montes et al., 2013b). Furthermore manure management (manure acidification, cover, or crust) has the potential to reduce NH_3 and CH_4 at the same time (Montes et al., 2013b; Hou et al., 2015). Shortened manure storage time would reduce the emission of CH_4 and N_2O. Some GHG mitigation option may have the potential to increase NH_3 emission.

For example, manure aeration or composting reduced CH_4 emission but promoted nitrification process, in which greater N_2O released from manure (Montes et al., 2013b).

Two factors promote NO_3^- leaching from soil to underground water: excess NO_3^-content and drainage of the soil (Di and Cameron, 2002). Reducing excess dietary N could reduce manure N content, which indirectly decreases N leaching after land application. Soil water content has a dual effect on N leaching and N_2O emission from denitrification. High water input (irrigation or precipitation) into soil promotes N_2O emission from denitrification; meanwhile, the high water input inhibits N leaching (Di and Cameron, 2002). Well-drained soils have a high risk of N leaching; however, these type of soils have lower rates of denitrification as they are more aerobic (greater presence of oxygen; Jarvis, 1993, Weier et al., 1993).

2.6 Summary of farm GHG mitigation via management strategies

Nutrition and manure management have the potential to reduce dairy farm GHG-EI directly while genetic selection, reproduction, and health status have indirect effects through changing the whole-farm milk productivity (kg milk per cow per year). The interaction of these factors is also important to consider. For example, increasing milk productivity through genetic selection may reduce the farm-level GHG-EI, however, the higher milk productivity may require greater DMI if feed efficiency is assumed constant. The greater DMI may lead to greater manure N and OM excretions, which potentially increases N leaching and volatilization. Furthermore, milk production improvement may suppress fertility (Shook, 2006; Nebel and McGilliard, 1993; Wiltbank et al., 2006) and increase disease risk. Both of these adverse effects may reduce the farm-level milk productivity and further increases the GHG-EI. The dissertation aims at estimating the interaction among management aspects, especially the commonly used management strategies, and the associated impacts on dairy farm GHG-EI and profitability.

2.7 Modeling techniques used in this dissertation

This section reviews major modeling techniques and simulation tools used in this dissertation: Life cycle assessment (**LCA**, Chapter 5 and 6), Integrated Farm System Model (**IFSM**, Chapter 3), and Markov Chain Model (Chapter 4). Furthermore, this section will focus on an analysis of LCA studies of milk produced on dairy farms from the literature.

2.7.1 Life cycle assessment

Life cycle assessment is a widely accepted method to quantify the environmental impact (GHG emission, acidification, eutrophication, water usage, land demand, etc.) of livestock production, and to identify and compare mitigation options (Beauchemin and McGeough, 2013). Key components in an LCA study include system boundary, inventory analysis, functional units, and allocation factors (Klöpffer, 1997; Beauchemin and McGeough, 2013).

System Boundaries. System boundaries vary according to the objective and scope of the study but are critical to establishing because they define the processes to be included in the assessment (International Organization for Standardization, **ISO**, 2006). An LCA can be used to estimate the environmental burdens of dairy products within different system boundaries, such as ‘cradle-to-farm gate’ or ‘cradle-to-grave’ (Thoma et al., 2013b; Klöpffer, 1997). It has been shown that the processing, transportation, marketing, and refrigeration on milk post-farm gate are relatively minor sources of emission compared to the emissions that occur before and on-farm. Thus, the cradle-to-farm gate LCA focuses on the dairy farm and inputs to the dairy farm. The primary emission sources on a dairy farm include crop and pasture production, enteric CH_4 emission, manure management emission; while the secondary on-farm emission sources include transportation, electricity, machinery, purchased feed, fertilizer, pesticide, etc. (Rotz et al., 2013). Thoma et al. (2013b) found 72% of the cradle-to-grave GHG-EI was on a farm (feed production, enteric fermentation, manure management, and farm electricity use). The cradle-to-grave LCA extended the cradle-to-farm gate system boundary to the purchase and disposal of dairy products with additional emission sources, including processing plant, wholesale, retailer, and consumer (Rotz et al., 2013; Thoma et al., 2013b).

A Dutch study estimated the off-farm cropland demand was 0.7 ha/cow per year on an organic dairy farm, in addition to 1.1 ha/cow per year on-farm land demand (Thomassen et al., 2008a). Including the off-farm cropland demand would decrease the Dutch organic dairy farm GHG emission from 13,405 kg eq. CO_2 per ha to 8,332 kg eq. CO_2 per ha. Whether to include the off-farm cropland or not influence on the result of GHG emission per ha of land. A clear definition of system boundary is needed to enable the comparison of farm-level GHG emission per ha between different farms, regions, or production systems.

Functional Unit. In LCA, the functional unit is the unit of production to which the emission will be assigned. A kilogram of ECM is often used as the functional unit for milk. However, investigators interested in land use or resource allocation are more likely to estimate GHG emission per ha in a farm to address the issues from grazing density or feed production (Beauchemin and McGeough, 2013; Salou et al., 2017). Different functional units may sometimes lead to contradicting results. For example, extended grazing time is always considered to increase enteric CH_4 emission per kg ECM because of higher forage intake from pasture; however, pasture has been promoted for decades to reduce farm-level GHG emission per ha due to its high potential for soil carbon sequestration (Rotz et al., 2009; Osterholz et al., 2014; Bell et al., 2011). Using different functional units may lead to contradicting results and make it hard to plan adequate management strategies. A common functional unit is also essential for comparing results across studies. In the LCA of milk, GHG emission (kg CO_2 eq.) per unit of milk production (ECM or fat-and-protein-corrected milk production (**FPCM**)) is often called ‘carbon footprint of milk.'

Allocation factor. Method of allocation partition the environmental impacts (calculated in the inventory analysis) across multiple co-products and is one of the most discussed methodological issues in the field of LCA. (Mackenzie et al., 2016). On the dairy farm, milk is the primary output. However, other products can be considered, such as beef, replacement heifers, manure or manure by-products (e.g., electricity). The process of allocating impacts to the individual products ensures that the analysis does not overstate the environmental burden of dairy production and ignore the contributions of the co-products (Casey and Holden, 2005; Cederberg and Stadig, 2003). International Dairy Federation (2010) developed a mass allocation factor calculation based on the expected ratio of meat and milk from a “typical” dairy farm. This method is commonly used in dairy farm LCA studies (Rotz et al., 2013; Beauchemin and McGeough, 2013):

$$Allocation\ factor\ to\ milk = 1 - 5.7717\ \times\ (M_{meat}\ /M_{milk}) \qquad \text{[eq. 2.1]}$$

Where M_{meat} is based on the annual meat (culled cows and bull calves) sale amount; M_{milk} is the annual milk sale amount.

Allocation factor calculation approach may change depending on the objective and scope of the LCA study, as well as the data quality (Rice et al., 2017). Other allocation methodologies have been established, such as the economic allocation, biophysical allocation, protein allocation (Thoma et al., 2013a; Mackenzie et al., 2016). Rice et al. (2017) compared 7 different allocation approaches in an LCA of Irish pasture-based dairy farms based on a survey of 256 dairy farms.

The evaluation showed that the allocation factor to milk varied from 75% (1.04 kg CO_2 eq. per kg FPCM, physical causation allocation) to 89% (1.22 kg CO_2 eq. per kg FPCM, the mass of carcass allocation). Each of the 7 allocation approaches has its advantages and shortcomings. For example, the mass method using the mass of live weight or carcass weight (eq. 2.1) overcomes the local market price variations in the economic allocation, which further enables the comparison among regions or countries.; however, this method treats culled cow and calf sale weight equally, ignoring stomach content, and is largely influenced by the replacement rate (Rice et al., 2017).

Inventory Analysis. Inventory analysis calculates the environmental impacts (i.e. GHG emission) of resources (feed, fertilizer, electricity, cows, etc.) that are used for producing one functional unit (kg of ECM, kg of FPCM, ha of land, MCal produced, etc.) (Klöpffer, 1997; Thoma et al., 2013b). The study objective or scope determines the selection of inventory analysis calculation approach of either emission factors of each resource or emission prediction models to estimate the GHG emission (kg CO_2 eq.) per functional unit. Emission prediction models contain specific variables such as milk fat and dietary NDF content in the Moraes et al. (2014) enteric CH_4 emission model. Emission factors (kg CO_2 eq. per kW electricity, per kg DMI, etc.) are the generic environmental impacts data per unit of resource input. The emission factors published by IPCC (2006) are widely used for the inventory analysis, especially if specific emission data or emission prediction model are not available. The IPCC emissions factors have three different tiers with different specification on regions, production system, and climate condition around the world, which enables the comparison across countries and regions. The variation in the inventory analysis results from different models or emission factors is large (Crosson et al., 2011). Thoma et al. (2013c) estimated the enteric CH_4 emission of 16 rations from published studies using 13 enteric CH_4 prediction models and emission factors. The root-mean-square-error (**RMSE**) of each prediction model or emission factor varied from 0.12 to 1.31 across the 16 different rations. For each model or emission factor, the relative errors between the predicted values and experiment measured values were not consistent in either positive or negative direction.

The inconsistency of all 4 key components makes the comparison difficult between LCA studies, and they may lead to a confusing interpretation of results. Crosson et al. (2011) reviewed and compared 31 published whole-farm GHG LCA models on beef and dairy farms. Each whole-farm model may have its system boundary, inventory analysis approach, allocation factor, and assumptions, which explained the considerable differences in the carbon footprint of milk and GHG emission (kg CO_2 eq.) per ha of land or per cow, among studies.

2.7.2 Integrated farm system model (IFSM)

Computer modeling has been widely used for simulating farm-level LCA to estimate GHG emissions. The whole-farm model describes and quantifies nutrient flow inside of the farm (i.e., N from feed to rumen digestion, digestion to manure N, manure N to soil N) and the material exchange with outside of the farm (i.e., purchasing concentrate feed from outside, Crosson et al., 2011).

Integrated farm system model (**IFSM**, Rotz et al., 2013) is a whole farm process-based model focused on the U.S. livestock industry. The model simulates the crop growth and management, feed storage, machinery, animal (dairy or beef cattle) performance, manure management, GHG-EI, nutrient (C, N, and P) cycle, and profitability (net return on management) for up to 25 yearly scenarios. Each scenario is independent of another one, and the carryover effects between scenarios are not included. Daily weather data of drives the model to simulate farm planting, tillage, harvesting, crop yield, quality, and production cost, etc. The model formulates a least-cost diet based on the feed availability for each animal group to reach certain milk production. Diet formulation also influences the manure composition. Manure nutrient changes during manure storage and after land application are also included in the model Emissions of enteric CH_4, manure management, crop production, replacement heifers, electricity usage, fuel, plastic, chemicals, feed storage are calculated in this model and expressed as kg CO_2 eq. per kg milk. Daily weather variation also influences on the emission calculation, such as manure storage emission, crop field emission, feed storage emission. Although the validation is rare in this type of whole-farm model because of the tremendous difficulties in measuring actual data, the model evaluation still has been done for different parts of the IFSM in several studies (Hoshide et al., 2011; Rotz et al., 2010). As a solid whole-farm LCA model, abundant research projects have been conducted using the IFSM model. Some of those studies are reviewed in the following section that discusses milk LCA studies and findings.

Although IFSM has a very detailed daily simulation that considers the daily weather data (temperature, precipitation, and solar radiation) and many other factors (such as machinery usage, labor usage, feed loss in storage, etc.), it still has some areas may need some future improvement. In the dairy herd section, the daily weather does not influence herd performance, which means neither of the heat nor cold stress is included. The model formulates the least cost diet for a fixed number (6) of cow groups internally based on feed availability and forage-to-concentrate level (low or high). As a result, IFSM is not able to evaluate the effect of dietary changes (such as replacing alfalfa haylage with corn silage, increasing lipid content, etc.) on the farm carbon footprint of milk. In addition to the diet formulation inflexible, the nutritional requirement calculations in the IFSM may need to be updated to the NRC (2001) equations, and the GWP values may need to be updated to the Myhre et al. (2013) 100-year period with climate-carbon feedbacks.

Alternatively, the emission associated with management strategies may be estimated by integrating an LCA into existing management models, such as diet formulation, or optimizers of culling decision models. Some research has been done on estimating GHG-EI through diet formulation models (Moraes et al., 2012). Diet formulation models are usually using linear programming techniques, in which the objective is to minimize the feed cost or maximize profit. Hawkins et al. (2015) developed a farm-level diet formulating linear program model to maximize farm net return and maintaining the same milk productivity. The farm profit ($ per year) decreased by 0.7% to reduce the farm-level GHG emission (kg CO_2 eq. per year) by 5% through changes in diet formulation. If the farm-level GHG emission (kg CO_2 eq. per year) reduction was 35%, farm profit ($ per year) decreased by 24.2% through changes in diet formulation. Diet formulation showed an important implication in dairy farm GHG emission (kg CO_2 eq. per year) mitigation. The mitigation cost through diet formulation became expensive as the GHG emission reduction amount increasing. Admittedly, performance models typically do not include other critical farm components such as manure management or crop production. Thus, adding GHG estimation into these pre-existing models has its limitations, such as missing the whole-farm level trade-offs or ignoring the carryover effects from one farm component to the next.

2.7.3 Markov-chain herd structure model

Markov-chain modeling technique has been used in simulating dairy herd structure in many studies (de Vries, 2004; Cabrera, 2010; Giordano et al., 2012; Kalantari and Cabrera, 2012). Markov-Chain model has multiple states in a continuous process or a system and considers the uncertainty (transition probability) between one state and the next possible state(s).

All the Markov chain models obey the Markov property that the transition from state i to state j depends only on the state currently occupied (Dijkhuizen and Morris, 1997; Hillier and Lieberman, 1990). In previous studies, Markov chain model finds the steady herd structure after a certain management changes, as well as the herd structure during the transition period reacting to the management changes (Kalantari and Cabrera, 2012). Take a monthly Markov chain herd structure model as an example. In any month (state), the total probability of a cow surviving to the next month or getting culled in the current month equals to 1 if only considers two possibilities following states (Kalantari and Cabrera, 2012). More complicated Markov Chain model in dairy research considers multiple statuses in the same state (month, year, or day), such as the pregnancy status, calving status, surviving status, or health status. A sub Markov chain module is built for each status; then all the sub modules integrate to form a complete model that controls the interactions between modules. One potential limitation of the Markov chain model is that the model easily becomes very complex and slow as more status and variables are included into the model (Cabrera, 2010).

Markov chain model can combine with linear programming to find the optimal culling decisions. Cabrera (2010) maximized the net revenue of each state in the linear programming part, and the used the Markov Chain model to build the herd structure. After the Markov Chain model reached the time horizon limits, the optimization model started to search for an optimal solution from the end of the simulated time horizon backward to the present time (Yates and Rehman, 1998). The optimal solution was a series of status changes at each state.

Although Markov chain model has not commonly in environment impact research, it simulates the development of scenarios across time and considers the uncertainties. Meinshausen et al. (2009) developed a Markov chain model with Monte Carlo simulation to estimate the probability of limiting global warming by 2 °C from the pre-industrial temperature before 2100 in different emission scenarios (such as decreased usage of fossil fuel). In dairy farm GHG research, Markov chain model has the potential to simulate the herd demographics to reflect the management strategy changes (such as culling rate) and further assist the farm-level evaluation of management changes on the carbon footprint of milk. Markov chain model can also estimate the dairy industry changes (number of farms, farm size, etc.) on environmental resource uses (land, water, feed) and carbon footprint of milk in the long-term.

2.7.4 Milk carbon footprint

Numerous partial LCA studies (cradle-to-farm gate) have been conducted on dairy farms to estimate the carbon footprint of milk and compare different management strategies on the carbon footprint. Although the direct comparison of LCA results across studies can be misleading (see above), the differences in results help elucidate relationships between management practices and carbon footprint under different scenarios.

The carbon footprint per unit of milk varied dramatically among studies. In the literature, the carbon footprint of milk for conventional dairy farms was between 0.46 to 1.5; the range was between 0.65 to 1.2 in grazing conventional farms (heavily pasture based) and 1.19 to 1.57 in organic dairy farms (Crosson et al., 2011b). Several studies compared organic, grazing, and conventional dairy farms with the same LCA model and showed different carbon footprint of milk among production systems. O'Brien et al. (2014) built a cradle-to farm gate LCA model to compare the carbon footprint of milk in Irish grazing farms, UK confinement system, and US confinement system. Results showed that the carbon footprint of milk was the lowest in UK confinement farms (895 kg CO_2 eq. per t ECM), followed by the US confinement farms (898 kg CO_2 eq. per t ECM) and Irish grazing farms (914 kg CO_2 eq. per t ECM); however, the differences among systems were small. Including soil carbon sequestration changed the ranking and enlarged the differences among systems. The lowest carbon footprint was in Irish grazing farms (837 kg CO_2 eq. per t ECM), followed by the UK confinement farms (884 kg CO_2 eq. per t ECM) and the US confinement farms (898 kg CO_2 eq. per t ECM). Pasture soil carbon sequestration was zero or a very low value in the confinement systems in the US and UK because of the zero or low pasture demand; however, accounting for the relatively high soil carbon sequestration amount in Irish grazing farms largely reduced the carbon footprint.

Most of the previous studies showed higher carbon footprint in organic dairy farms were higher than in the conventional dairy farms than organic dairy farms (Crosson et al., 2011b). Despite the total GHG emission (kg CO_2 eq. per cow year) may be lower in the organic farms due to lower DMI, however, the lower milk productivity in organic farms burdens more carbon footprint of milk (Olesen et al., 2006; Thomassen et al., 2008a; de Vries and de Boer, 2010; Dutreuil et al., 2014). In contrast, some studies found lower or similar carbon footprint of milk from organic dairy farms, compared with the intensive conventional milk production systems (Cederberg and Mattsson, 2000; Bos et al., 2014; Haas et al., 2001). The greater reduction of N_2O emission in organic dairy farms, including both direct (lower synthetic fertilizer usage) and indirect emission (lower N leaching), compensated the greater enteric CH_4 emission from higher forage intakes, and ultimately reduced the carbon footprint (Haas et al., 2001; Cederberg and Mattsson, 2000; Bos et al., 2014).

Extensive grazing has been promoted as an approach to reduce feed cost and carbon footprint because the pasture has lower emission than row crops or can sequester carbon by building soil OM (Machmuller et al., 2015; Stockmann et al., 2013). The impact of extending grazing period on dairy farm carbon footprint depends on the changes in milk production and climate limitation. The carbon footprint of grazing farms may be higher than the conventional farms if milk productivity was lower in the grazing farms. Dutreuil et al., (2014) conducted a LCA study based on a survey of Wisconsin dairy farms and found that grazing farms had a higher carbon footprint (0.66 kg CO_2 eq. per kg ECM) than the conventional dairy farms (0.58 kg CO_2 eq. per kg ECM) primarily because of the lower milk productivity (7,256 kg ECM per cow per year and 9,820 kg ECM per cow per year in grazing and confinement farms, respectively). Although the farm-level GHG emission (kg CO_2 eq. per year) was lower in the grazing farms, the lower milk production of cows in the former increased the carbon footprint of milk to above that of the conventional farms. A Higher proportion of feed from pasture with the same maturity also increases the diet CP content, which has the potential to increase manure N_2O emission (Wales et al., 1998).

Reducing the forage-to-concentrate ratio (from 83%, 90%, and 93% to 57%,68%, and 80% in early-, mid-, and late-lactation cows) and increasing milk productivity by 5% or 10% in organic and grazing dairy farms reduced carbon footprints of milk and GHG emission with 2 different functional units (kg CO_2 eq. per cow per d, kg CO_2 eq. per farm per year) (Dutreuil et al., 2014). In grazing and organic dairy farms, reducing forage-to-concentrate ratio increased milk productivity, the GHG-EI from concentrate feed production (on-farm or off-farm) and decreased the emission from the housing, grazing, and forage feed production (Dutreuil et al., 2014).

However, if milk production was the same or even higher in the pasture-based dairy farms, the carbon footprint of milk was lower in the pasture-based dairy compared with confinement dairy farms (Bos et al., 2014). O’Brien et al. (2016) estimated the effect of grazing practices in carbon footprint on Irish dairy farms. Results showed that higher milk productivity per cow, extending grazing season length and increasing percentage of grazed grass in total DMI significantly decreased the carbon foot print. Both Irish and New Zealand studies (Basset-Mens et al., 2009; Yan et al., 2010) demonstrated that longer grazing period, when associated with a reduction in stocking density and increasing total DMI, led to higher milk production per cow and lower carbon footprint of milk. In the Wisconsin study of Dutreuil et al. (2014), the authors also found incorporating longer grazing period may reduce the carbon footprint if milk production is kept constant.

Rotz et al. (2010) reported that incorporating a higher proportion of grazing practices (6-month grazing period in a year) into confinement dairy farms and maintain the same milk productivity (8,500 kg ECM per cow per year) reduced the farm-level carbon footprint of milk by 10% (0.69 vs. 0.62 kg CO2 eq. per kg ECM) in a 60-cow dairy farm. Increasing the grazing period in a year also reduced the secondary GHG-EI (including electricity and fossil fuel) by 14% due to the shorter lighting hours and fewer machinery operations.

Manure management type. As the second greatest contributor to the cradle-to-farm gate carbon footprint, manure management type has a substantial impact on milk carbon footprint (Thoma et al., 2013b; Bos et al., 2014). Thoma et al. (2013b) stated that anaerobic lagoon on larger farms and deep bedding on smaller farms were associated with greater GHG emission (primarily CH_4) than other systems such as a dry lot or solid storage that had either shorter storage time or more aeration. Solid manure piles in smaller farms show a benefit in reducing farm carbon footprint per kg milk. The larger farms tend to handle liquid manure because of the housing type (free-stall in larger farms vs. tie-stall in smaller farms). Flushing and scraping are commonly used in free-stall dairy farms to collect manure and increases the manure moisture content (Meyer et al., 2011). Aguirre-Villegas and Larson (2016) conducted a farm-level LCA to evaluate the effects of manure management systems on the carbon footprint of milk and GHG emission (g CO_2 eq. per t manure and g CO_2 eq. per animal unit per d). Longer storage period (12 vs. 6 vs. 3 months vs. no storage) and no crust increased the carbon footprint and the emission expressed per t of manure or per animal per day. Implementing manure process steps (solid-liquid separation, sand separation, or anaerobic digester) showed the potential to reduce the farm-level carbon footprint of milk and GHG emission (g CO_2 eq. per t manure and g CO_2 eq. per animal unit per d) in the same study.

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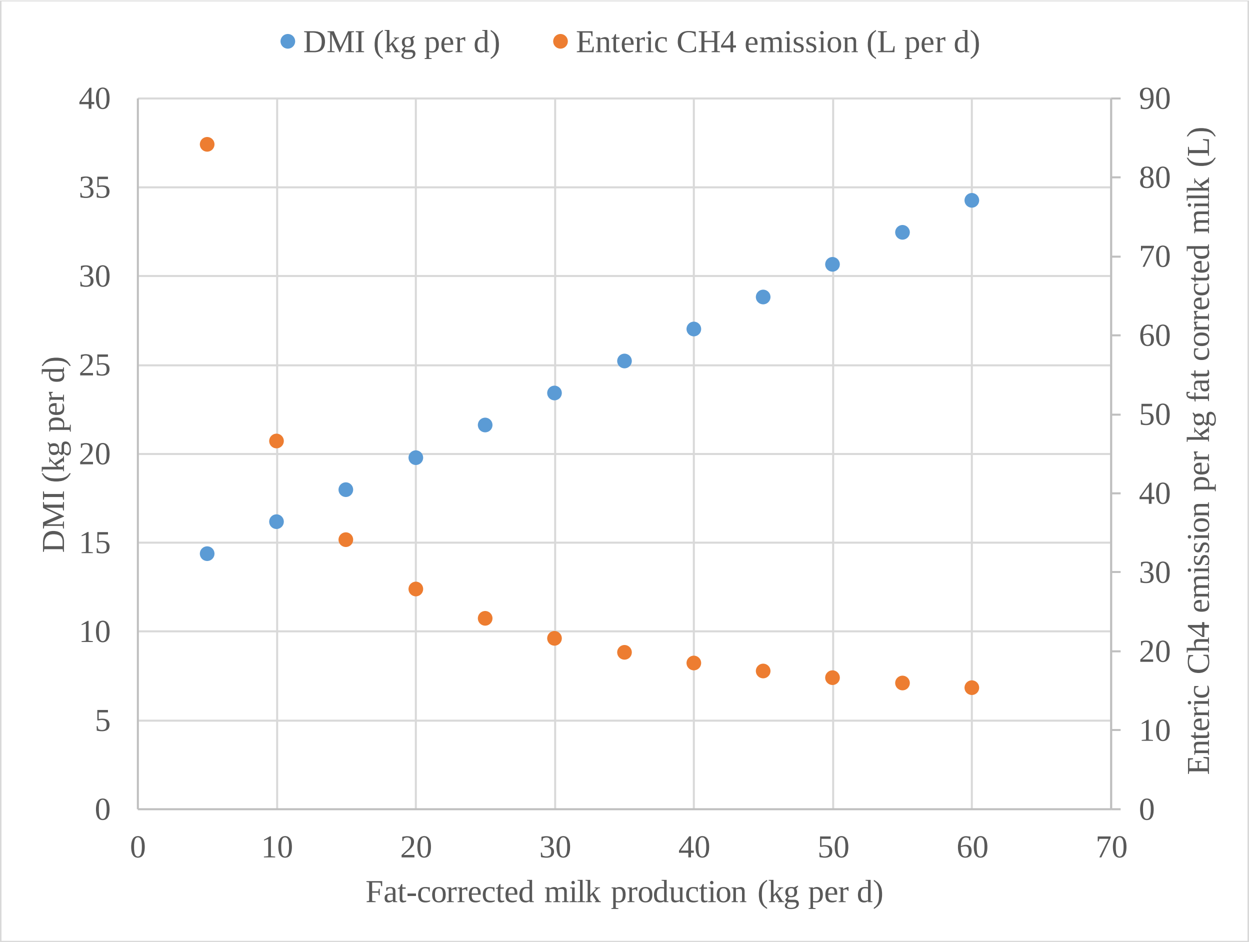
Figure 2.1 Relationship between daily fat-corrected milk production (kg per cow per d), daily dry matter intake (kg per cow per d), and the enteric CH_4 emission (L) per kg of fat corrected milk production. The cow is assumed to be in the 15th week in lactation with 680 kg body weight. Dry matter intake calculation equation is from NRC (2001); enteric CH_4 emission prediction model is the linear model from Ramin and Huhtanen (2013).



Chapter 3

Optimizing productivity, herd structure, environmental performance, and profitability of dairy cattle herds

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3.1 Abstract

This study used the Integrated Farm System Model to simulate the whole-farm performance of a representative Wisconsin dairy farm and predict its economic and environmental outputs based on 25 years of daily local weather data (1986 to 2010). The studied farm, located in southern Wisconsin, had 100 milking cows and 100 ha of cropland with no replacement heifers kept on the farm. Sensitivity analyses were conducted to test the impact of management strategies on energy corrected milk production (**ECM,** 4.0% fat and 3.5% protein), net return to management, and greenhouse gas (**GHG,** including biogenic CO_2) emission. The management strategies included: 1) target milk production, for which the model optimized available resources in order to attain; and 2) herd structure, represented by the percentage of first lactation cows. Weather conditions affected the outputs by changing the farm quantity and the quality of produced feed resources. As expected, when target milk production increased, the ECM increased positively and linearly to a certain level, and then it increased non-linearly at a decreasing rate, constrained by available feed nutrients. Thereafter, the ECM reached the maximum potential milk production and remained flat regardless of higher target milk production input. Greenhouse gas emissions decreased between 3.4% and 7.3% at different first lactation cow percentages. As the first lactation cow percent increased from 15% to 45% in 5% intervals, GHG increased between 9.4% and 11.3% at different levels of target milk production. High percentage of first lactation cows reduced the maximum potential milk production. Net return to management had a similar changing trend as ECM. As the target milk production increased from 9,979 to 11,793 kg, the net return to management increased between 31% and 46% at different first lactation cow percentages. Results revealed a win-win situation when increasing milk production or improving herd structure, which concurrently increased farm net return to management and decreased GHG emissions.

Key words: Greenhouse gas emission, farm profitability, simulation model

3.2 Introduction

Agricultural greenhouse gases (**GHG**) constitute 8.1% of total US GHG emissions (EPA, 2014). Livestock enteric fermentation and manure methane emission account for 34.4% of total anthropogenic CH_4 emission (EPA, 2014) and the dairy industry contributes 4% to global GHG emissions (FAO, 2010). Dairy farm GHG includes CO_2, CH_4, and N_2O from enteric fermentation, manure handling, crop production, and other processes (Rotz et al., 2010). Given these impacts, dairy cattle farming faces a major challenge: to reduce GHG emissions while maintaining or increasing profitability. Crosson (2011) reported that animal performance, including production and replacement decisions, influence the GHG from dairy farms. Increasing milk production through genetic and feeding improvement can decrease the per kg milk GHG (Rotz et al., 2010). Dutreuil et al. (2014) studied the economic effects of GHG mitigation strategies, such as changing the grazing schedule, the forage ratio in diet, and manure handling methods. Dutreuil et al. (2014) found that grazing cows in conventionally managed dairy farms would decrease GHG and increase net profit while keeping milk production constant. Also Dutreuil et al. (2014) reported that increasing concentrate supplementation in grazing farms would decrease GHG emissions and increase milk production, which might increase the net profit depending on the increased amount. Likewise, adding an extra covered manure storage facility decreased GHG emissions in conventional dairy farms because some GHG from manure was prevented from escaping to the atmosphere (Dutreuil et al., 2014). Garnsworthy et al. (2012) found that improving reproductive performance and replacement would reduce greenhouse gas emissions at the herd level by reducing the number of replacement animals, calving interval length, and increasing the average milk production.

Due to the complex interaction of farm dynamic processes, whole farm systems need to be included in joint GHG emissions and economic studies (del Prado et al., 2010). The Integrated Farm System Model (**IFSM,** Rotz et al., 2013), which assesses the combined impact of the main dairy farm factors, is uniquely positioned to conduct this kind of study (Belflower et al., 2012; Dutreuil et al., 2014; Rotz et al., 2014)

The present study uses the IFSM to estimate the concurrent environmental and economic effects of two farm management strategies: 1) target milk production, the production goal for which the model optimizes feed allocation, and 2) the proportion of cows in first lactation, a proxy of reproduction and replacement management.

3.3 Materials and Methods

3.3.1 The IFSM Model

The IFSM was used in this study to assess the economic and environmental output of a representative Wisconsin dairy farm. Farm performance was simulated using 25-yr of daily weather data for Madison, Wisconsin (1986-2010, Dane County Regional-Truax Field, WI, 43.13N 89.33W, Elev. 259 m). The IFSM was applied to integrate crop growth, feed storage, machinery usage, and herd management to simulate farm performance with the available on-farm resources and purchased feed (Rotz et al., 2013). Daily weather data were used to estimate the annual farm-produced feed resources by simulating crop growth, tillage, and harvest. In addition, weather data were used in the manure handling modules to estimate the manure ammonia emission as a function of temperature and wind speed. Weather data did not affect herd performance (Rotz et al., 2013). The IFSM model simulates each year separately and does not consider carryover effects from one year to the next, i.e., it simulates one year under historical yearly weather variability (Rotz et al., 2013).

The herd management module inside the IFSM optimizes feed allocation by maximizing the milk production and minimizing purchased feed cost. The herd module prioritizes on-farm feed use, supplementing with purchase feed as needed.

3.3.2 Farm characteristics

The representative dairy farm had 100 milking large Holstein cows (including dry cows) and 100 ha of rented cropland (43 ha alfalfa and 57 ha corn). Cow's mature weight was 759 kg per cow. The farm's topography was gently sloping. The farm soil type was medium clay loam with a soil phosphorus level of 30 to 50 ppm.

Alfalfa was planted and planned to have a 3-year stand life. A yield adjustment of 90% was set to mimic the field conditions in Wisconsin. The yield adjustment factor is used to give some relative control over the simulation process to adjust the model prediction; the shorter the growth period is, the lower the adjustment factor (Rotz et al., 2013). The farm applied 20% of the total available cattle manure to the alfalfa land. A population of 11,300 plants per ha was used on the corn crop. The relative maturity index was 110 d. The grain yield adjustment was 85% and the silage yield adjustment was 100% (no adjustment). The remaining 80% of the available manure was applied to the cornfields, along with 20 kg per ha of nitrate fertilizer.

The on-farm machinery included one 47 hp (35 kW) tractor, one 87 hp (65 kW) tractor, and one 108 hp (80kW) tractor. The 47 hp tractor was used for mowing, raking, drill seeding, and miscellaneous transporting. The 87 hp tractor was used for baling, feed mixing, silo filling, field cultivation, row cop planting, round bale loading, and pumping manure. The 108 hp tractor was used for forage chopping, manure handling, plowing, and disking. Grain harvest was custom hired. All the following tillage and planting operations were conducted only on suitable days with an upper layer soil moisture content allowing machine tractability. Alfalfa seeding started as early as April 25th and corn planted on or after May 5th. The following earliest operation dates were input, but the actual dates varied depending on weather, soil, or crop moisture conditions. Alfalfa had 4 cuttings per year: the earliest harvesting times fell around May 28th, July 1st, August 17th, and October 15th as weather permitted. Corn was harvested for silage after September 1st, for high moisture grain after October 1st, and for dried grain after October 21st. The high quality forage was stored in a 281-tonne DM bunker silo; grain crop silage was stored in a similarly sized bunker, and the high moisture grain was stored in a stave silo with 259 tonne DM capacity stave silo.

The farm used a flat barn parlor and straw-bedded free stalls with natural ventilation. Cows were bred and calved year-round. A loader and a mixer wagon were used to feed grain and silage. The cows were fed a low forage diet, which maintained the minimum amount of dietary fiber (relative forage to grain ratio in diet of 0.57, 0.68, and 0.80 for early, middle, and late lactation cows). Hay was provided in a self-fed hay feeder. The manure was collected and hauled using a scraper and slurry pump and then applied to the field within two days. Milk price was set at $0.40 per kg, slaughter price at $1.21 per kg, replacement heifer at $1,500 per animal, and the calf price at $150 per animal. The cost of purchasing replacement animals was the product of replacement heifer price times the number of first lactation cows. The cost of purchasing replacement animals was a fixed value across target milk production levels. Annual per cow fixed expenses were $372, including $110 for veterinary and medicine costs, $65 for semen and breeding costs, $150 for animal and milking supply costs, $12 for animal insurance, $10 for animal hauling costs, and $25 for Dairy Herd Improvement Association registration costs.

3.3.3 Net return to management

The model calculated the farm net return to management by subtracting the cost of production from the sum of all income sources. The cost of production included equipment, facilities, energy, labor, custom operation, land rental, purchased feed and bedding, animal purchase and livestock expenses, milk hauling and marketing cost, property tax, and the cost of seed, fertilizer, and chemicals used on the cropland. The revenues stemmed from milk sales, extra animal sales, and extra feed and crop sales (Rotz et al., 2013).

3.3.4 Sensitivity analyses

Sensitivity analyses were conducted on the target milk production, first lactation cow percent, and their interactions to test their impact on environmental and economic outputs. This study evaluated two key user-input variables of the IFSM model: target milk production and first lactation cow percent. Target milk production was varied to estimate the maximum potential milk production, which represented the biological production limitation. The model optimizes the allocation of on-farm and purchased resources to maximize the actual milk production to approach the target milk production. This maximum potential milk production represented the maximum biological milk production that the herd could actually attain due to the individual cow rumen size limitation and available feed fiber contents and digestibility. As the farm can always purchase feed, the rumen volume determines the biological maximum milk production. Thus, increasing the target milk production in the input estimated the cows' maximum capacity for producing milk. First lactation cow percent represented the herd structure that was closely associated with reproductive efficiency and replacement decisions. Target milk production was increased from 9,979 kg/cow per year to 11,793 kg/cow per year by an interval of 227 kg; the first lactation cow percentage was increased from 15% to 45% by intervals of 5%. The lowest first lactation cow percentage (15%) might not be realistic in commercial dairy farms; however, this extraordinary value was used to expand the sensitivity test range.

3.3.5 GHG emissions

Greenhouse gas (GHG) emission was expressed as CO_2 equivalent including biogenic CO_2 per kg of ECM (kg CO_2 eq. per kg ECM). Global-warming potentials of CH_4 and N_2O that are 25 and 298 times greater than CO_2, respectively, were used to calculate the CO_2 equivalents (Rotz et al., 2013). Biogenic CO_2 represents the net CO_2 assimilated from and released to the atmosphere, including assimilation in plant growth and animal body, and carbon sequestration (Dutreuil et al., 2014, Rotz et al., 2014). Carbon sequestration occurs when depositing manure to cropland as fertilizer. It is a chemical process where partial manure carbon is fixed into soil carbon or plants. Therefore, including biogenic CO_2 reduces the overall farm GHG emissions (Rotz et al., 2014).

3.4 Results and Discussion

3.4.1 Output Variation

Due to the separate calculation for each year and no carry-over effects in the IFSM model (Rotz et al., 2013), the large variation in the results at one given management level is explained by the difference in each year’s weather. These weather differences are primarily caused by variation in feed production, which affects the farm’s overall outcomes.

Table 3.1 shows the annual on-farm feed production, including high-quality hay, low-quality hay, high-quality silage, grain crop silage, high-moisture grain, dry grain, and forage. The farm produced feed resources determine the total feed cost (Table 3.2). When the target milk production was attained, milk income over feed cost reflected changes in feed purchase cost because the milk income was fixed with constant production. The highest milk income over feed cost ($2,656.67 per cow) was 38.8% greater than the lowest milk income over feed cost ($1,914.36 per cow). This difference represented the yearly variation in quantity and quality of farm-produced feed as affected by weather.

3.4.2 Milk production

As expected, the ECM (4.0% fat and 3.5% protein) increased linearly with the target milk production to a certain level, followed by the target milk production and ECM increasing non-linearly at a decreasing rate. Thereafter, the ECM remained flat at the maximum potential milk production regardless of higher target milk production input (Figure 3.1). The increase of ECM showed similar trends at each level of first lactation cow percentage. The more first lactation cows in a herd, a lower per cow milk production was reached. Hence, the turning point target milk production was lower when the percentage of first lactation cows was high. Regardless of the herd structure, cows were able to produce as much as the target on lower target milk production because the target level was lower than the maximum potential milk production. Non-mature first lactation cows that are still growing produce less milk, have a lower peak on their lactation curves, and show a greater milk persistency than their later lactation counterparts (Shanks et al., 1981). As a result, the greater the proportion of first lactation cows, the lower the maximum potential milk production.

3.4.3 Net return to management

The cost of purchasing replacement heifers was the major difference across herd structures when target milk production was lower than the maximum potential milk production (Table 3.3). The per-cow replacement heifer cost increased 200% from $225 at 15% first lactation cows to $675 at 45% first lactation cows, which was the greatest change in total cost. Once the target milk production exceeded the maximum potential milk production of the high first lactation cow percentage, the ECM of high first lactation cow percentage stayed the same. Meanwhile the ECM kept increasing at a low first lactation cow percentage with the same target milk production. As the target milk production increased, the high first lactation cow percentage had less purchase cost of feed and bedding due to the stable ECM compared to the low one, which compensated for the replacement heifer purchase cost. Feed and bedding cost per cow was $273.46 for 45% first lactation cows and it was $329.85 for 15% first lactation cows (Table 3.4) at a 11,793 kg/cow per yr target milk production.

Generally, the net return to management increased as the amount of first lactation cows decreased, indicating that more first lactation cows would result in less farm profit. St-Pierre (2013) found a similar result indicating that when the proportion of first lactation cows increased with culling rate from 35% to 40%, income over feed cost decreased $0.022 per kg milk. A herd structure with more mature cows increases revenue from selling extra bred heifers, or decreases cost of purchasing replacement heifers. Moreover, the more mature the cows, the higher the feed efficiency as they are able to produce the same amount of milk with less feed intake (Connor et al., 2013).

The net return to management was strongly and positively related to ECM produced (r=0.88) at each first lactation cow percent level. At the same ECM production level, net return on management was lower with a greater proportion of first lactation cows (Figure 3.2). A greater ECM led to a greater net return to management. As the target milk production increased from 9,979 to 11,793 kg, the net return to management increased between 31% and 46% as the proportion of first lactation cows increased (Table 3.5). At a given proportion of first lactation cows, greater target milk production generally led to a greater net return to management before exceeding the maximum potential milk production plateau. Regardless of increased input of target milk production, the farm net return plateaued after the target milk production reached the maximum potential production (Figure 3.3).

The interaction of target milk production and proportion of first lactation cows affecting the net return to management is depicted in Figure 3.3. From the lowest target milk production, the net return to management increase was greater on the low first lactation cow percent than in the high first lactation cow percent. From the lowest to the greatest first lactation cow percentages, the net return to management decreased non-linearly as the target milk production increased. The decrease in net return to management increased as the target milk production increased up to 11,340 kg/cow per year (Table 3.5). The following plateau was because the cow attained the maximum potential milk production when the target milk production exceeded the biological limitation of the animal. The maximum net return to management was associated with the greatest target milk production and the lowest first lactation cow percent. The minimum net return to management was associated with the lowest target milk production and the greatest first lactation cow percent.

Results of the current study confirmed that milk sales are the dominating factor in total net return (Lehenbauer and Oltjen, 1998; Macdonald et al., 2007). The reduction in milk sales between low and high first lactation cow percent had greater impact than the increase in animal sale revenue between the two levels. The first lactation cow percentage was an indicator of herd replacement policy together with reproduction efficiency; with greater culling rate, more replacement heifers were needed to keep the herd size constant, which resulted in a greater first lactation cow percentage. Furthermore, reproduction efficiency determined the number of available replacement cows on the farm and affected the replacement rate due to culling for reproduction failure. Replacement decisions impact farm profits (Olynk and Wolf, 2008;

Kalantari and Cabrera, 2012). The IFSM model determines the culling decision merely by the first lactation cow percentage, which influenced the representative farm net profit at each target milk production. In reality, culling decisions are more complex based on milk production, animal health, reproductive performance, and market prices (Groenendaal et al., 2004; Kalantari and Cabrera, 2012).

3.4.4 Greenhouse gases including biogenic CO_2

The relationship between GHG and target milk production by the first lactation cow percentage is shown in Figure 3.4. Carbon dioxide equivalent emission decreased with more milk production. As target milk production increased from 9,979 to 11,793 kg/cow per yr, CO_2 equivalent emission including biogenic CO_2 decreased between 3.4% and 7.3% at different proportions of first lactation cows. The results demonstrated that greater production would decrease GHG emissions per unit of produced milk (Beukes et al., 2010; Rotz et al., 2010). Elevating target milk production requires greater feed intake to meet the nutrient requirements. The higher target milk production indirectly increased total equivalent CO_2 emission; however, the greater ECM decreased the kg CO_2 per kg ECM (Rotz et al., 2010). In general, increasing milk production per cow is an efficient method to reduce GHG emissions while improving profitability.

A higher first lactation cow percentage led to higher GHG emissions. As the proportion of first lactation cows increased from 15 to 45%, CO_2 equivalent emissions increased between 9.4% and 11.3% at different target milk production levels (Table 3.6). A lower culling rate reduced the GHG per kg ECM, demonstrating that better reproductive performance or a lower culling rate would decrease the GHG emission (Beukes et al., 2010; O'Brien et al., 2011; Crosson et al., 2011b). First lactation cows have lower feed efficiency as they require more feed to produce the same amount of milk, corresponding with more CH_4 emission and urinary-N partition (Klein and Eckard, 2008; Beukes et al., 2010). The greater GHG per kg ECM on higher culling rates was due to the higher total GHG emission along with lower ECM/cow per yr. Both herd structure and target milk production impact GHG emissions (Table 3.6, Figure 3.4), in agreement with Crosson et al. (2011) indicating that animal performance influences the GHG emissions. The greatest GHG emissions per kg ECM occurred with the lowest target milk production and highest culling rate; the lowest GHG occurred with the highest target milk production and lowest culling rate (Figure 3.4).

The data demonstrated a negative relationship between GHG and net return to management (Figure 3.5). Regardless of the first lactation cow percent, higher CO_2 equivalent emissions were always associated with lower farm net return to management (R^2 >0.92; Figure 3.5). As the first lactation cow percentage increased, both CO_2 equivalent emissions and net return to management decreased at a given target milk production. This result suggests that reducing GHG by increasing herd average milk production or decreasing the first lactation cow percentage would improve whole-farm net return.

3.5 Conclusions

This study demonstrates that increased milk production per cow increases farm net profit and decreases the per kg milk GHG emissions, a win-win situation. Also, a decreased percentage of first lactation cows, a trait related to reproduction and replacement, increases average milk production, farm net profit, and decreases the per kg milk GHG emissions. Therefore, lower GHG emissions are associated with increased milk production and decreased first lactation cow percentages.

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Table 3.1. On-farm feed produced[1] (tonne DM).

Feed category	Mean ± SD	Median	Min	Max
High-quality hay	43.50 ± 28.03	54.7	0	79.50
Low-quality hay	14.50 ± 23.27	0	0	76.40
High-quality silage	247.60 ± 43.50	251.80	143.6	311.3
Grain crop silage	243.80 ± 1.87	243.7	241.1	250.2
High-moisture grain	173.60 ± 58.22	176.40	69.30	239.10
Dry grain	14.50 ± 26.93	0	0	104.00
Forage	295.80 ±52.22	306.80	150.60	365.50

[1] Results from simulations performed with the Integrated Farm System Model (Rotz et al., 2013) for 25-yr of daily weather data for southern central Wisconsin.

Table 3.2. Twenty-five year ECM production and per-cow milk income over feed cost results at different target milk production with 35% first lactation cows

	Target milk production		
	9,979 kg/cow per yr[1]	11,793 kg/cow per yr[2]	
Year[3]	Milk income over feed cost ($ per cow)	Energy corrected milk production	Milk income over feed cost ($ per cow)
1986	2,656.67	9,998	2,904.98
1987	2,186.03	9,898	2,404.01
1988	1,914.36	10,048	2,174.16
1989	2,259.18	9,998	2,507.04
1990	2,534.18	9,849	2,735.85
1991	2,509.71	9,948	2,743.80
1992	2,330.98	9,998	2,582.96
1993	2,404.90	9,898	2,635.12
1994	2,615.45	9,998	2,875.77
1995	2,256.93	9,948	2,493.04
1996	2,174.48	9,849	2,378.54
1997	2,248.14	9,799	2,434.17
1998	2,613.78	9,998	2,863.16
1999	2,626.22	9,998	2,888.52
2000	2,440.01	9,849	2,641.31
2001	2,487.02	9,898	2,704.03
2002	2,084.11	9,948	2,323.72
2003	2,095.84	9,849	2,299.45
2004	2,519.76	9,849	2,722.33
2005	2,136.85	10,048	2,405.06
2006	2,471.72	9,998	2,720.89
2007	2,209.00	9,998	2,459.24
2008	2,319.46	9,998	2,570.96
2009	2,161.25	9,849	2,363.82
2010	2,635.08	9,849	2,837.44
Mean	2,355.64	9,934	2,586.77
SD	207.78	75.40	209.54
Median	2,330.98	9,948	2,582.96
Min	1,914.36	9,799	2,174.16
Max	2,656.67	10,048	2,904.98

[1] Target milk production level was lower than the maximum potential milk production with 35% first lactation cows. Therefore, the ECM was 9,212 kg/cow per yr through all 25 years.

[2] Target milk production level exceeded the maximum potential milk production with 35% first-lactation-cows.

[3] Each year compromised a different daily weather dataset of maximum and minimum temperature, solar radiation, and rainfall, collected in Dane County Regional-Truax Field, WI, 43.13N 89.33W, Elev. 259 m.

Table 3.3. Cost and revenues (mean ± SD, $ per cow) of a Wisconsin representative farm (100 cows including dry cows and 100 ha of land) at target milk production of 9,979 kg/cow per yr[1] with different herd structures represented by varying first lactation cow percent[2].

	First lactation cow percent (%)						
Break-down cost or revenue category ($ per cow)	15	20	25	30	35	40	45
Equipment cost	546.88±4.90	546.85±4.89	546.83±4.89	546.80±4.88	546.77±4.87	546.74±4.86	546.71±4.86
Facilities cost	615.62±3.12	615.61±3.12	615.61±3.12	615.61±3.12	615.61±3.13	615.61±3.13	615.60±3.13
Energy cost	157.28±3.56	157.27±3.56	157.25±3.55	157.23±3.54	157.21±3.54	157.19±3.53	157.17±3.52
Labor cost	524.85±4.69	524.82±4.68	524.79±4.67	524.76±4.66	524.72±4.65	524.68±4.65	524.64±4.64
Custom operation cost	25.38±3.62	253.8±3.62	25.37±3.62	25.37±3.61	25.36±3.61	25.36±3.60	25.36±3.60
Seed, fertilizer and chemical cost	321.07±0	321.07±0	321.07±0	321.07±0	321.07±0	321.07±0	321.07±0
Land rental cost	321.11±0	321.11±0	321.11±0	321.11±0	321.11±0	321.11±0	321.11±0
Net purchased feed and bedding cost	213.91±221.57	214.11±221.39	214.32±221.20	214.61±22,109	214.80±22,086	215.14±220.71	215.47±220.39
Replacement heifer purchase cost	225.00±0	300.00±0	375.00±0	450.00±0	525.00±0	600.00±0	675.00±0
Livestock expenses	372.00±0	372.00±0	372.00±0	372.00±0	372.00±0	372.00±0	372.00±0
Milk hauling and marketing fees	219.99±0	219.99±0	219.99±0	219.99±0	219.99±0	219.99±0	219.99±0
Property tax	41.62±0	41.62±0	41.62±0	41.62±0	41.62±0	41.62±0	41.62±0
Total cost	3,584.71	3,659.83	3,734.96	3,810.17	3,885.26	3,960.51	4,035.74
Income from milk sales	4,025.98±0	4,025.98±0	4,025.98±0	4,025.98±0	4,025.98±0	4,025.98±0	4,025.98±0
Income from animal sales	230.57±0	275.66±0	320.74±0	365.83±0	410.92±0	456.00±0	501.09±0
Return to management and unpaid factors	671.86±204.83	641.81±204.68	611.77±204.52	581.66±204.44	551.64±204.24	521.48±204.11	491.33±203.82

[1] This target production level was lower than the maximum potential milk production for all first lactation cow percent levels and therefore this level of production was reached in all cases.

[2] Results from simulations performed with the Integrated Farm System Model (Rotz et al., 2013) using 25-yr of daily weather data for southern central Wisconsin.

Table 3.4. Cost and revenues (mean ± SD, $ per cow) of a Wisconsin representative farm (100 cows including dry cows and 100 ha land) at a target milk production of 11,793 kg/cow per yr[1, 2] with different herd structures represented by varying first lactation cow percent[3].

Break-down cost or revenue category ($ per cow)	First lactation cow percent (%)						
	15	20	25	30	35	40	45
Equipment cost	552.11±5.02	551.63±4.95	551.15±4.90	550.68±4.88	550.23±4.87	549.73±4.83	549.27±4.80
Facilities cost	615.84±3.62	615.83±3.59	615.79±3.50	615.78±3.48	615.76±3.45	615.72±3.38	615.70±3.33
Energy cost	167.05±3.69	166.21±3.64	165.37±3.56	164.53±3.53	163.74±3.59	162.84±3.50	162.04±3.47
Labor cost	531.35±4.63	530.77±4.56	530.19±4.51	529.61±4.51	529.05±4.51	528.44±4.47	527.87±4.46
Custom operation cost	25.43±3.66	25.42±3.66	25.41±3.65	25.40±3.64	25.39±3.63	25.39±3.63	25.38±3.62
Seed, fertilizer and chemical cost	321.07±0	321.07±0	321.07±0	321.07±0	321.07±0	321.07±0	321.07±0
Land rental cost	321.11±0	321.11±0	321.11±0	321.11±0	321.11±0	321.11±0	321.11±0
Net purchased feed and bedding cost	329.85±223.06	319.96±223.39	310.66±223.41	301.11±223.40	292.18±222.82	282.49±222.74	273.46±222.16
Replacement heifer purchase cost	225.00±0	300.00±0	375.00±0	450.00±0	525.00±0	600.00±0	675.00±0
Livestock expenses	372.00±0	372.00±0	372.00±0	372.00±0	372.00±0	372.00±1.76	372.00±1.76
Milk hauling and marketing fees	245.84±1.69	243.64±1.87	241.45±1.68	239.28±1.76	237.23±1.76	234.95±0	232.89±0
Property tax	41.62±0	41.62±0	41.62±0	41.62±0	41.62±0	41.62±0	41.62±0
Total cost	3,748.27	380,9.26	3,870.82	3,932.19	3,994.38	4,055.36	4,117.41
Income from milk sales	4,499.23±30.98	4,458.85±32.46	4,418.77±30.79	4,379.10±32.26	4,341.51±32.27	4,299.93±32.24	4,262.16±32.21
Income from animal sales	230.57±0	275.66±0	320.74±0	365.83±0	410.92±0	456.00±0	501.09±0
Return to management and unpaid factors	981.53±209.84	925.24±208.82	868.69±206.13	812.73±205.50	758.04±205.75	700.56±202.89	645.83±202.57

[1] This target production level exceeds the maximum potential milk production for all first lactation cow percent levels, therefore this production level was not reached in all cases

[2] The energy corrected milk production for 15%, 20%, 25%, 35%, 40%, and 45% first lactation cow percent were 10,295, 10,203, 10,111, 10,020, 9,934, 9,839, and 9,753 kg/cow per year, respectively.

[3] Results from simulations performed with the Integrated Farm System Model (Rotz et al., 2013) using 25-yr of daily weather data for southern central Wisconsin.

Table 3.5. Net return to management ($ per cow; mean ± SD) of a Wisconsin representative farm (100 cows including dry cows and 100 ha land) with different herd structures (represented by varying first lactation cow percent) and target milk production (kg/cow per yr)[1].

Target milk production	First lactation cow percent (%)							Decrease percent[3]
	15%	20%	25%	30%	35%	40%	45%	
9,979	671.86±204.83	641.81±204.68	611.77±204.52	581.66±204.44	551.64±204.24	521.48±204.11	491.33±203.82	36.74%
10,206	732.04±205.08	701.78±204.89	671.61±204.59	641.59±204.41	611.53±204.25	581.50±204.07	551.44±203.38	32.75%
10,433	791.89±205.78	761.75±205.58	731.37±205.07	701.31±204.89	671.03±204.42	641.22±203.92	611.23±203.81	29.56%
10,659	851.99±205.69	821.84±205.56	791.64±205.38	761.49±205.19	730.59±204.98	690.22±205.20	647.37±202.42	31.61%
10,886	911.65±206.14	881.47±205.95	846.04±206.25	808.53±206.83	757.94±204.92	700.40±202.67	645.74±202.19	41.18%
11,113	965.79±207.53	922.97±210.24	868.52±207.51	812.48±205.11	758.44±205.93	700.88±202.70	645.10±202.19	49.71%
11,340	979.99±207.71	926.00±208.78	868.40±207.19	812.92±205.11	758.31±206.32	700.72±202.69	645.52±202.19	51.81%
11,567	980.44±208.89	925.86±209.54	868.25±207.51	813.37±204.36	758.16±205.90	700.62±202.70	645.93±202.18	51.79%
11,793	981.53±209.84	925.24±208.82	868.69±206.13	812.73±205.50	758.04±205.75	700.56±202.89	645.83±202.57	51.98%
Increase percent[2]	31.47%	34.34%	37.42%	39.73%	42.00%	44.16%	46.09%	

[1] Results from simulations performed with the Integrated Farm System Model (Rotz et al., 2013) using 25-yr of daily weather data for southern central Wisconsin.

[2] Increase in net return to management when the target milk production increases from 9,979 to 11,793 kg/cow per yr

[3] Decrease in net return to management when first lactation cow percent increases from 15% to 45%

Table 3.6. Greenhouse gas emission including biogenic CO_2[1] (kg equivalent CO_2 per kg ECM, mean ± SD) with different target milk production (kg/cow per yr) and herd structure (represented by varying first lactation cow percent)[2].

Target milk production	First lactation cow percent (%)							Increase percent[3]
	15	20	25	30	35	40	45	
9,979	0.53±0.04	0.55±0.04	0.56±0.04	0.57±0.04	0.58±0.04	0.58±0.04	0.59±0.04	11.32%
10,206	0.53±0.04	0.54±0.04	0.55±0.04	0.56±0.04	0.57±0.04	0.58±0.04	0.58±0.04	9.43%[5]
10,433	0.52±0.04	0.53±0.04	0.54±0.04	0.55±0.04	0.56±0.04	0.57±0.04	0.58±0.04	11.54%
10,659	0.51±0.04	0.52±0.04	0.54±0.04	0.55±0.04	0.56±0.04	0.57±0.04	0.57±0.04	11.76%
10,886	0.51±0.04	0.52±0.04	0.53±0.04	0.54±0.04	0.55±0.04	0.56±0.04	0.57±0.04	11.76%
11,113	0.50±0.04	0.51±0.04	0.53±0.04	0.54±0.04	0.55±0.04	0.56±0.04	0.57±0.04	14.00%
Decrease percent[4]	5.66%	7.27%[4]	5.36%	5.26%	5.17%	3.45%	3.39%	

[1] Biogenic CO_2 represents the net CO_2 assimilated from and released to the atmosphere, including assimilation in plant growth and animal body, and carbon sequestration (Dutreuil et al., 2014, Rotz et al., 2014)

[2] Results from simulations performed with the Integrated Farm System Model (Rotz et al., 2013) using 25-yr of daily weather data for southern central Wisconsin.

[3] Increase in greenhouse gas emission when the first lactation cow percent increases from 15% to 45%

[4] Decrease in greenhouse gas emission when the target milk production increases from 9,979 to 11,113 kg/cow per yr

[5] Small absolute values and 2-decimal rounding as reported by the model cause this value to appear inconsistent. Nonetheless, it is clear that overall results still follow the general GHG emissions trend.

Figure 3.1. Relationship between target milk production (kg/cow per yr) and energy corrected milk production obtained (kg/ cow per yr) for different herd structure (represented by varying first lactation cow percent)

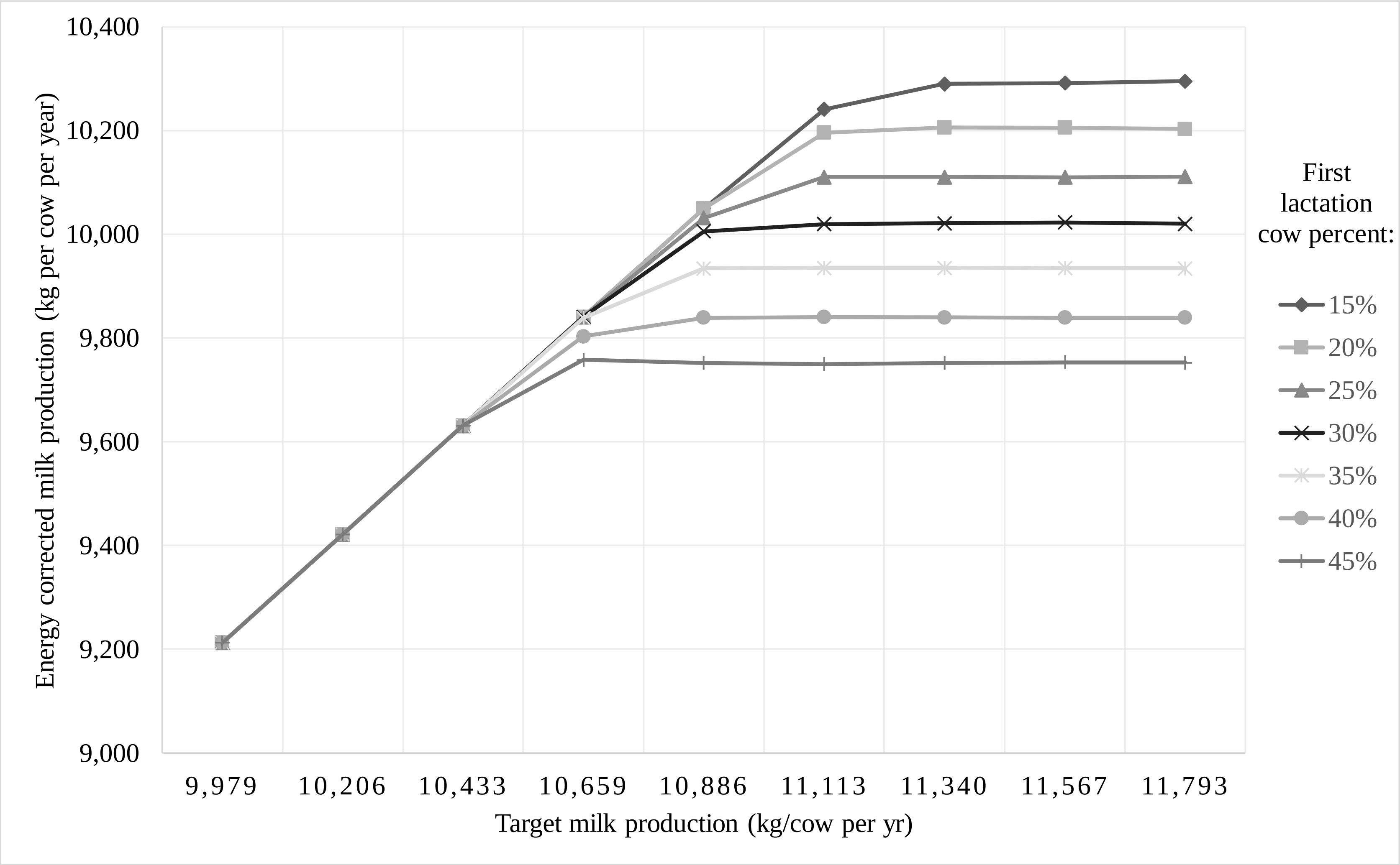


Figure 3.2. Relationship between energy corrected milk production (ECM, kg/cow per yr) and net return to management ($) for different herd structure (represented by varying first lactation cow percent)

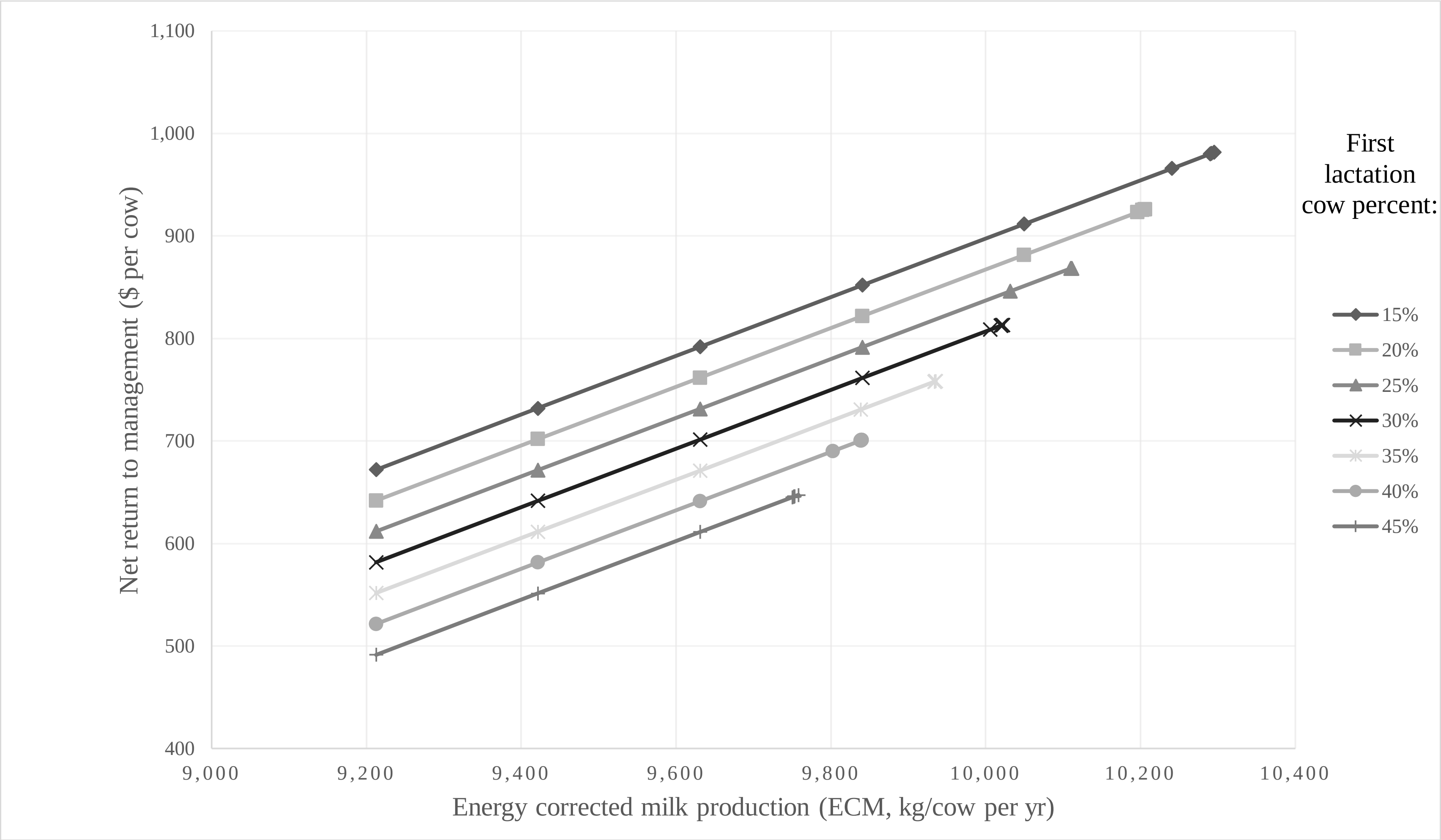


Figure 3.3. Relationship between target milk production (kg per cow per yr) and net return to management ($ per cow) with different herd structure (represented by varying first lactation cow percent)

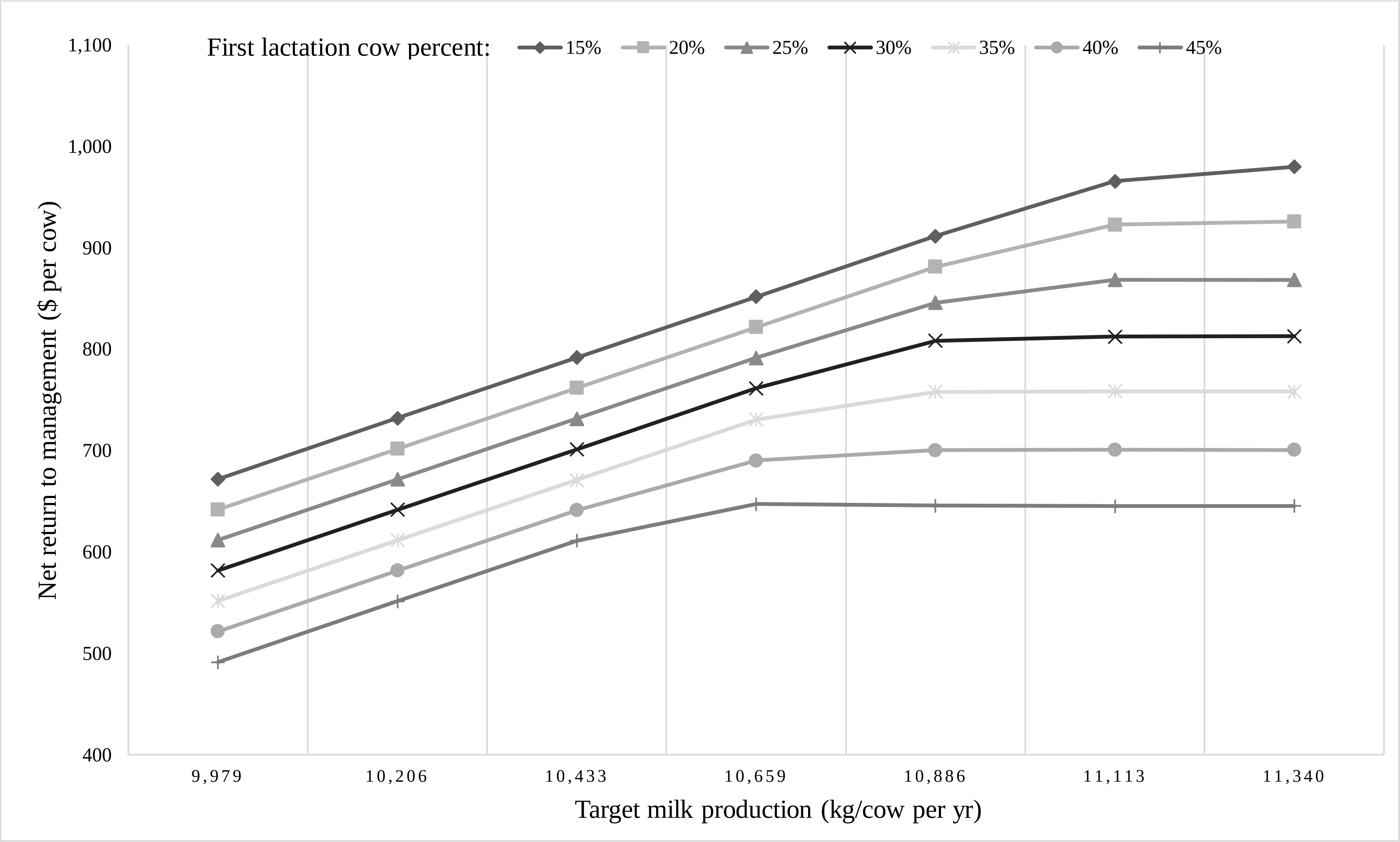


Figure 3.4. The effect of the interaction of target milk production and herd structure (represented by varying first lactation cow percent) on greenhouse gas including biogenic CO_2 emission (kg CO_2 eq. per kg ECM). Biogenic CO_2 represents the net CO_2 assimilated from and released to the atmosphere, including assimilation in plant growth and animal body, and carbon sequestration (Dutreuil et al., 2014, Rotz et al., 2014)

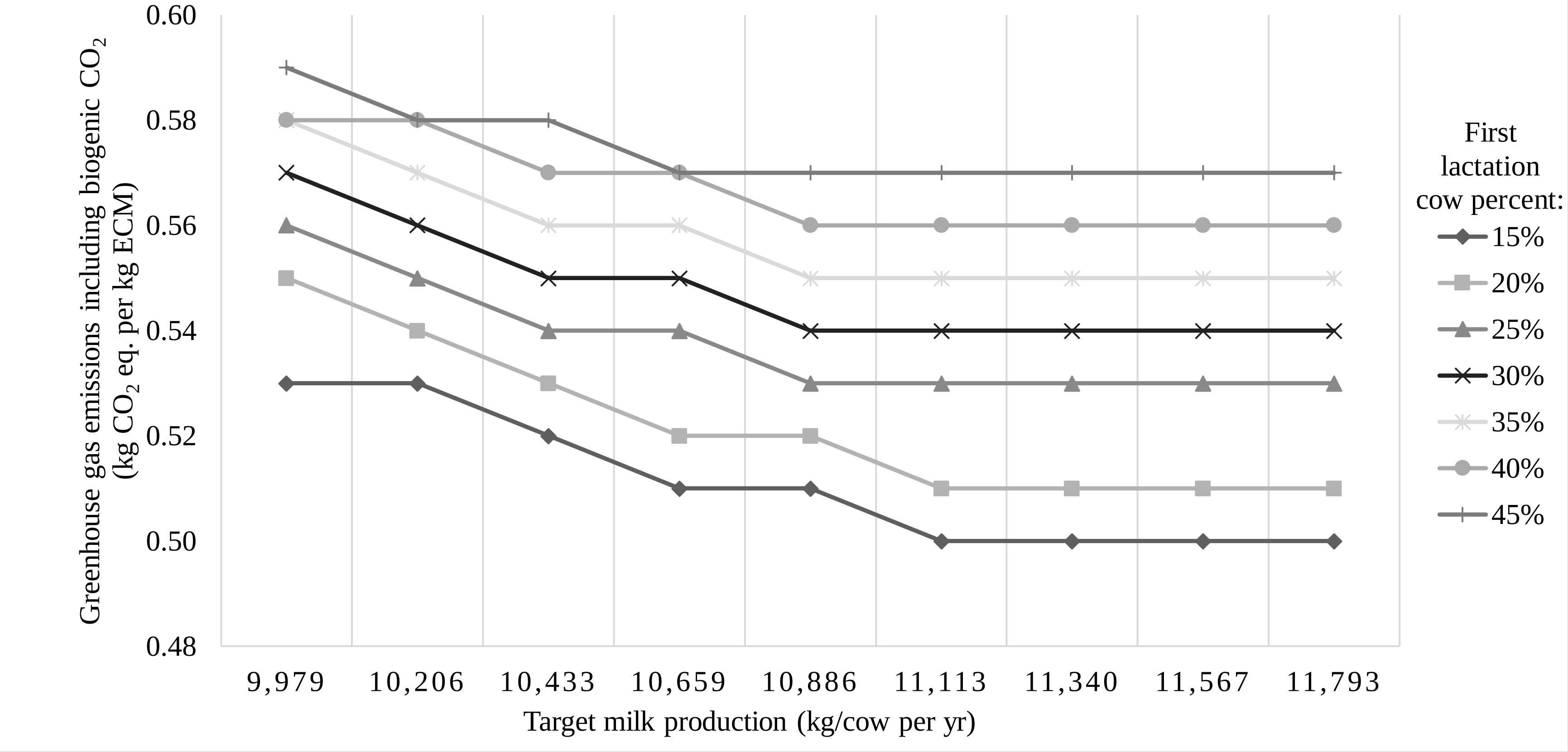
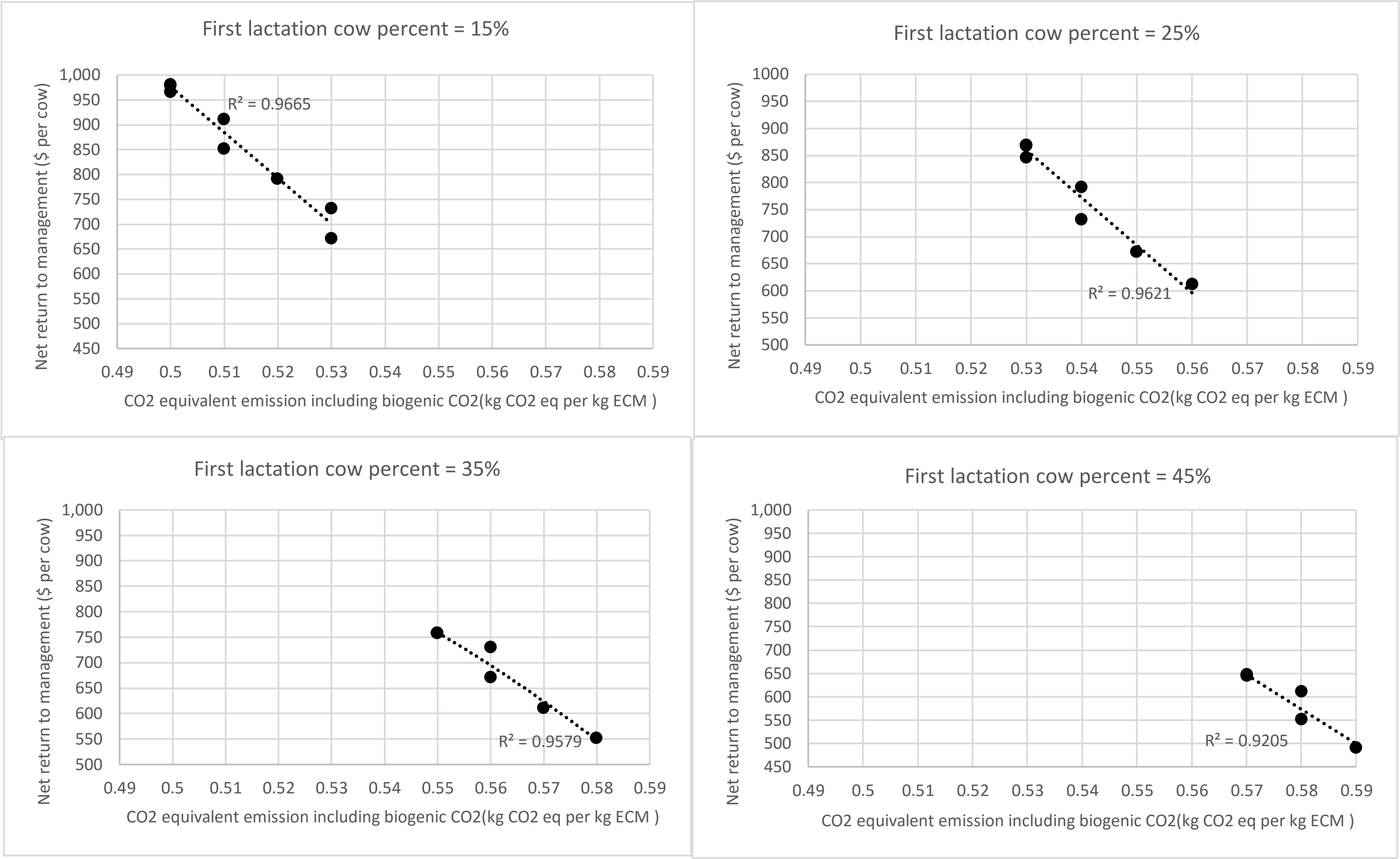


Figure 3.5. Linear regression correlation between greenhouse gas emission (CO_2 kg eq. per kg ECM) and net return to management ($ per cow) with different herd structure (represented by varying first cow lactation percent).



Chapter 4

Estimating the Effect of Herd Structure Change and Milk Productivity Improvement on Farm Profitability and Enteric Methane Emission through a Markov Chain Model

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4.1 Abstract

Cow’s performance and herd management strategies such as productivity and herd structure influence dairy enteric CH_4 emission and profitability. This study aimed to quantify the effects of culling rate (**CUR**) milk productivity improvement (**MPI,** a proxy for genetic and management progress), and the interaction between them on enteric CH_4 emission and farm profitability. Hence, a Markov Chain herd structure model was built and used to simulate the young stock on a weekly-basis and adult cows on a monthly-basis for 15 calving cycles (**CC**, each with 13-month length). Enteric CH_4 emission and farm profit (milk income over feed cost minus replacement transaction cost) were calculated as the average for one CC. The model was used to study CUR from 25% to 45% with 5% intervals and annual MPI of 1%, 1.5%, and 2%. Every tested scenario started at a herd’s steady state. Milk production in 35% CUR herds (9,985 kg per cow per yr) was almost the same as herds with other CUR levels. Herds with 45% CUR had the lowest milk production (9,979 kg per cow per yr), followed by 25%, 40%, and 30% CUR herds. Higher CUR herds (30% to 45%) with 1.5% or 2% MPI started to have greater productivity (milk per cow per yr) than 25% CUR with 1% MPI during the 4th CC due to faster milk production increase. The higher CUR herd always had greater emission per kg of milk than the lower CUR herds due to greater amount of emission from the larger group of replacement heifers. Overall, the lowest emission occurred when 25% CUR + 2% MPI herds and the highest when 45% CUR + 1% MPI herds. With the same MPI, higher CUR herds always had higher emission per kg of FCM. Farm profit was $5.65/cow per d for 25% CUR and $5.45/cow per d for 45% CUR at the beginning. At the end of 15 CC, herds with 25% CUR + 2% MPI had the highest profit ($8.03 per cow per d), and herds with 45% CUR + 1% MPI had the lowest profit ($6.60 per cow per d). With the same CUR, higher MPI always led to a higher farm profit. With the same MPI, lower CUR resulted in a higher farm profit. This study confirmed that MPI is the ultimate approach to reducing enteric CH_4 emission and higher CUR leads to higher enteric CH_4 emission per unit of milk with the same MPI. Milk productivity improvement had a greater impact on enteric CH_4 emission and profitability than CUR. Slaughter prices determined the profit ranking among herds with different CUR levels.

Key Words:

Enteric CH_4 emission, Markov Chain model, Herd structure, Milk production

4.2 Introduction

The dairy industry contributes 4% to global greenhouse gas (**GHG**) emission (FAO, 2010). Enteric methane (CH_4) is the largest section and accounts for over half of total dairy farm emission (Knapp et al., 2014). Cow performance and herd management strategies such as productivity and culling rates influence dairy enteric CH_4 emission, (Crosson et al., 2011a). Culling decisions are highly oriented towards farm profitability (Monti et al., 1999). Previous research has developed several models to determine the optimal culling rate (**CUR**) under different market scenarios to maximize farm profitability (Groenendaal et al., 2004; Cabrera, 2010). Aggressive culling may increase the replacement transaction cost, but its final impact depends on market prices.

Decreasing culling rate CUR has been demonstrated to be an effective approach to reducing enteric CH_4 emission per kg of milk because of fewer replacement heifers needed and higher milk production from more mature cows (Garnsworthy et al., 2012; Liang and Cabrera, 2015). On the other hand, milk productivity improvement through genetic selection and management is considered a ‘long-term’ mitigation strategy (Hristov et al., 2013; Wall, Simm, & Moran, 2010). Milk production increases continuously with genetic selection and management improvement, but interacts with herd’s CUR. Annual milk productivity improvement (**MPI**) has ranged between 1.0 to 1.5% since 2009 according to the Council of Dairy Cattle Breeding (Trend in Milk Breeding Value for Holstein or Red & White). Cows with higher milk production, higher feed efficiency, and fewer methanogens produce lower enteric CH_4 per kg of milk.

High CUR increases the proportion of younger cows that carry more advanced genetics to improve production and feed efficiency in the long-term. However, high CUR increases the enteric emission by requiring more replacement heifers. The potential conflict of these two mitigation strategies has not been studied. This study aims to quantify the effect of CUR, MPI, and their interaction on enteric CH_4 emission and farm profitability.

4.3 Materials and Methods

4.3.1 Model and Herd Structure

A model was developed based on a Markov Chain herd structure following a simplified version of Cabrera (2012) in Microsoft 2013 Excel (Seattle, WA). The stage (time) component was month after calving or month in milk (**MIM**) for adult cows and age in weeks for young stock. The transition probabilities included survival rate between two successive stages. The structure of a 1,000-lactating cow herd was simulated from newborn to the end of 6th lactation. The number of lactating and dry cows in each stage was calculated upon calving interval length (**CI**, in months) and CUR. Number of younger animals (calves and heifers) was calculated upon weaning time (default at 8 wk), age at first calving (**AFC**, default 102 wk), proportion of heifer calves born (default 47%), stillbirth rate (default 7%), and calf and heifer removal rate before entering first lactation (default 15.5%, of which 7% was mortality rate and 8.5% was sold to beef operations).

Calving cycle (**CC**) was used as a unit of time; one CC was the same as the CI length (13 months). The model simulated the herd performance for 15 CC, which was equal to 195 months. Milk production, farm economics, and enteric CH_4 emission were reported as the average of each CC.

4.3.2 Herd performance

Herd performance included milk production, DMI, body weight, and enteric CH_4 emission and was simulated for adult cows and young stock. Equations are listed in Table 4.1.

Body weight. Body weight was calculated using several target body weights at different growth time points (Table 4.2). Monthly or weekly body weight gain or body weight loss was equal and linear between two nearby target body weights. For example, body weight loss (50 kg per cow) associated with negative energy balance occurred in the first 60 d of lactation. The body weight loss was 25 kg for each month during the negative energy balance period (first 60 days in lactation).

Milk production. Default rolling herd average milk production (**RHAM**) was 11,357 kg/cow per year. Monthly milk production was calculated using the MilkBot® lactation curve model (Ehrlich, 2011), considering RHAM, lactation number, and MIM. Milk production was predicted separately for the first, second, and third lactation. Milk production and lactation curve after the third lactation were set as the same as the third lactation. Fat-corrected milk (**FCM**) was calculated using NRC (2001) equation based on milk production and milk fat content of 3.5%.

DMI. Dry matter intake for calves and heifers was predicted using the Hoffman et al. (2008) approach for Holsteins. The prediction was based on body weight (Appendix 4.I). Dry matter intake for adult cows was predicted using the NRC (2001) equation, considering lactation stage, body weight, and FCM.

Enteric CH4 emission. Before weaning, calves fed milk or milk replacer had no enteric CH_4 emission because they had negligible microbial activity in the rumen. After weaning, enteric CH_4 emission was calculated using the Intergovernmental Panel of Climate Change equation (IPCC, 2006): 6.5% of total gross energy ended up as enteric CH_4 energy. Total gross energy intake for weaned calves and heifers was calculated with the NRC (2001) equations, including maintenance energy, growth energy, and pregnancy energy (for bred heifers). Surplus heifers were sold to dairy operations before the first calving (one month before AFC) in the default scenario. Emissions and meat of surplus heifers sold were passed to the purchasing farm and therefore were not included in the calculation. Emissions from heifers and calves that died on-farm were included into the heifer emission. However, their carcasses were not included in meat sales. If removed heifers were sold to a feedlot for beef purposes, their enteric CH_4 emission was added to the total farm CH_4 pool, and their meat was added into the total meat sale amount, which was used to calculate the allocation factor between milk and meat. Purchased heifers brought in the same amount of emission as a heifer raised on-farm. For adult cows, enteric CH_4 emission was calculated using the equation from Ramin and Huhtanen (2013), which predicted CH_4 emission from DMI. Enteric CH_4 emission reported in this study was the aggregation from both adult cows and heifers. Allocation factor to milk was calculated using the equation from the International Dairy Federation (IDF, 2010), based on milk and meat sales. Global warming potential of 34 was used to convert CH_4 emission to CO_2 equivalent (**CO_2 eq.**), which is the 100-year global warming potential value with climate-carbon feedbacks (Myhre et al., 2013).

4.3.3 Culling rate

Replacement heifers entered the adult herd every month. Heifer culling and mortality rate were assumed to be equal each month. The total heifer removal rate was constant in all adult cow CUR levels. Five CUR for adult cows were included, ranging from 25% to 45% with 5% intervals. Adult cow monthly CUR for each lactation was obtained from De Vries et al. (2010). Culling rate changed herd structure, allocation factor to milk, number of calves born on a farm, and number of replacement heifers needed each year.

4.3.4 Milk productivity improvement

Based on the observed trend for milk production from 2009 to 2015 (Council of Dairy Cattle Breeding, Trend in Milk BV for Holstein or Red & White, Bowie MD), 3 levels of MPI (1%, 1.5%, and 2% per yr) were included in the model. Milk productivity improvement includes both progress from genetic selection and management aspects (nutrition, health, reproduction, *etc*.). Herds with different CUR and MPI levels had the same production in each lactation during the first CC. First lactation cows had a production level **P** (gentic potential milk production of 11,357 kg per cow per year); second lactation cows had P-1**,** which was 1% lower in milk production (gentic potential milk production of 11,242 kg per cow per yr); and so forth until cows in 6th lactation that had P-5 (gentic potential milk production of 10,806 kg per cow per yr).

Milk productivity improvement was expressed as the difference in potential milk production from a heifer entering the herd in the current CC compared with a heifer entering the herd during the previous CC. For example, with 1% MPI, all replacement heifers entering the herd with all CUR levels during the second CC had the same potential milk production of 11,470 kg per yr (1% increase from level P). At the end of the second CC, all the first lactation cows should have the same potential milk production (11,470 kg per cow per yr). During the third CC, all heifers entering the herd with 1% MPI had a potential milk production of 11,585 kg per yr (1% improvement over 11,470 kg per yr). Replacement heifers with one MPI level greater production began to enter the herd when first lactation cows that had one MPI level lower production calved into the second lactation. With 1% MPI, RHAM increased by 1% linearly every CC because cows always had 1% greater potential milk production than the cow in the same lactation during the last CC. With 1.5% or 2% MPI, the RHAM increase was nonlinear and lower than the MPI level (1.5% or 2%) before the end of the 6th CC; the linear RHAM increase occurred after the 6th CC. Lactation curves changed correspondingly as the RHA increased through CC (Figure 4.1). The average milk production per cow per yr for each combination of CUR and MPI is listed in Table 4.3.

4.3.5 Economic analysis

Heifer rearing cost. Rearing cost had 3 components: female calf value and feed cost. Heifer feed DM cost was $0.13 per kg DM. Female calf value at birth was $420 per head (Akins et al., 2015). Heifer purchase cost was the same as the heifer sale price ($1,333 per head). In the base scenario, surplus heifers were raised on farm until one month before first calving (24-month of age) and sold to dairy operations.

Slaughter value. Slaughter value was the product of body weight and slaughter price. Cow's body weight at culling was a function of the cow's age when leaving the herd. The default slaughter price was $1.7 per kg of BW.

Herd replacement transaction cost. Herd-level replacement transaction cost included heifer rearing cost, culled cow slaughter value, bull calf sale, and surplus heifer sale value. The equation is listed in Appendix 4.I.

Income over feed cost (IOFC) and Farm Profit. Income over feed cost was the difference between the milk sale and the feed cost. Milk ($0.32 per kg), feed ($0.16 per kg DM), and slaughter prices ($1.68 per kg) in the base scenario were the average prices for 2016. Farm profit was defined as IOFC minus the replacement transaction cost.

4.3.6 Sensitivity analysis

Sensitivity analysis was conducted to estimate 3 market prices scenarios, including milk price, feed price, and slaughter price. We also used the model to test the effect of extending AFC from 24 months to 26 months and selling surplus heifers at birth.

The 3 scenarios were: 1) high milk price and high slaughter price; 2) low milk price; and 3) low slaughter price. All price scenarios were derived from actual monthly market price combinations that occurred between 2015 and 2016 in the US. The first scenario occurred in January 2015 and had milk price at $0.41 per kg FCM, feed price at $0.17 per kg DM, and slaughter price at $2.5 per kg. The second scenario occurred in February 2016 and had milk price at $0.30 per kg, feed price at $0.16 per kg, and slaughter price at $1.7 per kg. The third scenario occurred in October 2016 and had milk price at $0.36 per kg FCM, feed price at $0.15 per kg DM, and slaughter price at $1.4 per kg.

4.4 Results and Discussion

4.4.1 Herd Structure

Culling rate determined the percent of cows leaving the herd in one year and the proportion of younger lactating cows compared with mature cows (Figure 4.2). High CUR led to a younger herd. Heifer structure largely depended on AFC and the removal rate before the first lactation. Time of surplus heifer sale also affected the heifer herd structure, which further influenced enteric emission and heifer sale revenue.

4.4.2 Milk Production across Time

Milk productivity improvement was consistent across the entire simulation. With the same CUR, higher MPI resulted in a greater increase in milk production. After 15 CC, yearly milk production per cow in the 35% CUR herd increased by 15% (9,985 to 11,436 kg FCM per cow per yr), 21% (9,985 to 12,126 kg FCM per cow per yr), and 28.8% (9,985 to 12,856 kg FCM per cow per yr), with 1%, 1.5%, and 2% MPI, respectively.

4.4.3 Culling rate

Culling rate influenced herd structure (Figure 4.2) by changing the number of cows leaving the herd in one year and the associated number of replacement heifers entering the herd. Low CUR may indicate a herd with good reproductive performance and health, because fewer cows are culled for reproductive failure or diseases. However, a high CUR herd is not necessarily indicative of poor reproduction and health management, because some cows could be culled to improve milk production or to take advantage of market conditions. In the first CC, yearly milk production per cow in 35% CUR herds (9,985 kg FCM per cow per yr) was slightly higher than herds with other CUR levels (Table 4.2). Herds with 45% CUR had the lowest milk production, followed by 25%, 40%, and 30% CUR herds. Average milk production of different CUR herds in the first CC was in agreement with Allaire (1995), in which optimal CUR was between 30% to 35% to maximize milk production. Higher CUR increased the number of animals in first and second lactation, which had higher potential milk production than mature cows (third and later lactations), but these animals did not have a chance to express their potential fully because they are not yet mature. Higher CUR increased total milk production from younger cows; however, it also reduced the number of mature cows. Figure 4.3 shows the 25% and 45% CUR herds' monthly milk production from the 1st, 3rd, and 6th lactation cows in the first CC. Total milk production from 1st lactation cows was higher in 45% CUR herds than 25% CUR herds. However, the 25% CUR herds had higher total milk production from 3rd and 6th lactation cows compared with the 45% CUR herd. When increasing CUR from 25% to 35%, the benefits from a greater number of younger lactating cows with better genetics in 35% CUR herds was higher than the milk production reduction from fewer mature cows. When CUR was higher than 35%, the benefits from younger animals failed to compensate for the milk production reduction from fewer mature cows and led to lower milk production overall compared with 25% CUR.

With 1% MPI, 35% CUR herds had the highest milk production throughout the entire simulation of 15 CC, and the ranking of different CUR herds for milk production remained the same as in the first CC. The difference between 35%, 30%, and 40% CUR herds was less than 2.07 kg per cow per yr, which indicated that the CUR level had minimum effect on the average milk production per cow per yr. With 1.5% MPI, the production advantage of 35% CUR herds disappeared after 3 CC. Higher CUR started to have higher milk production after the third CC until the end of 15 CC. Herds with 45% CUR that had the lowest milk production in the first CC (0.06% lower than 35% CUR herds and 0.03% lower than 25% CUR herds), became 0.19% higher than 25% CUR herds and 0.04% higher than 35% CUR herds after 15 CC.

Greater MPI accelerated milk production in high CUR herds. With 2% MPI, 45% CUR herds started to have the highest milk production after the second CC. After 15 CC, 45% CUR herds had 0.41% higher milk production than 25% CUR herds and 0.14% higher milk production than 35% CUR herds. The influence of MPI was continuous, meanwhile CUR influenced milk production in the short-term (Figure 4.4). The advantage of the optimal CUR on milk production would be diminished by greater MPI over time. In contrast, Liang and Cabrera (2015) found that greater CUR led to lower potential maximum milk production without MPI across time; MPI in this study helped the high CUR herds continue to increasing milk production in the long-term.

With the same CUR, higher MPI led to higher milk production with time. In herds with 25% CUR, 1.5% MPI and 2% MPI scenarios resulted in 5.9% and 12.2% higher milk production than the1% MPI scenario. The milk production difference between high and low MPI enlarged with higher CUR. In herds with 45% CUR, the 1.5% MPI and 2% MPI scenarios resulted in 6.1% and 12.6% higher milk production than the 1% MPI scenario. The advantage in milk production expressed with higher CUR herds was due to a greater number of young cows carrying better genetics.

4.4.4 Enteric CH_4 emission

In the first CC, allocation factor was greater in the lower CUR herd (0.85 in 25% CUR herd), compared with higher CUR herds (0.79 in 45% CUR herd). Allocation factors increased over time in this study, regardless of CUR and MPI. With the same CUR level, milk production increased with time due to MPI, while meat sales were fixed, which is related to herd structure, the percentage of female calves born, timing and purpose (meat or dairy) of surplus heifer sales, and stillbirth rates. High CUR herds had more cows sold, whereas low CUR herds had more surplus heifers sold. After 15 CC, the difference in allocation factor between the 25% CUR (0.87) and 45% CUR (0.84) herds reduced as milk production increased. As the allocation factor to milk increased with time, the emissions allocated to meat by selling surplus heifers or culled cows decreased.

Enteric CH_4 emission from raising a heifer to first calving was 2,906 kg CO_2 eq. per head with 24 month AFC. Extended AFC by 2 months increased it to 3,026 kg CO_2 eq. Culled heifer emission related positively with CUR, because higher CUR herds need more heifers raised on a farm. When surplus heifers were sold before first calving, their accumulated enteric emission was 2,546 kg CO_2 eq. per head. In the first CC, the young stock contributed 15.6%, 17.2%, 18.9%, 20.6%, and 23.1% of whole-farm enteric CH_4 emission for 25%, 30%, 35%, 40% and 45% CUR herds, respectively. The proportion of young stock emission in whole-farm emission decreased over time, because adult cows' emission increased.

In the first CC, the average enteric CH_4 emission (for both milk and meat) across different CUR was 0.60 kg CO_2 eq. per kg of FCM (range from 0.58 to 0.63 kg CO_2 eq. per kg of FCM, 7.4% higher in 45% CUR herds). Although milk production was not negatively linearly related with CUR (Table 4.3), higher CUR herds had higher emission compared with lower CUR herds because of a greater amount of accumulated enteric CH_4 emission from replacement heifers (Table 4.3). After adjusting for the allocation factor to milk, the low allocation factor in high CUR herds compensated its high enteric emission. Enteric emission per kg FCM was close in different CUR herds (range from 0.49 to 0.50 kg CO_2 eq. per kg FCM).

Overall, the lowest emission was from 25% CUR + 2% MPI herds and the highest was from 45% CUR + 1% MPI herds (Table 4.5 and Figure 4.5). With the same MPI, higher CUR herds always had higher enteric emission per kg FCM. Although higher CUR herds may have higher milk production with 1.5% and 2% MPI after several CC, the greater amount of heifer emission determined the greater emission per kg FCM in higher CUR herds. The difference between 45% CUR and 25% CUR decreased with time, and greater MPI facilitated the reduction in difference. After 15 CC, 45% CUR herds' emission was 7.0%, 6.7%, and 6.4% greater than 25% CUR herds with 1%, 1.5%, and 2% MPI, respectively. With the same CUR, greater MPI always led to lower enteric emission per kg FCM because of more milk production.

A possible interaction of CUR and MPI on enteric emission was interesting. Albeit higher CUR herds started with higher emission per kg FCM, the herd with greater MPI level compensated higher emission compared with a herd with lower MPI level. Herds with 30% CUR

+ 1.5% MPI began to have lower emission than 25% CUR +1% MPI during the 8th CC; the reversal point appeared later for 35% CUR + 1.5% MPI herds (during the 11th CC). For herds with 40% or 45% CUR, 1.5% MPI failed to compensate for emission difference during 15 CC in this study. If MPI increased to 2.0%, all higher CUR herds (> 25%) ended up with lower emission than 25% CUR + 1% MPI. The reversal point first showed during the 5th CC in 30% CUR +2% MPI herd; 45% CUR +2% MPI herd had the latest reverse point, which appeared during the 13th CC. Results indicated that greater MPI paired with higher CUR had the possibility to have lower emission than herds with lower CUR and lower MPI. Similar to the milk production trend, CUR had a short-term effect on enteric emission per kg FCM, while MPI had a long-term effect on enteric emission per kg FCM.

Results from this study aligned with many previous findings indicating that improving milk productivity is the ultimate approach to reducing greenhouse gas emission, especially enteric CH_4 emission from dairy cattle (Montes et al., 2013b; Knapp et al., 2014). Also, in agreement with Garnsworthy et al. (2012) and Liang and Cabrera (2015), this study found that higher CUR resulted in a higher enteric CH_4 emission per kg FCM with the same MPI level However, incorporating a higher MPI into a higher CUR herd may lead to lower enteric CH_4 emission than a lower CUR herd with lower MPI. High CUR herds that wanted to take advantage of high slaughter price could reduce the enteric emission by improving milk production via genetic selection, nutrition, and farm management.

4.4.5 Economic performance

On-farm heifer rearing cost was $1,122 per head for 24 month AFC, including $702 of calf and heifer feed cost and $420 calf value. Total DMI per heifer was 5,418 kg DM per head, which is close to the estimation by Tranel, (2014, 5,443 kg DM per head). Total heifer rearing feed cost (to first calving) was lower than the replacement animal feed cost from a Wisconsin survey ($1,0689 per head including $165 ± 92 per head of calf feed cost and $909 ± 427 per head of heifer rearing cost, Akins et al., 2015) due to lower heifer feed price in this study. The average cost of a culled calf or heifer was $489 per head including the feed cost, genomic testing at birth, and calf value. The total rearing cost of culled heifers was higher with high CUR herds because more heifers were needed on the farm. The greater number of heifers raised on the farm increased the number of heifers culled before first calving proportionally. Herds with 25%-40% CUR could maintain herd size as a closed herd, 45% CUR herds had to purchase 5.4% replacement heifers externally every year.

Slaughter value was $1,067, $1,057, $1,048, $1,030, and $1,032 per cow for herds with 25%, 30%, 35%, 40%, and 45% CUR. Culled cows from higher CUR herds were younger than lower CUR herds and had lower body weight, which resulted in lower slaughter value. The differences between heifer rearing cost and culled cow slaughter values were $55, $65, $74, $82, and $90 per head, respectively. The heifer sale value at 23-month age was $1,333 per head, which resulted in a $211 revenue per head sold as surplus heifer. Herd-level replacement transaction costs were negative with default market conditions for all CUR levels, indicating that the replacement transaction was a source of revenue in all CUR level herds. The revenues were $91,687, $79,397, $66,481, $52,966, and $39,983 per CC with 25%, 30%, 35%, 40%, and 45% CUR. The reason was the high heifer sale price. Low CUR herds had greater transaction revenue, because more surplus heifers were sold.

Farm IOFC was $5.36 per cow per d for 25% CUR herds and $5.40 per cow per d for 45% CUR in the first CC. Despite 45% CUR herds having the lowest milk production in first CC, the greater proportion of younger cows in 45% CUR herds decreased the herd-level DMI and associated feed cost, which elevated IOFC per cow per d. Farm IOFC increased with time, depending on MPI levels. Levels of 1%, 1.5%, and 2% MPI increased farm IOFC by 19.6%, 28.9%, and 38.2%, on average. As discussed above, the negative farm replacement transaction cost made the farm profit higher than the farm IOFC. Farm profit was $5.59 per cow per d for 25% CUR and $5.50 per cow per d for 45% CUR in the first CC, after including the replacement transaction cost from IOFC (Table 4.4). Herds with 25% CUR + 2% MPI had the highest profit and herds with 45% CUR + 1% MPI had the lowest profit; the difference between 25% CUR+2% MPI herds and 45% CUR + 1% MPI herds enlarged over time. With the same CUR, higher MPI always led to a higher farm profit. With the same MPI, lower CUR led to higher farm profit under the default market scenario. Higher MPI narrowed the profit gap between 45% and 25% CUR herds, compared with lower MPI over time. In the first CC, 45% CUR herds' profit was 1.60% lower than herds with 25% CUR. With 2% MPI, 45% CUR herds' profit was 0.64% lower than 25% CUR herds after 15 CC. In addition, with 45% CUR herds' profit was 1.35% lower than 25% CUR herds with 1% MPI after 15 CC.

Although higher CUR herds had lower profit compared with lower CUR herds with the same MPI, farm profit from high CUR herds surpassed low CUR herds' profits with increasing MPI level. Herds with 45% CUR and 1.5% MPI began to have a higher profit than 25% CUR and 1% MPI herds during the 5th CC. Herds with 45% CUR and 2% MPI began to have higher profit during the 4th and 5th CC, compared with 25% CUR herds with 1% and 1.5% MPI, respectively (Table 4.5 and Figure 4.6). Culling rates determined the replacement transaction cost that changed the farm profit, while MPI continuously involved improving milk production. Benefits from higher MPI compensated the difference in replacement transaction cost of various CUR levels as time passed.

4.4.6 Effect of Market Prices

In the first scenario (high milk price and high slaughter price), higher milk to feed price ratio increased farm IOFC to $7.55 per cow per d for 25% CUR herds and $7.60 for 45% CUR herds. High slaughter price ($2.50 per kg) increased slaughter value to $1,588, $1,573, $1,560, $1,547, and $1,536 per cow, which were all higher than the heifer rearing cost ($1,122 per heifer) and turned the cost of replacing a cow to a negative value. This market scenario was favorable for high CUR herds that had more culled cows sold for slaughter. Farm profit increased to $8.23 per cow per d for 25% CUR herds and $8.35 per cow per d for 45% CUR herds in the first CC. The highest profit was from 45% CUR + 2% MPI herds and lowest profit was from 25% CUR + 1% MPI herds. Higher CUR herds had greater profit than lower CUR herds in all CC, regardless of MPI levels. Higher MPI level still led to a higher profit than lower MPI with the same CUR.

In the second scenario (low milk price), farm IOFC decreased to $4.76 per cow per d for 25% CUR herds and $4.80 for 45% CUR herds. Farm profit was $5.00 per cow per d for 25% CUR herds and $4.92 per cow per d for 45% CUR herds. This market scenario was very close to the baseline market scenario except for lower milk price. Trends in farm IOFC and profit were similar. The profit gap between 25% and 45% CUR herds enlarged with lower milk price (0.9% vs. 1.0% in the first CC and 0.1% vs. 0.2% after 15 CC with 2% MPI)

The third market scenario (high milk price and low slaughter price) increased farm IOFC and farm profit and broadened the gap between low and high CUR herds. Farm IOFC was $6.66 per cow per d for 25% CUR herds and $6.70 per cow per d for 45% CUR herds. Farm profit was $6.74 per cow per d for 25% CUR herds and $6.57 per cow per d for 45% CUR herds. Herds' profit with 25% CUR was 2.52% higher than 45% CUR herds in the first CC, which was greater than the difference of 1.63% in the baseline market scenario. The gap shrank to 2.11% with 1% MPI and 1.29% with 2% MPI after 15 CC. Compared with the baseline price scenario, the 13.7% higher milk price increased farm profit regardless of different CUR and MPI levels. However, the 17.6% lower slaughter price consolidated the farm profit advantage of low CUR.

Previous research has demonstrated that high slaughter price, low milk price, and high feed price would bring forward the optimal culling time and increase the optimal culling rate (Rogers et al., 1988; Cabrera, 2010; Liang et al., 2016). The baseline market scenario had a relatively high heifer sale price determining that selling one surplus heifer was positive and selling surplus heifers increased the farm profit. Cows' slaughter value was lower than replacement heifer rearing cost in the baseline scenario, indicating that replacing one lactating cow with a replacement heifer decreased profit. The cost of replacing culled cows partially compensated the revenue of selling surplus heifers. The offset amounts depended on the number of surplus heifers and culled lactating cows. Herds with 25% CUR had more surplus heifers to sell and fewer culled cows than higher CUR herds (CUR > 25%). As a result, 25% CUR herds had higher farm profit than 45% CUR herds. In the high slaughter price scenario, a cow's slaughter price was higher than the rearing cost of a replacement heifer, so the margin of replacing one more cow was positive. Nonetheless, 45% CUR herds had fewer surplus heifers compared with 25% CUR herds, the greater number of culled cows made up the difference in surplus heifer sales and led to greater farm profit under the high slaughter price scenario. Milk and feed prices were the major influencing factors in farms' profit (Wolf et al., 2009). Variation in milk-to-feed price ratio shifted the farm profit up and down; however, only slaughter price changed the profit ranking between different CUR herds. This result agreed with Rogers et al. (1988) indicating that the impact of changes in milk and feed prices was much greater than that of changes in replacement heifer cost. The second market scenario had lower milk price and the same slaughter price as the baseline scenario. Farm profit in the second market scenario was lower than the baseline scenario, whereas herds with different CUR stayed in the same ranking. In the third scenario, with higher milk price and lower slaughter price, farm profits were higher than the baseline scenario. However, the difference between different CUR herds was greater.

4.4.7 Effect of Age at First Calving and Surplus Heifer Selling Time on Heifer Enteric Emission

Delayed AFC increased heifer enteric emission and heifer rearing costs. An AFC delay from 24-month to 26-month increased heifer enteric CH_4 emission per head from 2,905 kg CO_{22} eq. to 3,027 kg CO_2 eq. and increased heifer rearing costs from $1,122 to $1,166. Delaying AFC to 28-month increased heifer enteric emission to 3,074 kg $CO_2$2 eq. per head and increased heifer rearing costs to $1,193 per head. Delayed AFC further increased enteric CH_4 emission per kg FCM by increasing heifer emissions.

Selling surplus heifers at birth decreased the enteric emission and feed cost attributed to surplus heifers. A previous study found the GHG emission decreased by 4.9 to 6.7% before adjusting for the allocation factor (Weiske et al., 2006). In this study, herds with 45% CUR had insufficient replacement heifers, so the sale of surplus heifers had no effect. Herds with 45% CUR needed to purchase heifers externally to maintain herd size, which increased emissions input into the herd. Selling surplus heifers earlier also reduced meat sales, which slightly increased the allocation factor to milk (data not shown). These 2 factors canceled out in the results: the total enteric emission of selling surplus heifers at birth was lower than selling one month before calving, and the enteric emission allocated to milk of selling heifer at birth was slightly higher than selling one-month before calving. Surplus heifers sold at birth also saved feed costs, and the farm profit of selling surplus heifers at birth was higher than when selling one month before calving. The increase in farm profit was from 1.32% to 1.81% in 25% CUR herds, varying by MPI levels. The farm profit increase was lower with the higher CUR herds, because more heifers were needed to maintain herd size, and fewer surplus heifers were available. The profitability of selling surplus heifers at an early age depended on the market conditions. Weiske et al. (2006) found that selling surplus heifers at birth decreased farm profit in conventional dairy farms because of the higher meat price and associated higher heifer sale value when mature.

This study only analyzed enteric emission in the dairy herd. Emission from cropland and manure management were not included. Herd structure and MPI would change cropland emission by changing the feed demand. Manure management emission are related to herd structure and MPI, as well as manure management type. Higher CUR herds require more heifers on farm, which will increase the feed demand and manure amount on the farm. The relationship between herd management strategies and farm-level greenhouse gas emission needs to be further tested.

4.5 Conclusions

Results from this study confirmed that improving milk productivity is the best strategy to reduce enteric CH_4 emission and increase farm profit in the long-term. Improved milk productivity is effectively achieved by genetic milk productivity improvement. Culling rate changes farm profit and enteric CH_4 emission in the short-term. Slaughter price highly influences the effect of culling on farm profit. Higher culling had a detrimental effect on mitigating enteric CH_4 emission with the same level of milk productivity improvement. Having higher milk productivity improvement in higher culling herds could counteract the adverse effect on enteric CH_4 emission.

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Table 4.1. Most important equations contained in this model

Item	Equation	Unit
Transaction cost per calving cycle (herd level)	= Number of culled cows × Culled cow body weight ×Slaughter price + Number of surplus heifers × (Surplus heifer sale price × Surplus heifer body weight – Surplus heifer rearing cost) –Number of culled heifers × Culled heifer rearing cost – Number of heifers purchased from outside × Heifer purchase price	$ per calving interval
Farm income over feed cost (IOFC) per cow per d	= (Milk production in 1 CC × milk price – Lactating cow DMI × Lactating cow DMI price)/(Number of lactating cows × calving interval length in days)	$ per cow per d
Farm profit per cow per d	= Farm IOFC per cow per d – (Transaction cost per CC/(Number of lactating cows × calving interval length in days))	$ per cow per d
Allocation factor to milk	$= 1-5.7717\times(M_{milk}/M_{meat})$	
Heifer enteric CH_4 emission	= 6.5% × Total gross energy intake per d	MCal per head per d
Lactating cow enteric CH_4 emission	$= 62 + 25.05\times$ DMI	L CH_4 per cow pr d
Dry matter intake per cow per d	NRC equation	Kg DM per cow per d
4% Fat corrected milk	=0.4 × Milk production + 15 × (Milk production × Milk fat content (%))	Kg

Table 4.2. Target body weight at each growth time point.

	Body weight (kg per head)	Comment
Birth weight	41	Authors assumption
Weaning weight	82	Double of birth
Heifer breeding weight	391	55% of shrunk mature body weight (NRC, 2001)
First calving weight	607	82% of mature weight (NRC, 2001)
First lactation after negative energy balance period (60 DIM)	557	
Second calving weight	681	92% of mature weight (NRC, 2001)
Second lactation after negative energy balance period (60 DIM)	631	
Mature weight	740	Authors assumption for large Holsteins
Third and later lactation after negative energy balance period (60 DIM)	690	

Table 4.3. Average milk production per cow per yr in each of 15 calving cycles (**CC**[1]) with different culling rate (**CUR**) and milk productivity improvement (**MPI**) per CC. Results in 35% CUR herds are reported as the absolute value, results in other CUR levels are reported as the difference in percentage from the production of the 35% CUR and the same MPI.

Calving cycle	Herd culling rate and milk productivity improvement per calving cycle, %														
	25	25	25	30	30	30	35	35	35	40	40	40	45	45	45
	1.0%	1.5%	2.0%	1.0%	1.5%	2.0%	1.0%	1.5%	2.0%	1.0%	1.5%	2.0%	1.0%	1.5%	2.0%
1	-3.5	-3.5	-3.5	-0.4	-0.4	-0.4	9,985	9,985	9,985	-2.0	-2.0	-2.0	-6.1	-6.1	-6.1
2	-4.0	-5.6	-7.3	-0.6	-1.4	-2.2	10,048	10,058	10,068	-1.8	-1.0	-0.1	-5.7	-4.0	-2.3
3	-4.0	-9.0	-14.0	-0.6	-3.1	-5.5	10,149	10,183	10,217	-1.8	+0.6	+3.0	-5.7	-0.9	+3.9
3	-4.1	-12.6	-21.2	-0.6	-4.8	-9.0	10,250	10,319	10,389	-1.9	+2.2	+6.3	-5.8	+2.2	+10.2
5	-4.1	-15.6	-27.2	-0.6	-6.2	-11.9	10,353	10,465	10,579	-1.9	+3.4	+8.8	-5.9	+4.5	+15.0
6	-4.1	-17.5	-31.1	-0.6	-7.1	-13.7	10,456	10,618	10,782	-1.9	+4.2	+10.4	-5.9	+5.9	+17.9
7	-4.2	-18.2	-32.6	-0.6	-7.4	-14.4	10,561	10,776	10,996	-1.9	+4.4	+11.0	-6.0	+6.3	+18.9
8	-4.2	-18.5	-33.3	-0.6	-7.5	-14.7	10,667	10,938	11,215	-1.9	+4.5	+11.2	-6.0	+6.4	+19.3
9	-4.3	-18.8	-34.0	-0.6	-7.6	-15.0	10,773	11,102	11,440	-2.0	+4.6	+11.4	-6.1	+6.5	+19.7
10	-4.3	-19.0	-34.6	-0.6	-7.8	-15.3	10,881	11,268	11,669	-2.0	+4.6	+11.7	-6.2	+6.6	+20.1
11	-4.4	-19.3	-34.5	-0.6	-7.9	-15.2	10,990	11,438	11,896	-2.0	+4.7	+11.5	-6.2	+6.7	+19.6
12	-4.4	-19.6	-33.2	-0.6	-8.0	-14.5	11,100	11,609	12,121	-2.0	+4.8	+10.7	-6.3	+6.8	+18.1
13	-4.4	-19.9	-32.9	-0.7	-8.1	-14.3	11,211	11,783	12,357	-2.0	+4.9	+10.5	-6.3	+6.9	+17.5
14	-4.5	-19.6	-33.5	-0.7	-7.9	-14.6	11,323	11,956	12,604	-2.1	+4.6	+10.7	-6.4	+6.4	+17.8
15	-4.5	-18.4	-34.2	-0.7	-7.3	-14.9	11,436	12,126	12,856	-2.1	+4.0	+10.9	-6.5	+5.0	+18.2
Change from the first CC	+14.5 %	+21.3 %	+28.5 %	+14.5 %	+21.4 %	+28.6 %	+14.5 %	+21.4 %	+28.8 %	+14.5 %	+21.5 %	+28.9 %	+14.5 %	+21.6 %	+29.0 %

[1] CC: Calving cycle is a 13-mo time unit defined in this study. The length of one calving cycle was 13-mo and it was related with the calving interval length.

Table 4.4. Enteric CH_4 emission allocated to milk per kg FCM (kg CO_2 eq. per kg FCM) with different culling rates (**CUR**) and milk productivity improvement (**MPI**) levels across 15 calving cycles (**CC**[1]) and 24-mo age at first calving scenario.

	Herd culling rate and milk productivity improvement per generation														
Calving cycle	25	25	25	30	30	30	35	35	35	40	40	40	45	45	45
	1%	1.5%	2%	1%	1.5%	2%	1%	1.5%	2%	1%	1.5%	2%	1%	1.5%	2%
1	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.50	0.50	0.50
2	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.50	0.50	0.50
3	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
3	0.49	0.48	0.48	0.49	0.48	0.48	0.49	0.48	0.48	0.49	0.48	0.48	0.49	0.49	0.49
5	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.49	0.49	0.48
6	0.48	0.48	0.47	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.49	0.48	0.48
7	0.48	0.47	0.47	0.48	0.48	0.47	0.48	0.48	0.47	0.48	0.48	0.47	0.49	0.48	0.48
8	0.48	0.47	0.47	0.48	0.47	0.47	0.48	0.47	0.47	0.48	0.47	0.47	0.48	0.48	0.47
9	0.47	0.47	0.46	0.47	0.47	0.46	0.48	0.47	0.46	0.48	0.47	0.46	0.48	0.47	0.47
10	0.47	0.46	0.46	0.47	0.47	0.46	0.47	0.47	0.46	0.47	0.47	0.46	0.48	0.47	0.46
11	0.47	0.46	0.45	0.47	0.46	0.45	0.47	0.46	0.45	0.47	0.46	0.45	0.48	0.47	0.46
12	0.47	0.46	0.45	0.47	0.46	0.45	0.47	0.46	0.45	0.47	0.46	0.45	0.48	0.47	0.46
13	0.47	0.45	0.44	0.47	0.46	0.45	0.47	0.46	0.45	0.47	0.46	0.45	0.47	0.46	0.45
14	0.46	0.45	0.44	0.46	0.45	0.44	0.46	0.45	0.44	0.47	0.45	0.44	0.47	0.46	0.45
15	0.46	0.45	0.44	0.46	0.45	0.44	0.46	0.45	0.44	0.46	0.45	0.44	0.47	0.46	0.44
Change from the first calving cycle	-6.4%	-9.0%	-11.4%	-6.3%	-8.8%	-11.3%	-6.1%	-8.6%	-11.1%	-5.9%	-8.4%	-10.8%	-5.8%	-8.2%	-10.6%

[1] CC: Calving cycle is a time unit defined in this study. The length of one calving cycle was 13-month and related with the calving interval length.

Table 4.5. Farm profit (subtracted transaction replacement cost from income over feed cost) $ per cow per d with different levels of culling rate (**CUR**) and milk productivity improvement (**MPI**) on milk production through 15 calving cycles (**CC**[1]) time under the baseline scenario.

	Herd culling rate and milk productivity improvement per generation														
Calving	25	25	25	30	30	30	35	35	35	40	40	40	45	45	45
cycle	1%	1.5%	2%	1%	1.5%	2%	1%	1.5%	2%	1%	1.5%	2%	1%	1.5%	2%
1	5.59	5.59	5.59	5.58	5.58	5.58	5.56	5.56	5.56	5.53	5.53	5.53	5.50	5.50	5.50
2	5.64	5.65	5.65	5.62	5.63	5.64	5.60	5.61	5.62	5.58	5.59	5.59	5.55	5.56	5.57
3	5.71	5.73	5.76	5.70	5.72	5.74	5.67	5.70	5.72	5.65	5.68	5.70	5.62	5.65	5.68
3	5.79	5.83	5.88	5.77	5.82	5.86	5.75	5.80	5.85	5.72	5.78	5.83	5.70	5.75	5.81
5	5.86	5.94	6.01	5.84	5.92	6.00	5.82	5.91	5.99	5.80	5.88	5.97	5.77	5.86	5.95
6	5.94	6.04	6.15	5.92	6.03	6.15	5.90	6.02	6.14	5.87	6.00	6.12	5.85	5.97	6.10
7	6.01	6.16	6.31	6.00	6.15	6.30	5.97	6.13	6.29	5.95	6.11	6.28	5.92	6.09	6.26
8	6.09	6.28	6.47	6.07	6.26	6.46	6.05	6.25	6.45	6.03	6.23	6.44	6.00	6.21	6.42
9	6.17	6.40	6.63	6.15	6.38	6.62	6.13	6.37	6.61	6.10	6.35	6.60	6.08	6.33	6.58
10	6.25	6.52	6.80	6.23	6.51	6.79	6.21	6.49	6.78	6.18	6.47	6.77	6.16	6.45	6.75
11	6.32	6.64	6.96	6.31	6.63	6.96	6.29	6.61	6.95	6.26	6.59	6.93	6.23	6.57	6.91
12	6.40	6.76	7.13	6.39	6.75	7.12	6.37	6.74	7.11	6.34	6.72	7.10	6.31	6.69	7.08
13	6.49	6.89	7.30	6.47	6.88	7.29	6.45	6.86	7.28	6.42	6.84	7.27	6.40	6.82	7.25
14	6.57	7.02	7.48	6.55	7.00	7.47	6.53	6.99	7.46	6.50	6.97	7.45	6.48	6.95	7.43
15	6.65	7.14	7.66	6.63	7.13	7.65	6.61	7.11	7.64	6.59	7.09	7.63	6.56	7.07	7.61
Change from the first calving cycle	18.9%	27.6%	36.9%	18.9%	27.8%	37.3%	19.0%	28.0%	37.6%	19.1%	28.2%	37.9%	19.2%	28.5%	38.3%

[1] CC: Calving cycle is a time unit defined in this study. The length of one calving cycle was 13-month and related with the calving interval length.

Figure 4.1. Lactation curve (fat-corrected milk production) for cows in the first, second, and third lactation in the 1st calving cycle (CC). The first lactation cows had the genetic potential of P (potential production of 11,357 per cow per year; the second lactation cows had the genetic potential of P-1 (potential production of 11,244 per cow per year; the third lactation cows had the genetic potential of P-2 (potential production of 11,133 per cow per year. The 12th and 13th mo in lactation are the dry period.

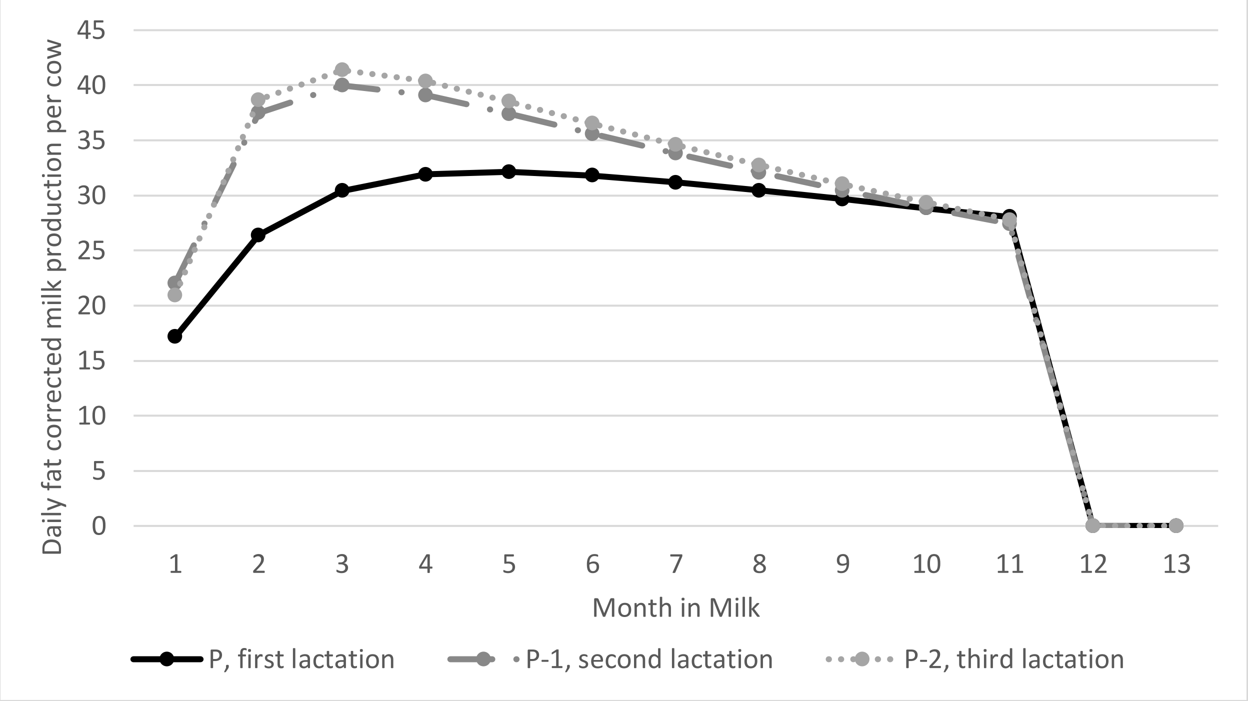


Figure 4.2. Herd structure of the 1,000 adult cows in the first, second, and third and later lactations with different culling rate.

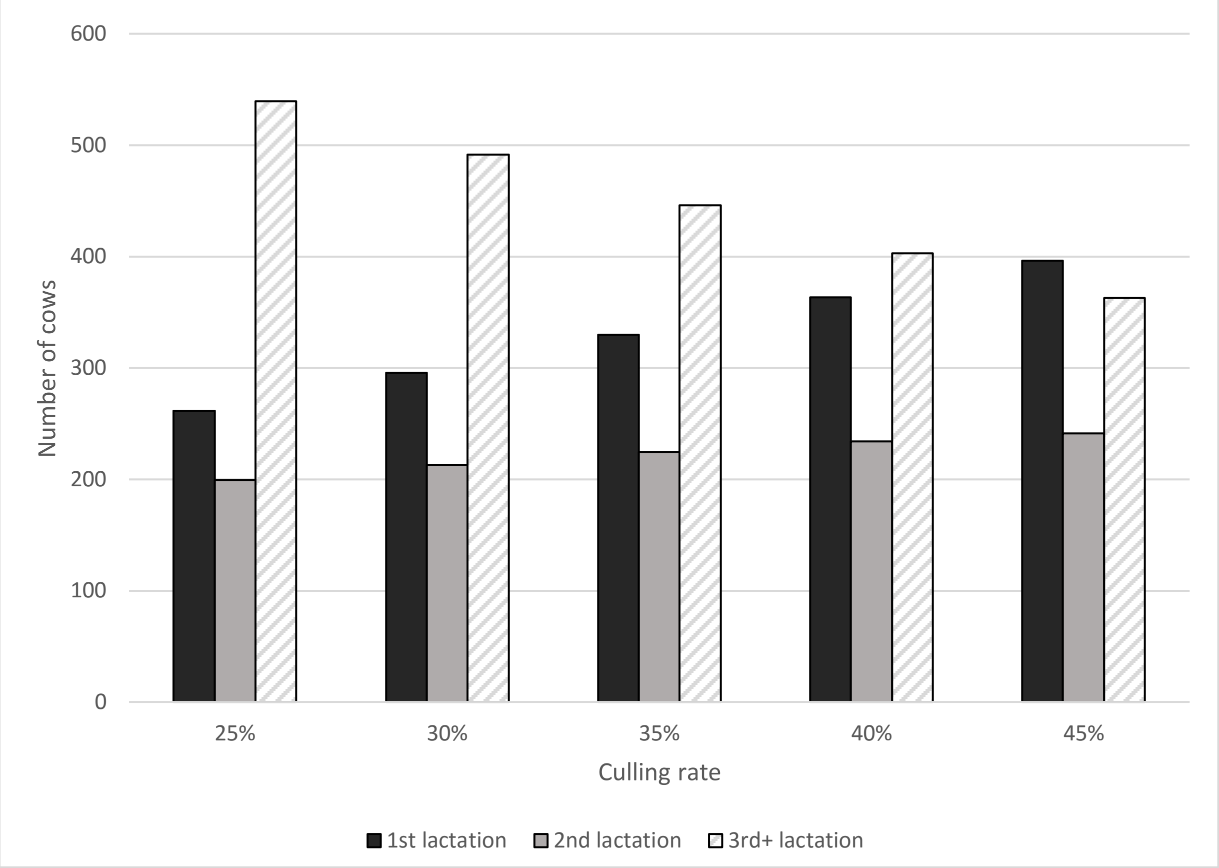


Figure 4.3. Total monthly milk production (kg) for the all the cows in the 1st, 3rd, and 6th lactation of the 25% and 45% culling rate (CUR) herds. The 12th and 13th mo in lactation are the dry period. Higher CUR herds had more milk production in the 1st lactation from the greater number of younger cows. Lower CUR herds had more milk production in the 3rd and 6th lactation from the greater number of mature cows.

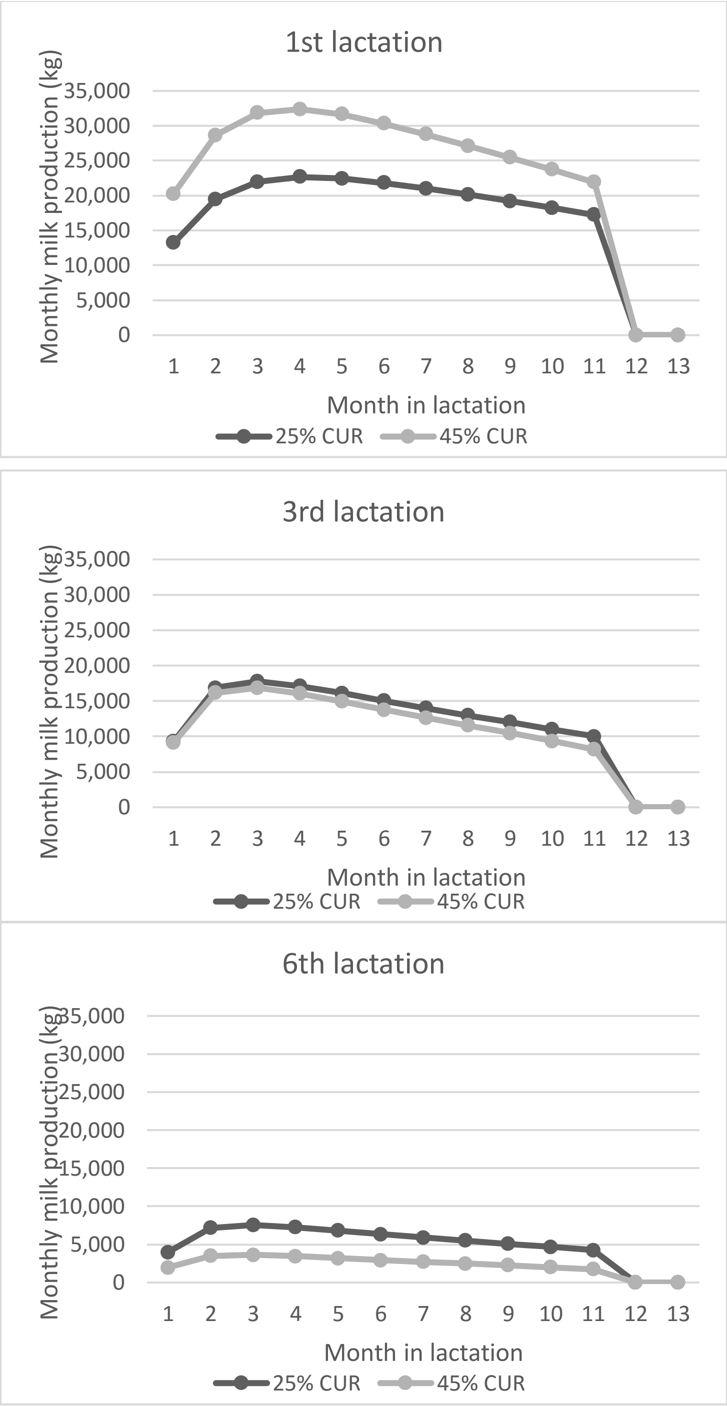
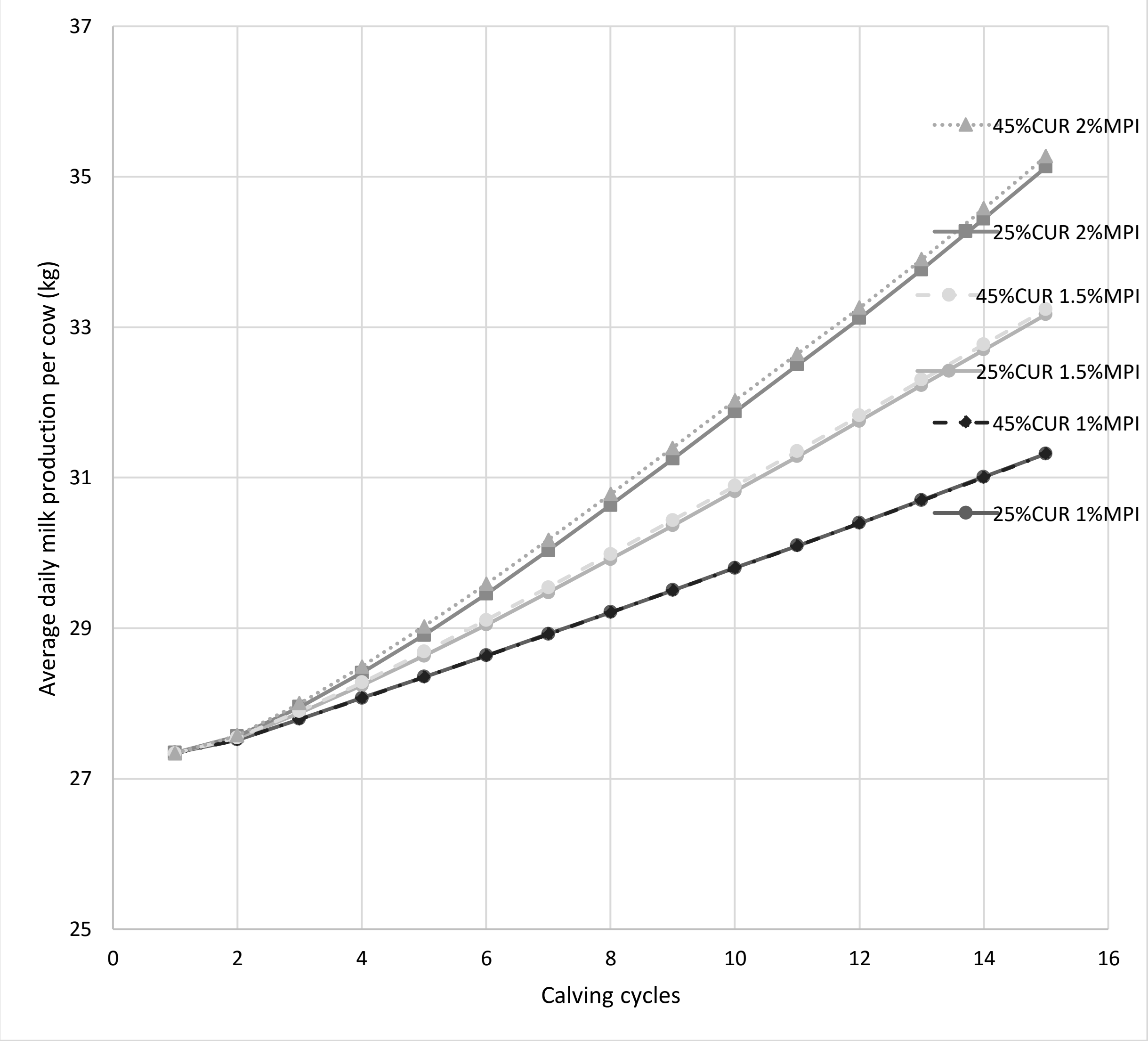
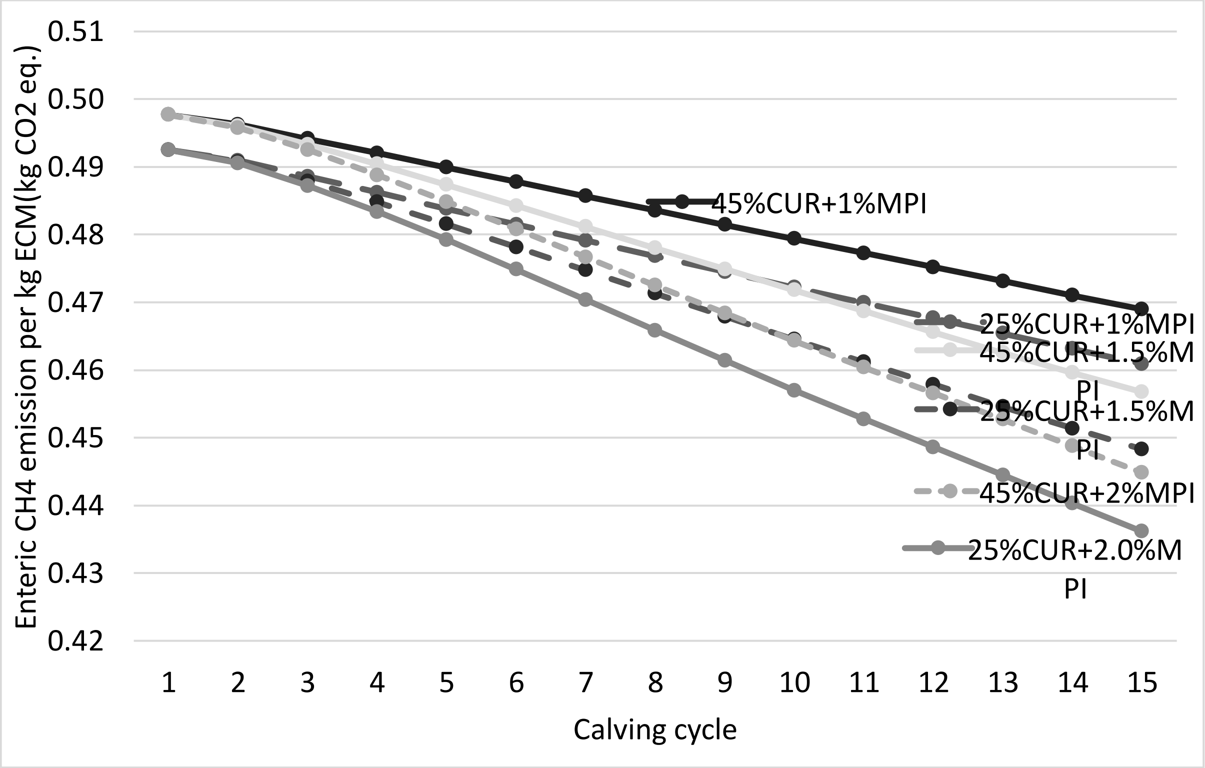


Figure 4.4. Milk production per cow per d for herds with 25% and 45% culling rates (**CUR**) and three different levels of milk productivity improvement (**MPI**) per calving cycle (**CC**[1], 1.0%, 1.5%, and 2.0%).



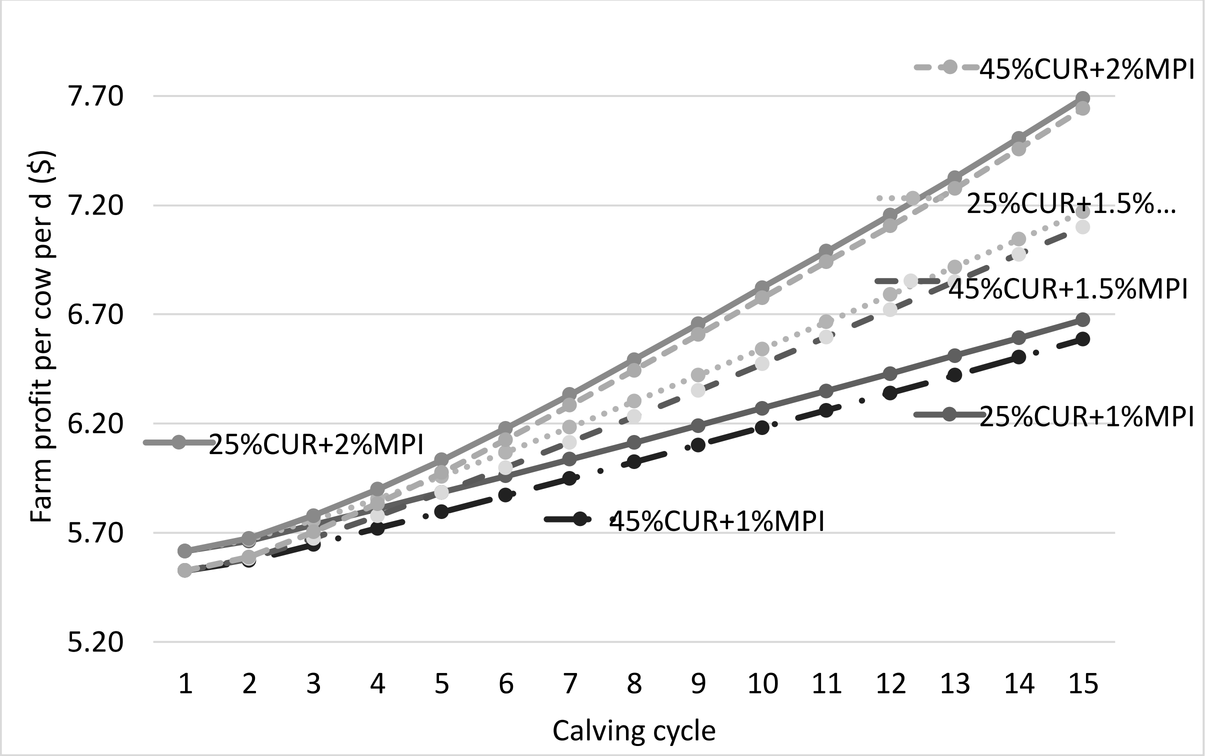
[1] CC: Calving cycle is a time unit defined in this study. The length of one calving cycle set as 13-mo and related with the calving interval length.

Figure 4.5. Enteric CH4 emission per kg FCM (kg CO22 eq.) with 25% and 45% culling rates (CUR) and 3 different levels of milk productivity improvement (MPI) per calving cycle (CC1, 1.0%, 1.5%, and 2.0%).



[1]CC: Calving cycle is a time unit defined in this study. The length of one calving cycle set as 13-month and related with the calving interval length.

Figure 4.6. Farm profit per cow per d for herds with 25% and 45% culling rates (**CUR**) and 3 different levels of milk productivity improvement per generation (1.0%, 1.5%, and 2.0%). Mo 0 represented the first calving interval in which the herd had the same genetics in each lactation.



[1] CC: Calving cycle is a time unit defined in this study. The length of one calving cycle set as 13-month and related with the calving interval length.

Chapter 5

Effect of feeding strategies and cropping systems on greenhouse gas emission from Wisconsin certified organic dairy farms

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5.1 Abstract

Organic agriculture continues to expand in the United States (U.S.), both in total hectares and market share. However, management practices used by dairy organic producers, and their resulting environmental impacts, vary across farms. This study used a partial life cycle assessment approach to estimate the impact of different feeding strategies and associated crop production on greenhouse gas emissions (GHG) from Wisconsin certified organic dairy farms. Field and livestock-driven emissions were calculated using two datasets. One was a 20-year dataset from the Wisconsin Integrated Cropping System Trial (WICST) documenting management inputs, crop and pasture yields, and soil characteristics, used to estimate field-level emissions from land associated with feed production (row crop and pasture), including nitrous oxide (N_2O) and soil carbon sequestration. The other one was a dataset summarizing organic farm management in Wisconsin, which was used to estimate replacement heifer emission (eq. CO_2), enteric methane (CH_4), and manure management (N_2O and CH_4). Three combinations of corn grain (**CG**) and soybean (**SB**) as concentrate (ALLCORN: 100% CG, BASELINE: 75%CG+25%SB, and HALFCORN: 50%CG+50%SB) were assigned to each of 4 representative management strategies as determined by survey data. Overall, GHG emissions associated with crop production was 1,297 ± 136 kg eq. CO_2 per t ECM without accounting for soil carbon changes (**ΔSC**), and GHG emission with ΔSC was 1,457 ± 111 kg eq. CO_2 per t ECM, with greater reliance on pasture resulting in less ΔSC. Higher level of milk production was a major driver associated with reduction in GHG emission per t ECM. Emissions per t ECM increased with increasing proportion of SB in the ration; however, including SB in the crop rotation decreased N_2O emission per t ECM from cropland due to lower applications of organically-approved N fertility inputs. More SB at the expense of CG in the ration reduced enteric CH_4

emission per t ECM (because of greater dietary fat content) but increased N_2O emission per t ECM from manure (because of greater N content). An increased reliance on pasture for feed at the expense of grain resulted in decreased in milk production, subsequently leading to substantially higher emissions per t ECM.

Key Words: partial life cycle assessment, carbon footprint, grazing management

5.2 Introduction

The market for organic products continues to expand both in the US and abroad, reaching approximately $35 billion sales in 2014 (USDA Economic Research Service, 2013). Organic milk demand has recently surpassed available supply, unable to keep pace with consumer demand in 2015 (Greene and McBride, 2015). As new farms transition to organic production to meet the rising demand for organic milk, farmers likely will need to adjust the feeding strategies used for their conventional herds to achieve the required minimum of 30% DMI from pasture during the grazing season, as outlined by the United States Department of Agriculture National Organic Program (USDA-NOP, 2013). Within this regulatory framework, however, different approaches relating to both crop production strategy and feed ration composition exist that could be adopted by organic dairy farmers. Wisconsin's organic dairy farms currently exhibit a wide range of these approaches, including varying reliance on pasture or concentrates (Hardie et al., 2014); these farms could serve as models for transitioning producers aspiring to attain specific production, economic, and environmental benchmarks under organic management.

Across all of agriculture, increasing attention has been focused on greenhouse gas (**GHG**) emissions resulting from production practices and their associated impacts on climate change (Intergovernmental Panel on Climate Change, IPCC, 2013). Agriculture contributes approximately 9% to total GHG emissions in the US and 14% of emissions globally (EPA, 2014). While the dairy industry is not a particularly significant source of total global anthropogenic GHG emissions (4% in 2010), the US dairy industry has committed to a 25% reduction of GHG by 2020 relative to 2009 (Innovation Center for US Dairy®). The major sources and sinks of GHG on the dairy farm are associated with crop production (CO_2 and N_2O), enteric fermentation of feed by livestock (CH_4), and manure management (CH_4 and N_2O).

Variations in diet formulation, and the associated crop production to supply that diet, can affect the quantity of GHG emissions of the various systems, as highlighted by several studies demonstrating the importance of feed quantity and quality to reduce livestock GHG emission intensity (Johnson et al., 2007; Ogino et al., 2007; Beauchemin et al., 2010; Pelletier et al., 2010).

Life cycle assessment (**LCA**) has been used to evaluate the GHG emissions from dairy operations on a whole-farm level. Studies have compared GHG emissions of confinement-based feeding operations to pasture-based systems, including organically-managed systems that include pasture (Cederberg and Mattsson, 2000; Weiske et al., 2006). Several studies indicated that the amount of concentrate fed to dairy herds, and its associated crop production-based GHG emissions and subsequent impacts on feed digestibility, enteric methane emissions, and milk productivity (Aguerre et al., 2011; Beauchemin et al., 2008).

As farms make the transition to certified organic practices, critical decisions must be made with respect to feeding strategies and diet composition. Thus, with increasing numbers of dairy operations under organic management, the optimization of feeding strategies provides an opportunity to minimize the carbon footprint of organic dairy farms in Wisconsin while maintaining productivity. Therefore, the objective of this study was to compare the impacts of potential feeding strategies and the associated crop hectares on GHG emissions of Wisconsin certified organic dairy farms.

5.3 Materials and Methods

5.3.1 Feeding Strategies

An analysis from a 2010 survey of Wisconsin certified organic dairy farms’ management characteristics (Hardie et al., 2014) revealed 4 feeding strategies and production outputs typifying Wisconsin organic dairy farms. Farms were clustered using 9 parameters under 3 general categories: 1) general farm characteristics and management (herd size, percent of Holstein cows, and milking frequency); 2) non-pasture-based feeding practices (number of cow groups, amount of concentrate fed, and feed supplements); and 3) grazing practices (percent of land used as pasture, pasture occupancy period, and grazing season length). Detailed descriptions of herd and management factors for the farms in each of the clusters (number of cows, rolling herd milk average, percent Holstein cows, concentrate fed, land used as pasture, length of grazing season, and average hours per day on pasture) are summarized in Table 5.1 (Hardie et al., 2014). Greenhouse gas emission allocation between milk and meat was calculated for each cluster, which was based on the weight of meat (bull calf and beef sale) and milk sale (IDF, 2010). Results reported as GHG emission per t ECM represented the GHG emission allocated to one t ECM, with an exception in Table 5.7, in which N_2O and CH_4 emission from each emission source and soil carbon loss value were total emission for both milk and meat.

Cluster 1 was comprised of 8 farms with an average herd size of 128 cows. The predominate breed in cluster 1 was Holstein, with lesser represented breeds including Jersey, Milking Shorthorn, Brown Swiss, Swedish Red, Normande, Dutch Belted, Linebacks, and Fleckvieh (Hardie, 2013). The lactating cows of the farms described by this cluster heavily relied on supplementation and minimally on pasture. Cow management was the most similar to conventional management strategies among all 4 clusters; it had the least-hours per day on pasture compared with the other 3 clusters, low percentage of land designated to pasture, high levels of concentrate feeding and high DMI. The productivity per cow (i.e., ECM) was second-highest among the clusters.

Cluster 2 was comprised of 5 farms with an average of 50 cows each of varying breeds (both purebred and crossbred of Jersey, Milk Shorthorn, Normande, Brown Swiss, Ayrshire, and New Zealand Friesian; only one farm had 12% purebred Holsteins; Hardie, 2013) and that used seasonal calving. Farms in cluster 2 grazed more days annually than other clusters, had the greatest percent of land under pasture, and utilized the least amount of concentrate. In part due to seasonal milking, the productivity of these herds was the lowest of all clusters.

Cluster 3 was comprised of 32 farms with an average herd size of 41 cows. Similar strategies were used as in cluster 1 for feeding their smaller herds, feeding 6 kg per d of concentrate per cow. Cluster 3 was 89% purebred Holstein; other purebred cows were Jersey and Lineback breeds. The other crossbred cows had the genetics of Holstein, Jersey, Milking Shorthorn, Brown Swiss, Angus, Guernsey, Swedish Red, Normande, Dutch Belted, Montbeliarde, Lineback, Danish Red, Friesian, or Norwegian Red (Hardie, 2013). Average hours on pasture per day for cows were greater than cluster 1. Although percent time grazing of pasture was similar, the percentage of land designated as pasture in cluster 3 was substantially greater than the farms of cluster 1. The predominant breed of these herds was Holstein. The highest rolling herd average milk production was found on the farms of this cluster.

Cluster 4 was comprised of 24 farms with an average herd size of 43 cows, typically not milking purebred Holstein. Crossbreds in cluster 4 had similar genetics as cluster 3 (Hardie, 2013). Cows of cluster 4 farms spent more time on pasture during the grazing season, with more land designated to pasture than clusters 1 and 3. During the non-grazing season, lactating cow feeding strategies were similar to clusters 1 and 3. Milk production was less than that of farms from clusters 1 and 3.

5.3.2 Cropland and Pasture Greenhouse Gas Emissions

The Wisconsin Integrated Cropping Systems Trial (**WICST**), a long-term cropping system experiment established in 1989 located in Arlington, Wisconsin, has been used to collect crop production and soil data from 0.28 ha plots managed to represent production practices representative of Wisconsin agriculture (Posner et al., 2008; Posner et al., 1995; Sanford et al., 2012). The various cropping systems studied in the WICST trial include both organic grain-based and forage-based systems that are managed according to the USDA National Organic Program regulations and represent cash grain (corn-soybean-wheat rotation) and forage production strategies (corn-oat/alfalfa-alfalfa rotation) used among Wisconsin's organic dairy farmers (Posner et al., 2008). Inputs (seed, fertilizer/nutrients pesticides, etc.) as well as crop and pasture yield measurements are collected annually, with each phase of the crop rotation represented each year, providing a robust estimate of the yield potential on organically managed crop land in southern Wisconsin. Using the average yield data from a 16-yr period (1993-2008), the hectares required to produce the annual feed needs per cow for each of the model feeding strategies (corn grain (**CG**) and soybean (**SB**)) in concentrate, silage, alfalfa haylage, and pasture) were estimated for each cluster. These values were calculated according to the annual DM consumption of the lactating herd, annual crop yields, and feed moisture content using the reported values of each cluster was daily feed consumption from Hardie et al. (2014).

Emissions of N_2O and CH_4 from cropland and pasture were predicted based on input and yield data from the 16-yr (1993 to 2008) period on which this information was collected from the organic grain and forage rotations and pasture treatments on WICST. Using IPCC (2006b) equations, direct N_2O emissions from crop production and indirect N_2O emissions from leaching and volatilization were calculated. Emissions were converted to CO_2 equivalent (**eq. CO_2**)

emissions according to IPCC global warming potential values of 298 for N_2O and 34 for CH_4, (100-year time horizon with climate-carbon feedbacks, Myhre et al., 2013).

Changes in soil carbon quantities resulting from the crop management strategies represented in the WICST trial were calculated by comparing soil carbon concentrations in samples collected at the start of the trial started (in 1989) to samples collected 20 years later (Sanford et al., 2012). While this timeframe is relatively short, previous studies have demonstrated that soil l carbon changes resulting from crop production activities can be measured over this span of time (Bellamy et al., 2005 and Milesi Delaye et al., 2013). Protocols for determining soil carbon changes and associated data were detailed in Sanford et al. (2012). For the purposes of this analysis, annual soil carbon change (**ΔSC**) was calculated as the average annual soil change over the 20-yr period (1989 to 2008) assuming a linear trend.

5.3.3 Enteric Methane Estimation

The DMI of lactating cows in each of the 4 clusters was collected as farmer-reported data and summarized by Hardie et al. (2014). As part of Hardie et al. (2014) survey, farmers were asked to provide the DM amount of each feed type (concentrate, corn silage, alfalfa haylage, vitamin and mineral) fed to cows in both the non-grazing and grazing seasons. The DMI consumed from pasture were calculated as the difference between the estimated total DMI (provided by the surveyed farmers) and DM consumed from supplemented feed during the grazing season. Dry matter intake from different feeding strategies for each cluster were summarized in Table 5.2 from Hardie et al. (2014). Three concentrates scenarios were also listed in Table 5.2, which was described in the 'concentrate scenarios' section.

Enteric CH_4 emissions are impacted by multiple factors including DMI, NDF, fat, and energy content in the diet (Johnson and Johnson, 1995). In most cases, the IPCC equation (2006) was used for enteric CH_4 emission calculation; however, a model from Moraes et al. (2014, Appendix 5.I) was used to predict CH_4 emissions from enteric fermentation to better capture the variation of diet formulation (gross energy (**GE**) intake, dietary NDF, and dietary ether extract) in studied clusters. Additionally, the Moraes et al. model was used as the equation from IPCC (2006) would require several parameters (i.e., daily body weight gain) that were not reported in the original survey.

Feed ingredient chemical composition (Appendix 5.II) was collected from Nutrient Requirements of Dairy Cattle (NRC, 2001); GE was further calculated based on the carbohydrate, protein and ether extract proportion. High crude protein contents (19%-24% in different cluster, Table 5.3) were due to the high DMI from pasture (Wales et al., 1998), which had relatively greater CP content than the other feed ingredients (Appendix 5.II). Body weight of cows and milk fat were obtained from the survey results (Hardie, 2013).

5.3.4 Manure Management GHG Emissions

Estimations of GHG emissions associated with manure management included manure deposited on pasture during grazing, manure storage, and manure applied to the field through mechanical spreading. Manure N excretion was calculated as the difference between dietary N and milk N. The proportion of manure N deposited on pasture was determined by the annual length of the grazing season, hours in a day on pasture during the grazing period, and the monthly DMI from pasture during the grazing season; all of the three parameters were obtained from the survey (Hardie, 2013 and Table 5.1). For example, cows from cluster 1 spent 16.9 hr (70.4% of 24 hr) on pasture during the grazing period that started on Apr. 19th and ended on Nov.

7th; thus, 70.4% of the cows' manure during grazing period was deposited on pasture, with remaining proportion collected from confinement housing. Deposited manure N content and volatile solid content were determined by the monthly DMI of each feed ingredient for each grazing month (April to November). The survey results (Hardie et al., 2014) indicated that most of the organic farms handled lactating cow manure in liquid form. Eleven farms handled only solid manure (16%) from lactating cows: Clusters 1 and 2 all handled liquid manure, cluster 3 had 8 farms (25%) that handled solid manure and cluster 4 had 3 farms (12.5%) that handled solid manure. As such, it was assumed that all farms only handle liquid manure. Forty-six farms reported the storage time of liquid manure in earthen basin, 35 of them had storage time longer than 6 months. Thus we assumed that manure collected in confinement housing was stored in an earthen basin for 6 months, followed by applying to crop and pasture land. Emissions of CH_4 and N_2O from manure management were estimated with IPCC (2006a) equations listed in Appendix 5.I.

5.3.5 Replacement heifer emission

Greenhouse gas emission from heifers was based on percent of first lactation cows, herd size, and body weight (Table 5.1). Heifer body weight is 92% of mature cow body weight (NRC 2001). An emission factor of 11 kg eq. CO_2 per kg of body weight (Rotz et al., 2013) was assigned to replacement heifers. Calculation is listed in Appendix 5.I. Greenhouse gas emission per heifer was 6,172, 5,541, 5,992, and 5,385 kg eq. CO_2 for cluster 1, 2, 3, and 4, respectively.

5.3.6 Concentrate Scenarios

In order to estimate the impact of diversification of feed supplementation strategies, 3 combinations of CG and SB were designed to evaluate the plausible respective GHG emissions of feeding concentrate of varying ingredient composition. These combinations were (CG:SB): 1)

100:0 (**ALLCORN**), 2) 75:25 (**BASELINE**), and 3) 50:50 (**HALFCORN**). All the concentrate combination scenarios on each cluster are represented in Table 5.2. Chemical composition of each concentrate scenario is depicted in Table 5.3, including CP, NDF, ADF, NFC, ash, and GE. Crop land needed to produce the necessary amount of grain for each diet was modified as appropriate for the different diets. The BASELINE was used as the base scenario for comparison. Dry matter intake in each cluster fulfilled the cow's nutrient requirement (Hardie et al., 2014); diet ration in each cluster and concentration scenario also fulfilled the cow's protein and energy requirements according to NRC (2001) calculation (data not shown).

5.3.7 Assumptions

The GHG evaluated in this study in the context of crop production were N_2O and CH_4. Carbon dioxide emitted by livestock and CO_2 from plant respiration were considered as part of the continuous biological process of carbon fixation, utilization, and respiration (Knapp et al., 2014) and therefore not included. Secondary emissions of transportation and machinery fuel combust, electricity, and plastic use were not included in this study because data for these calculations (i.e., fuel usage, electricity, transportation) were not available from the original survey.

Base land area required for crop production were calculated using 16-year yield averages from WICST to project hectares of production used to supply the feed volumes reported by farms characteristic of the different clusters. This projection includes both land that was used by the dairy directly, as well as land associated with production of purchased feed.

The pasture system on the WICST trial was not managed using certified organic production methods. However, the only external inputs used in this system (in addition to manure deposited by grazing cows) were minimal applications of synthetic fertilizer and spottreatment of noxious weeds with clopyralid herbicide. As per the IPCC (2006b) estimations, 1% of total N applied is lost as N_2O emissions, regardless of the source of the N. Thus, assumptions were made that similar yields would be produced from an organically managed pasture, and that organic farmers would apply the equivalent amount of N as manure, with a similar proportion of N lost as N_2O.

Colmenero and Broderick (2006) found that replacing corn grain with soybean meal did not affect DMI, milk production or diet digestibility when dietary CP level increased from 17.8% to 19.4%, which was similar to the dietary CP range of our study. In addition, Sirohi et al. (2011) found that replacing raw soybean with roasted soybean had no effect on performance (DMI and milk production) in lactating crossbred cows. Therefore, DMI and milk production were assumed to be constant, regardless of the combination of CG and SB in the ration.

5.4 Results

5.4.1 Allocation to Milk and Meat

Cluster 1, 3, and 4 had similar allocation factor to milk (0.82-0.85). However, cluster 2 had a lower allocation factor (0.71) as compared to the other 3 clusters (Table 5.1), as cluster 2 had low milk production and a greater proportion of first lactation cows, both of which contribute to the low allocation factor to milk.

5.4.2 Land Required and Associated Emissions

Average annual DM yields (mean ± SD, kg DM per ha) of crops were as follows: CG (8,530 ± 1,941), corn silage (22,838 ± 5,194), SB (2,772 ± 757), alfalfa hay (11,057 ±1,353), alfalfa haylage (9,399 ± 1,150), and pasture grass (8,454 ± 2,921). As the proportion of CG decreased in the ration and the proportion of SB increased, total cropland needed to supply the concentrate feed increased for all 4 clusters (Table 5.4), due to the relatively lower yields of SB than CG.

On a per-cow basis, cluster 1 required the greatest land base for feed production, followed by clusters 3, 4, and 2. The land demand required for feed production, as determined by average crop yields from WICST and the amount of feed defined by the different feeding strategies, trended with the total DMI per cow per d of each cluster (22.1, 15.2, 20.9, and 18.1 kg of DM per cow per day, for cluster 1, 2, 3, and 4, respectively). Cluster 2 utilized the largest pasture areas and the least row cropland of the 4 clusters, due to its long grazing period and heavy reliance on pasture for feeding. Clusters 3 and 4 were moderate with respect to their land base needs for feed production, falling between the other 2 clusters. Milk production per ha of land (kg ECM per ha of land) was highest in cluster 3, followed by cluster 4, 1, and 2. Increasing SB proportion in concentrate decreased the milk production per ha of land because of lower yield of SB, compared with corn grain (Table 5.4).

5.4.3 Cropland and Pasture N_2O Emissions

The per-ha emission from each type of cropland or pasture, including direct N_2O emission from crop and cover crop residue, indirect N_2O emissions from N leaching and NH_3 volatilization, and SC, are depicted in Table 5.5. Without accounting for ΔSC, the production of organic corn resulted in the greatest N_2O emissions (1,569 kg eq. CO_2 per ha), followed by the production of organic alfalfa hay, pasture, and SB. According to 20-yr of soil carbon data collected from WICST, all cropland and pasture data indicated a loss of soil carbon, with the magnitude of loss greater in row crops and less in perennial forage and pasture systems (Sanford et al., 2012).

Direct N_2O from crop and cover crop residual was the major component of total N_2O emission in alfalfa hay, SB, and pasture. Estimated indirect N_2O emissions resulting from leaching and volatilization were substantially lower for SB compared to other crop types and pasture, although still relatively low within the other 3 crop types (Table 5.5).

Total N_2O emissions (average at 102 kg eq.CO_2 per t ECM) from cropland (including row crops and pasture), as depicted in Table 5.6, contributed to 8.0% of total GHG emission per kg of ECM (average at 1,297 kg eq.CO_2 per t ECM). Overall, the clusters with feeding strategies emphasizing more time on pasture (2 and 4) resulted in lower GHG emissions associated with cropland, both with and without accounting for ΔSC. Average N_2O emission from cropland was 107, 102, and 97 kg eq. CO_2 per t ECM with ALLCORN, BASELINE, and HALFCORN scenarios, respectively. Without considering ΔSC associated with the land required for feed production of each of the clusters, emissions decreased as the proportion of SB in the diet increased because of lower N fertilization requirements of SB as compared with CG.

When evaluated on land emissions per t ECM basis, without accounting for ΔSC, cluster 2 had the greatest GHG emissions, followed by clusters 1, 4, and 3. However, when accounting for ΔSC associated with the various crop rotation and production strategies, these rankings changed. Cluster 1 had the greatest land GHG emission, followed by clusters 4, 3, and 2.

5.4.4 Methane Emission from Enteric Fermentation

Enteric CH_4 emission contributed 45.6% of total farm GHG emission without ΔSC. Cluster 2 resulted in the greatest enteric CH_4 (kg eq. CO_2 per t ECM) emission, followed by clusters 4, 1, and 3. Average enteric CH_4 emission was 593, 592, and 591 kg eq. CO_2 per t ECM with ALLCORN, BASELINE, and HALFCORN scenarios, respectively. Increasing SB proportion in concentrate resulted in a limited reduction in the enteric CH_4 emission per kg ECM due to its higher fat content. Ranking among clusters remained the same under all 3 concentrate scenarios.

5.4.5 Methane and N2O Emission from Manure Management

Emissions (both N_2O and CH_4) from manure management contributed 26.3% to the farm total GHG emission without ΔSC. Emission of both GHGs occurred during manure management processes. Nitrous oxide was primarily emitted as a result of direct manure deposition on the pasture and after manure applied on cropland, whereas CH_4 emission associated with manure storage was much greater than deposited manure on pasture and manure land application (Table 5.6). Higher SB proportion in concentrate increased the dietary CP (Table 5.3) content and led to greater N content in manure, which eventually increased N_2O emission during manure management. Higher SB proportion in concentrate also increased manure volatile solid content by increasing dietary GE content, which led to higher CH_4 emissions during manure management.

Manure Deposited during Grazing. GHG emissions from manure deposited on pasture during grazing, including N2O and CH4 in kg, eq. CO2, are reported in Table 5.6 on an emission per t ECM basis. Cluster 2 had the greatest GHG emission from manure deposited on pasture, followed by clusters 4, 1, and 3. This ranking was the same as the grazing time on pasture; i.e., cluster 2 had the longest grazing time on pasture over a year, followed by cluster 4, cluster 1, and cluster 3 (Table 5.1). Despite cluster 4 had higher allocation factor to milk than cluster 2 (0.84 vs. 0.71, Table 5.1), greater ECM production in cluster 4 resulted in decreased GHG emission per t ECM (5,495 vs. 3,857 kg per cow per yr, Table 5.1).

Manure Storage. Emission from manure storage was greatest from cluster 1, followed by cluster 2, cluster 4, and cluster 3 (Table 5.6).

Manure Land Application. N_2O was the dominant GHG resulting from manure applied to the cropland (Table 6). Total GHG emissions per t ECM (for both milk and meat) after manure land application were greatest in cluster 2 and followed by cluster 1. Cluster 3 was the lowest in ALLCORN and BASELINE while cluster 4 was the lowest in HALFCORN (Table 5.6). Allocation factors changed the comparison between clusters. Cluster 1 had the highest GHG emission allocated to per t ECM in BASELINE and HALFCORN, whereas cluster 2 had the highest GHG emission allocated to per t ECM in ALLFORN. Cluster 3 had the lowest GHG emission allocated to per t ECM in BASELINE and ALLCORN whereas cluster 4 had the lowest GHG emission allocated per t ECM in HALFCORN.

5.4.6 Replacement heifer emission

Replacement heifer GHG emission was 20.1% of total GHG emission per t ECM without ∆SC. Cluster 2 had the highest replacement heifer emission, followed by Cluster 1, 4, and 3. Replacement heifer emission per kg ECM was highly related to percent of first lactation cows and milk production.

5.4.7 Farm-Level GHG emission

Farm-level GHG emission results were reported in Table 5.7. Farm-level GHG emission per t ECM ranking was similar with and without considering ∆SC. HALFCORN had the greatest GHG emission per t ECM and the value decreased as SB proportion in concentrate decreasing. Cluster 2 having the highest emission per t ECM and cluster 3 the lowest emission per t ECM under all 3 scenarios.

5.5 Discussion

5.5.1 Production System and Functional Unit

The primary objective of this paper was to evaluate the impact of different herd feeding strategies to inform best strategies to reduce the GHG emission of Wisconsin dairy farms transitioning to organic production, using real-world values with respect to herd management, DMI intake, and crop production variables. Taking into account in-field emissions associated with crop production required to meet feed needs, as well as the GHG emissions resulting from herd enteric fermentation and manure production and management, our goal was to holistically assess the combined impact of feeding strategies and the associated manure and land use management on GHG emission. Although integrating both the crop and animal management effects on GHG emissions, we focused our assessment on calculations using per t ECM as the functional unit in the dairy production system. While emissions per t ECM is the most widely used functional units in dairy farm LCA (Thomassen and De Boer, 2005; Opio et al., 2013), the evaluation of emissions on a per-ha land and a per-cow basis may provide unique interpretations and insights into LCA for organic dairies. Expressing GHG emissions as per-ha of land may more accurately reflect the impacts of land use change and optimization of crop production approaches, thus impacting the creation of policies that promote the expansion of pasture-based feed strategies and related incentives with respect to carbon sequestration potential. Expressing results as per-cow can provide estimates of changes in emissions resulting from herd expansion, as well as provide comparisons of the relative emissions of herds with varying genetics. In the results described above, estimations of farm-level emissions (including row and pasture cropland, associated soil carbon change, enteric fermentation, and manure management) reflected several aspects of management and productivity, including herd size, feeding strategies, and herd productivity.

Although secondary emissions were not included in this assessment, they can contribute substantially to the farm-level GHG emission. Secondary emissions include emissions from concentrate production, fertilizer production, fuel combustion, and electricity (O'Brien et al. (2014). Thoma et al. (2013) estimated farm energy (both electricity and fuel on farm) contributed 4% to the carbon footprint of fluid milk in the U.S. across the entire supply chain and 12.8% of GHG emission on farm (feed and milk production). However, when considering secondary emissions on Wisconsin's organic dairy farms, several of these emission sources can be considered negligible. Emissions associated with fertilizer production are minimal within organic production systems due to prohibited use of synthetic nitrogen. Emissions associated with transportation of feed could be greater for organic farms than conventional farms, as organic feed may be less readily available in certain areas of the U.S.; however, the majority of organic dairy farms in Wisconsin produce enough feed within their own operation to meet their herd's requirements.

However, across organic management strategies for organic dairies, differences in secondary emissions may emerge due to different herd management approaches. Longer grazing time organic farms may have lower energy usage than the organic farms with shorter grazing time for less electricity in lighting, ventilation, etc (Rotz et al., 2010). Farms that heavily relied on concentrate (i.e. Cluster 1 and 3) may have higher secondary emission from concentrate production than farms that have greater intake from pasture (Cluster 2 and 4). Despite these potential secondary emission difference between clusters, if secondary emissions were included in our analyses, cluster 3 would remain lowest with respect to GHG emission per t ECM, and cluster 2 would remain highest, due to the magnitude of difference between cluster 3 and 2 clusters (31.6%). However, the inclusion of secondary emissions may change the comparison between cluster 4 and 1, as the two clusters were more similar in GHG emissions per t ECM.

Cluster 1, 3, and 4 had a close allocation factor as compared to the default value of 0.856 from IDF (2010). The low allocation factor to milk in cluster 2 reduced the difference of GHG emission allocation to per t ECM among clusters. Although cluster 2 had the lowest milk production in all 4 clusters, the high percent of first lactation cows and number of bull calves sold per yr distributed a larger proportion of GHG emission to meat and decreased the allocation factor to milk.

5.5.2 Soybean Proportion in Concentrate and Greenhouse Gas Emission

Overall feeding strategies, as well as the SB proportion in the concentrate, influenced the land demand and associated field GHG emission, enteric CH_4 emission, and manure GHG emission associated with farms in each cluster. As shown in Table 5.7, the GHG emission from in-field emissions and enteric fermentation decreased as the proportion of SB in the concentrate increased for all clusters, as expressed on a per t ECM basis. Decreased reliance on corn in the crop rotation resulted in decreased N fertilization required for crop production, further resulting in less N_2O emissions as compared to strategies more reliant on the production of corn. These results (Table 5.5) are similar to results of Osterholz et al. (2014), in which direct measurements of N_2O emissions were obtained from the WICST experiment. Greater SB proportion in the concentrate increased dietary ether extract content, which could reduce enteric CH_4 emission by suppressing rumen methanogen population and reducing fiber digestibility (Table 5.3 and Knapp et al., 2014). The higher dietary CP due to greater SB proportion in concentrate increased the N content in manure with same milk protein percent and greater GE value increased volatile solid value in manure.

5.5.3 Feeding Strategies and Cropping Strategies

We assumed that all the feed was produced under the typical organic cropping practices and pasture management that are represented in the WICST, either produced on-farm or as purchased feed (Table 5.5). Different phases of typical crop rotations in Wisconsin, including those in organic production systems, are associated with different degrees of N_2O emissions and ΔSC (Osterholz et al., 2014; Sanford et al., 2012). Corn had the greatest eq. CO_2 emission per ha without ΔSC, followed by alfalfa hay, pasture, and SB. This ranking was primarily driven by the inputs required for the production for the associated crops, with N being delivered as organically-approved amendments.

The impact of cropping system (row crop, hay, and pasture) associated with a feeding strategy on GHG emissions per ha of land differed when ΔSC were considered. Results from WICST trial failed to demonstrate the occurrence of soil organic carbon sequestration, indicating soil carbon loss was occurring in all crop production strategies, including grain, forage, and pasture-based systems (Table 5.5). However, whereas the magnitude of ΔSC was similar (and marked) in the row crop and hay systems, ΔSC was nearer to a net zero in land used for pasture. Thus, pasture demonstrated lower total GHG emissions per ha of land than other crop types. The Wisconsin Cropping Systems Trial at University of Wisconsin (WICST) is unique in that it considers the longevity and the breadth of cropping system approaches, intended to mirror the agricultural landscape of the US upper Midwest region. Many other long-term systems trials focus on row crops and do not include a pasture treatment. The nearest comparison, both with respect to location and approach, might be the long-term experiment at the Kellogg Biological

Station at Michigan State University. That long-term experiment included a mown grassland treatment, but not a managed pasture specifically (Grandy and Robertson, 2007). Whereas such studies show more carbon sequestration potential in the mown grassland, trends are similar as what has been found at the WICST, with alfalfa and grassland treatments demonstrating higher soil carbon levels as compared to other annual row crop treatments.

More generally, research has demonstrated that perennial grasslands are often found to be net C sinks (Allard et al., 2007; Soussana et al., 2007; Peichl et al., 2011) and management intended to increase forage production increase soil carbon (Conant et al., 2001; Allard et al., 2007; Ammann et al., 2007). However, the degree to which pastures sequester carbon can vary; Skinner and Dell (2015) found that a high fertility pasture that had been perennial grassland for more than 40 yr was a significant net CO_2 source, whereas a lower fertility pasture that had been tilled and replanted more recently was neither a source nor a sink. Additionally, the degree to which land under various management strategies sequesters and/or loses carbon can decrease over time, as previously depleted stocks are replenished and soils return to equilibrium conditions where inputs and outputs are balanced (Smith, 2004).

5.5.4 Grazing Practice and Greenhouse Gas Emission

Previous studies have demonstrated that pastures can sequester carbon by building soil organic matter (Powlson et al., 2011; Stockmann et al., 2013; Machmuller et al., 2015). However, the data derived from the rich mollisol soils of the WICST trial showed that, although pastures were closer to achieving zero net emissions, pastures do not necessarily sequester substantial amounts of soil carbon as measured in the 20-yr timeframe represented in the WICST (Sanford et al., 2012). Nevertheless, pasture-based systems were shown to be more carbon-neutral than other crop production strategies, which explained the low GHG emission from cluster 2 under BASELINE and ALLCORN considering ∆SC.

When considering the impact of increased incorporation of pasture into an organic dairy feeding strategy on GHG emissions, our analysis, using real-world milk production values achieved by organic farms using these feeding models, illustrates several important points that must be considered when assessing the benefits of pasture-based production. First, from the data collected on working organic farms through the Hardie et al. (2014) survey, farms that were more heavily integrating pasture into feeding strategies tend to have lower overall milk productivity. This is particularly evident in cluster 2, which almost solely relied on DMI from pasture for herd's feed needs, to the point of employing a seasonal milking strategy with drying-off periods during the off-pasture season (Table 5.1). Additionally, this difference further magnified when comparing clusters 3 and 4; while both strategies significantly integrated pasture into the herd feeding strategy, as required by organic regulation, cluster 4 tended to integrate more herd time on pasture while still supplementing with the same quantity of feeds, with an observed decrease in milk production (Tables 1 and 5.2). More intensive grazing practices led to higher GHG emission per t ECM (Table 6, Figure 5.1), as intensive grazing practices combined with low concentrate inputs was associated with a decrease in milk production.

In addition to emissions related to differences in cropping systems associated with feeding strategies, the high protein content of pasture grass (Appendix 5.I) increased diet CP during the grazing season, which resulted in higher N_2O emission by increasing the amount of nitrogen deposited on pasture. Longer time on pasture resulted in greater forage intake, which increased enteric fermentation. The magnitude of difference between the clusters with respect to grazing deposits were much greater compared to manure storage and spreading associated emission.

These studies also align with our analysis in their demonstration of the positive impact of increased milk production on decreasing GHG emissions per unit of milk. Compared to Wisconsin, Ireland experiences a longer grazing season (248 d and 198 d for Ireland and Wisconsin). However, average milk production (3,764 kg of milk per cow per yr delivered in New Zealand, 5,181 kg FCPM per cow per yr in Ireland, and 5,793 kg ECM per cow per yr in Wisconsin) was lower in Ireland than Wisconsin, with similar values reported from New Zealand. Feed supplement (concentrate, corn silage, alfalfa hay, and alfalfa haylage) differed across the three regions, with amounts of concentrates fed (1.1 kg per cow per d in New Zealand, 1.7 kg per cow per d in Ireland, 5.5 kg per cow per d in Wisconsin) lower in New Zealand and Ireland as compared to Wisconsin, with higher DMI derived from pasture. In New Zealand and Ireland, dairy farms aim to maximize milk production from pasture through extending the grazing period and implementing seasonal calving prior to the start of the grazing season. However, among the Wisconsin organic dairy farms, only low-input organic farms (cluster 2) fully implemented seasonal calving.

Although similarities exist with results of studies conducted in other regions, differences between our results and those obtained from pasture-based and low-input farms in other countries may be reflective of the shorter length of the pasture season in Wisconsin’s colder climate. With less time annually to maximize forage production, many Wisconsin organic farms (Cluster 1, 3, and 4) feed more feed supplement, which translates into higher milk production (Hardie et al., 2011). Only the lower-input Wisconsin organic dairies (cluster 2) had similar feed supplement inputs (2 kg per cow per d) compared to New Zealand and Irish farms; however, with a shorter grazing season, Wisconsin farms also experienced lower milk production. Different grazing seasonality, pasture availability and quality, feed prices, and milk prices may all influence farmers decisions and choices of management strategies, and thus the GHG emissions associated with farms elected to employ pasture-based and low-input methods.

5.5.5 Greenhouse Gas Emission per t ECM

Results of this study agree with previous results demonstrating that GHG emissions are negatively correlated with milk production with high production diluting the emission from maintenance (Figure 1), and that that high-producing herds had lower GHG emissions per kg ECM) (Liang and Cabrera, 2015). Higher milk production is associated with higher DMI, which may lead to higher land requirement and more enteric fermentation. However, when considering emission per t ECM, the benefits of higher milk production outweigh the greater emissions from the field or the enteric. The calculations demonstrate greater GHG emissions from farms heavily reliant on pasture (cluster 2) on a t ECM basis (Figure 1). Strategic supplementation of concentrate to lactating cows during the grazing season could overall lower emissions per kg ECM by increasing production. More concentrate in diets resulted in an increase in milk production. The implementation of improved pasture management or grazing practices (e.g., management intensive rotational grazing.), including the maintenance of optimal carbohydrate and protein concentrations in the forage, are essential to maintain high pasture quality to optimize increase milk production, as more than 30% of DMI must be from pasture. Other methods to improve productivity include improving reproductive performance and health status, which indirectly reduce GHG emission per t ECM.

5.5.6 Organic Dairy Farm Considerations and Challenges

Increasingly, pasture-based systems have been promoted as tools to reduce the carbon footprint of livestock production systems and are discussed in the development of policy decisions (Merrill et al., 2015). Whereas our study supports the benefit of pasture from a crop-production perspective, it also demonstrates that within a broader system context, the assessment becomes more nuanced as GHG emissions generated from livestock management are integrated into the calculations, particularly when the related productivity is taken into account.

While pasture can remain a strategy to lower overall GHG emissions from certain livestock production approaches, more holistic optimization of management must be achieved to ensure pasture quality, pasture productivity, and milk production that balances production, profit, and sustainability goals. On many organic dairy farms, pasture productivity may require further management improvements, with yields and DM production not reaching their potential; thus, some organic dairies may not be deriving the feed value potential of this crop land base, impacting milk production. Organic dairy farms with well-managed grazing practices and adequate levels of concentrate in diet can both increase farm profitability (Hardie et al., 2014) and reduce GHG emission per kg of milk.

Effects of different dairy breeds on farm production and GHG emissions was not strongly included in this project. However, breeds of cows in organic farms strongly influence milk production and body condition scores (Roesch et al., 2005). Hristov et al. (2013) also suggested a possible breed effect on GHG per kg of milk, as Holsteins may have lower feed efficiency and lower protein and fat content in milk than other dairy breeds raised on pasture. Organic dairy farms must emphasize health traits, longevity, and fertility in addition to milk production in their breeding programs (Hardarson, 2001). Cows on some organic dairy farms (such as cluster 2) may have a herd with lower genetic potential of milk production than on the other farms, although they may be better suited for the different health needs of cows raised on pasture.

Additionally, the assessment of GHG emissions becomes further complicated by other non-production variables faced by organic dairy farms that are not considered in this study. These considerations and challenges include achieving the standards outlined in the federal organic regulation, land suitability (both on-farm and locally) for the production of tillage-intensive annual crops, marketing strategies of organic products, overall feed source stability and security, and farm financials. Further research is also needed on the effect of grazing management and feeding strategies on non-GHG environmental performance such as biodiversity, ammonia volatilization, and N leaching and P run-off in organic dairy farms.

5.6 Conclusions

Growing organic demand by consumers may attract conventional farms to transition to organic certification. During transition, farmers must make critical management decisions to meet organic regulations while considering environmental and production performance. Two decisions foundational to organic dairy farm management, herd feeding strategies and grazing practices, influence on farm GHG emissions not only due to emissions related to crop production, but by substantially changing the productivity of the herd. Managing more land as pasture, and deriving a greater proportion of the herds' feed requirements from pasture can increase the GHG emissions per t ECM, if pasture and feed management are not optimized to maintain milk production potential. Different combinations of corn grain and soybean in concentrate had a relatively minor impact on emissions per t ECM. Future research is needed to simultaneously optimize crop and milk production, GHG emissions, and farm profitability on organic dairy farms.

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Table 5.1. Descriptive statistical results of 4 clusters[1] and the total sampling farms from Hardie et al. (2014). Energy-corrected milk production (ECM), feed efficiency, and grazing time on pasture in a year were calculated based on data from Hardie et al. (2014). Other results were calculated based on survey results from Hardie (2013).

	C1	C2	C3	C4
Number of farms	8	5	32	24
Number of cows per farm	129	50	41	43
Rolling herd average milk production (kg per cow per year)	6,878	3,632	7,457	5,417
Energy-corrected milk production (kg per cow per year)[2]	6,657	3,857	7,164	5,495
Percent of purebred Holstein cows	90	0	89	6
Percent of first lactation cows	31.6	32.7	29.7	26.1
Number of bull calf sold per yr	39	19	15	16
Concentrate fed per cow per day (kg per day)	8.0	2.0	6.0	6.0
Dry matter intake (DMI, kg per cow per day)	22.1	15.2	20.9	18.1
Percent of Land used as pasture	22	100	31	49
Grazing period starting and ending time	Apr. 19 Nov. 7	Apr. 26 Nov. 28	May 1 Oct. 21	Apr. 21 Nov. 8
Grazing period length (days)	203	216	176	199
Average hours per day on pasture during grazing season	17	22	19	21
Grazing time on pasture (days per yr)[3]	143	194	141	174
Allocation factor to milk[4]	0.82	0.71	0.85	0.84

[1] Cluster 1 = C1, cluster 2 = C2, cluster 3 = C3, and cluster 4 = C4.

[2] ECM = [0.25 + 0.122 × fat (%) + 0.077 × protein (%)] × milk production (kg) (Sjaunja et al., 1990).

[3] Grazing time on pasture in a year is the actual time (days) cows graze on pasture during one-year period, calculated as grazing period length × (average hours per day on pasture during grazing season ÷ 24).

[4] Allocation factor to milk is the proportion of total GHG emission allocated to milk. It is calculated as $1-5.7717 \times (M_{meat}/M_{milk})$ (IDF, 2010).

Table 5.2. Daily lactating cow DMI (kg per cow per d) of different feed type for each cluster[1] from Hardie et al. (2014). Daily corn grain and soybean DMI for 3 concentrate scenarios[2] (BASELINE, ALLCORN, and HALFCORN) were calculated based on daily concentrate intake from each cluster.

	Concentrate Scenarios												
Cluster	BASELINE		ALLCORN		HALFCORN		Total concentrate	Corn silage	Hay	Alfalfa haylage	Vitamin and mineral	Grazing[3]	Total DMI
	Corn grain	Soybean	Corn grain	Soybean	Corn grain	Soybean							
1	3.72	1.24	4.95	0	2.48	2.48	5.0	2.7	2	7.9	0.5	4.2	22.1
2	1.52	0.51	2.03	0	1.02	1.02	2.0	0	3.2	0	0.1	9.8	15.2
3	3.02	1.01	4.03	0	2.01	2.01	4.0	2.0	3.1	6.0	0.3	5.5	20.9
4	1.32	0.44	1.76	0	0.88	0.88	1.8	1.3	3.1	4.7	0.2	7.0	18.1
Average							3.2	1.5	2.9	4.7	0.3	6.6	19.1

[1] Cluster 1 fed the greatest amount of concentrate; Cluster 2 grazed longest time and fed the least concentrate; Cluster 3 and cluster 4 were moderate between clusters 1 and 2.

[2] BASELINE = 75% corn grain and 25% soybean seed; ALLCORN = all corn grain; HALFCORN = 50% corn grain and 50% soybean.

[3] Grazing DMI was calculated as the difference between the total DMI and other feed intake (concentrate, corn silage, hay, haylage, and vitamin and mineral).

Table 5.3. Chemical composition of the diet in each feeding strategy Cluster[1] under 3 different concentrate scenarios[2]. The ALLCORN and HALFCORN scenario results are represented as the difference from the BASELINE scenario

	BASELINE				ALLCORN				HALFCORN			
	C1	C2	C 3	C4	C1	C2	C 3	C4	C1	C2	C 3	C4
CP (% of DM)	19	24	20	22	-1.7	-1.0	-1.5	-0.8	+1.6	+1.0	+1.4	0.7
NDF (% of DM)	36	40	37	40	-0.5	-0.4	-0.4	0	+0.6	+0.3	+0.5	+0.4
ADF (% of DM)	25	24	25	27	-0.5	-0.3	-0.4	-0.1	+0.5	+0.3	+0.5	+0.4
NFC (% of DM)	36	28	34	29	3.4	1.9	2.8	1.4	-3.1	-2.0	-2.7	-1.5
Ether extract (% of DM)	3.7	3.3	3.5	3	-0.9	-0.5	-0.7	-0.4	+0.8	+0.4	+0.7	+0.4
Ash (% of DM)	5.2	5.4	5.4	5.9	-0.4	0.1	-0.2	-0.2	+0.1	+0.3	+0.1	0
Gross energy (MCal per cow per d)	94	65	89	77	-1.5	-0.5	-1.0	-0.6	+1.0	+0.6	+1.1	+0.3
Gross energy (MCal per kg DM)	4.3	4.3	4.3	4.2	-0.07	-0.03	-0.05	-0.04	+0.05	+0.04	+0.05	+0.02

[1] Cluster 1 (C1) fed the greatest amount of concentrate; Cluster 2 (C2) grazed longest time and fed the least concentrate; Cluster 3 (C3) and Cluster 4 (C4) were moderate between C1 and 2. Details summarized in Table 1.

[2] BASELINE = 75% corn grain and 25% soybean seed; ALLCORN = all corn grain; HALFCORN = 50% corn grain and 50% soybean.

Table 5.4. Cropland (corn, soybean, and alfalfa) and pasture required per cow for feed supply for each feeding strategy Cluster[1] under 3 concentrate scenarios[2]. The ALLCORN and HALFCORN scenario results are represented as the difference from the BASELINE scenario

	BASELINE				ALLCORN				HALFCORN			
	C1	C2	C 3	C4	C1	C2	C 3	C4	C1	C2	C 3	C4
Corn	0.20	0.07	0.16	0.08	+0.05	+0.02	+0.04	+0.02	-0.05	-0.02	-0.04	-0.02
Soybean	0.16	0.07	0.13	0.06	-0.16	-0.07	-0.13	-0.06	+0.16	+0.07	+0.13	+0.06
Alfalfa	0.37	0.11	0.34	0.29	0	0	0	0	0	0	0	0
Pasture	0.18	0.43	0.24	0.30	0	0	0	0	0	0	0	0
Total land	0.91	0.66	0.87	0.72	-0.11	-0.05	-0.09	-0.04	+0.11	+0.05	+0.09	+0.04
Milk production per ha of land (kg ECM per ha)[3]	7,278	5,819	8,260	7,586	+996	+426	+951	+434	-782	-371	-773	-389

[1] Cluster 1 (C1) fed the greatest amount of concentrate; Cluster 2 (C2) grazed longest time and fed the least concentrate; Cluster 3 (C3) and Cluster 4 (C4) were moderate between C1 and 2. Details summarized in Table 1.

[2] BASELINE = 75% corn grain and 25% soybean seed; ALLCORN = all corn grain; HALFCORN = 50% corn grain and 50% soybean.

[3] Milk production per ha of land = ECM per cow per yr ÷ Land demand per cow per yr.

Table 5.5. Nitrous Oxide emission from per-ha of cropland and pasture (mean ± SD, kg eq. CO_2 per ha per yr), including direct N_2O emission from crop and cover crop residue, indirect N_2O emissions from N leaching and NH_3 volatilization, and soil carbon change (**ΔSC**). Negative values of ΔSC indicated soil carbon loss.

	Corn	Soybean	Hay	Pasture
Direct N_2O emission from crop and cover crop residue	372 ± 84	135 ± 37	912 ± 112	297 ± 102
Direct N_2O Emissions from N applied as fertilizer and manure inputs	782 ± 120	0	0	178 ± 315
Indirect N_2O emissions from leaching and volatilization	416 ± 56	30 ± 8.3	205 ± 25	249 ± 137
Total N_2O emission per ha of land without soil carbon change	1,569 ± 206	165 ±45	1,117 ± 137	723 ± 543
Soil carbon change (ΔSC)	-2,310	-2,347	-2,310	-30
Total N_2O emission per ha of land with soil carbon change	3,879 ± 206	2,512 ± 45	3,427 ± 137	753± 543

Table 5.6. Emission of all included sources from all lactating cows for each feeding strategy cluster[1] under different concentrate scenarios[2] per farm per yr and per t of energy corrected milk (ECM). The ALLCORN and HALFCORN scenario results are represented as the difference from the BASELINE scenario. Emission per t ECM shown in this table was adjusted with allocation factor to milk[3].

		BASELINE				ALLCORN				HALFCORN			
		C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
Emission per farm per yr													
Land emission without ΔSC[4] (kg eq. CO_2)		114,456	26,936	33,702	28,808	+7,253	+1,154	+1,875	+861	-7253	-1154	-1875	-861
Land emissions with ΔSC (kg eq. CO_2)		334,949	55,156	93,928	71,241	-26,326	-4,187	-6,805	-3,125	+26,326	+4,187	+6,805	+3,125
Enteric CH_4 emission (kg CH_4)		17,320	5,325	5,272	5,073	+19	+21	+11	+11	-52	-7	-6	-17
Manure deposited during grazing	N_2O (kg N_2O)	359	166	114	142	-34.1	-8.3	-8.0	-4.5	+34.1	+8.3	+8.0	+4.5
	CH_4 (kg CH_4)	223	82	66	72	-2.5	-0.6	-0.6	-0.3	+2.5	+0.6	+0.6	+0.3
Manure storage	N_2O (kg N_2O)	131	33	40	33	-13	-1.4	-3.6	-1.5	+13	+1.4	+3.6	+1.5
	CH_4 (kg CH_4)	3,442	707	1,065	821	-39.4	-4.2	-10.9	-4.3	+39.2	+4.2	+10.8	+4.3
Manure land application	N_2O (kg N_2O)	260	66	80	66	-26	-2.8	-7.3	-2.9	+26	+2.8	+7.3	+2.9
	CH_4 (kg CH_4)	30.1	6.4	9.5	7.4	-0.36	-0.04	-0.10	-0.04	+0.35	+0.04	+0.10	+0.04
Emission (kg eq. CO_2) per t ECM													
Land emission without ΔSC		110	100	97	103	+7.0	+4.3	+5.4	+3.1	-7.0	-4.3	-5.4	-3.1
Land emission with ΔSC		322	204	271	254	-25	-16	-20	-11	+25	+16	+20	+11
Enteric fermentation emission		565	670	518	614	+0.6	+2.6	+1.1	+1.3	-1.7	-0.9	-0.6	-2.1
Manure management	Manure deposited during grazing	110	194	105	159	-9.8	-9.2	-6.9	-4.9	+9.8	+9.2	+6.9	+4.9
	Manure storage	150	125	139	135	-5.1	-2.1	-4.2	-2.1	+5.1	+2.1	+4.2	+2.1
	Manure land application	75	73	70	71	-7.6	-3.1	-6.3	-3.1	+7.1	+3.1	+6.3	+3.1

[1] Cluster 1 (C1) fed the greatest amount of concentrate; Cluster 2 (C2) grazed longest time and fed the least concentrate; Cluster 3 (C3) and Cluster 4 (C4) were moderate between C1 and 2. Details summarized in Table 1.

[2] BASELINE = using 75% corn grain and 25% soybean seed; ALLCORN = using all corn grain; HALFCORN = using 50% corn grain and 50% soybean.

[3] Allocation factor to milk was calculated based on the weight of meat (bull calf and beef sale) and milk sale (IDF, 2010).

[4] ΔSC = soil carbon change

Table 5.7. Emission source and total farm carbon footprint (kg eq. CO_2 per t ECM and kg eq. CO_2 per ha of land) for each feeding strategy cluster[1] under three concentrate scenarios[2]. The ALLCORN and HALFCORN scenario results are represented as the difference from the BASELINE scenario.

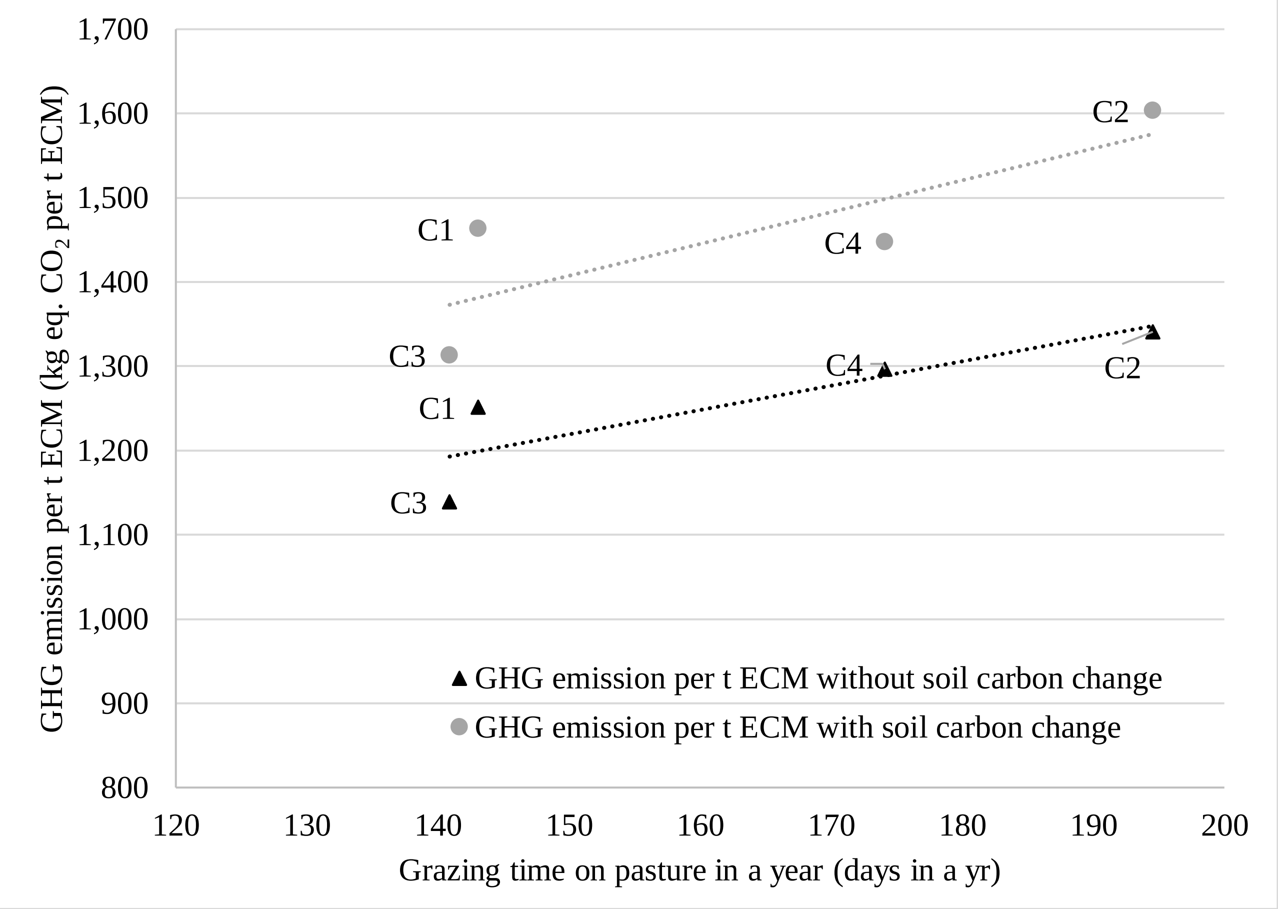
	BASELINE				ALLCORN				HALFCORN			
	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
N_2O (kg eq. CO_2 per t ECM)[3]												
Cropland and Pasture	133	140	107	122	+8.4	+6.0	+6.0	+3.6	-8.4	-6.0	-6.0	-3.6
Grazing Manure Deposit	125	257	116	179	-11.8	-12.8	-8.1	-5.7	+11.8	+12.8	+8.1	+5.7
Manure Storage	45.4	51.0	40.7	41.6	-4.6	-2.2	-3.7	-1.8	+4.6	+2.2	+3.7	+1.8
Manure Land Application	90.3	101.5	81.0	82.9	-9.2	-4.4	-7.4	-3.7	+9.2	+4.4	+7.4	+3.7
CH_4 (kg eq. CO_2 per t ECM)[3]												
Enteric Fermentation	686	939	610	730	+0.7	+3.7	+1.3	+1.6	-2.07	-1.2	-0.7	-2.5
Grazing Manure Deposit	8.8	14.5	7.6	10.4	-0.10	-0.11	-0.07	-0.05	+0.10	+0.11	+0.07	+0.05
Manure Storage	136	125	123	118	-1.6	-0.7	-1.3	-0.62	+1.6	+0.74	+1.3	+0.62
Manure Land Application	1.2	1.1	1.1	1.1	-0.01	-0.01	-0.01	-0.01	+0.01	+0.01	+0.01	+0.01
Soil carbon change (ΔSC, kg eq. CO_2 per t ECM)[3]	-254	-145	-190	-177	-41.1	-29.1	-29.0	-17.7	+41.1	+29.1	+29.0	+17.7
Replacement Heifer Emission (kg eq. CO_2 per t ECM)	293	470	249	256	0	0	0	0	0	0	0	0
GHG Emission without ΔSC (kg eq. CO_2 per t ECM)[3]	1,252	1,499	1,139	1,297	-15.0	-7.6	-10.8	-5.6	+13.9	+9.3	+11.3	+4.8
GHG Emission with ΔSC (kg eq. CO_2 per t ECM)[3]	1,464	1,603	1,313	1,448	-47	-27	-36	-20	+46	+34	+36	+19

[1] Cluster 1 (C1) fed the greatest amount of concentrate; Cluster 2 (C2) grazed longest time and fed the least concentrate; Cluster 3 (C3) and Cluster 4 (C4) were moderate between C1 and 2. Details summarized in Table 1.

[2] BASELINE = using 75% corn grain and 25% soybean seed; ALLCORN = using all corn grain; HALFCORN = using 50% corn grain and 50% soybean.

[3] Nitrous oxide and CH4 emission and soil carbon change (ΔSC) values in the table were the total emission for both milk and meat. Greenhouse gas emission per t ECM (kg eq. CO_2 per t ECM) was GHG emission allocated to milk adjusted with allocation factor to milk. Negative values of ΔSC indicated soil carbon loss.

Figure 5.1. Relationship between grazing time on pasture (d in one yr) and greenhouse gas emission allocated to milk. Cluster 1 fed the greatest amount of concentrate; cluster 2 grazed longest time and fed the least concentrate; cluster 3 and cluster 4 were moderate between clusters 1 and 2.



Appendix 5.I. Manure management CH_4 and N_2O emission factors from IPCC (2006), including manure deposited on pasture during grazing, liquid manure storage, and manure spread to the field.

Emission source	Prediction equation or Emission factor	Unit
Enteric fermentation		
Methane (CH_4)	-9.311+0.042×GE^1+0.094×NDF-0.381×EE+0.008×BW^2+1.621×MF^3	MJ per cow per d
Deposited manure during grazing		
Nitrous oxide (N_2O)	0.02 × manure N deposited on pasture	Kg per kg of N
Methane (CH_4)	0.01 × manure VS^4 deposited on pasture × 0.67 × B_0^{5} × 365	Kg per year
Manure storage		
Nitrous oxide (N_2O)	0.005 × slurry manure N stored	Kg per kg of N
Methane (CH_4)	0.1 × manure VS stored × 0.67 × B_0 × 365	Kg per year
Manure land application		
Nitrous oxide (N_2O)	0.01 × manure N spread	Kg per kg of N
Methane (CH_4)	0.001 × manure VS spread × 0.67 × B_0 × 365	Kg per year
Replacement heifer GHG emission	11 × body weight × 0.92 × percent of first lactation cow × herd size	Kg eq. CO_2 per farm per yr

[1] GE = Gross Energy, MJ per cow per d.

[2] BW = Body weight, kg per cow.

[3] MF = Milk fat, %.

[4] VS (volatile solid, kg per d) = $[Gross\ energy\ intake\ (MJ/d) \times \left(1 - \frac{Feed\ digestibility\ (\%)}{100}\right) + (0.04 \times Gross\ energy\ intake\ (MJ/d)) \times \left(\frac{100-Ash(\%)}{18.45\ \times 100}\right)]$. Feed digestibility was set as 65% according to North America dairy cattle default digestibility value (IPCC, 2006, Table 10-A).

[5] B_0 is the maximum methane-producing capacity, set as 0.24 according to North America dairy cattle default value (IPCC, 2006, Table 10-A).

Appendix 5.II. Average feed ingredient chemical composition. Crude protein (CP), NDF, ADF, ether extract (EE), ash, non-fiber carbohydrate value was calculated as the mean of book values from NRC (2001). Gross energy value calculated based on CP, EE, and carbohydrate value in each ingredient[1].

	Corn grain	Soybean (whole seed)	Corn silage	Alfalfa hay	Alfalfa silage	Pasture	Vitamin and Mineral
Crude protein (% of DM)	9.4	39.2	8.8	20.2	21.9	26.5	0
NDF (% of DM)	9.5	19.5	45	39.6	43.2	45.8	0
ADF (% of DM)	3.4	13.1	28.1	31.2	35.2	25.0	0
Lignin (% of DM)	0.9	1.2	2.6	7	7.3	2.1	0
Ether extract (% of DM)	4.2	19.2	3.2	2.1	2.2	2.7	0
Ash (% of DM)	1.5	5.9	4.3	10	10.5	9.8	100
Non-fiber carbohydrate (% of DM)	75.4	16.2	38.7	28.1	22.2	15.2	0
Gross Energy (MCal/kg DM)	4.5	5.5	4.3	4.2	4.2	4.3	0

[1] $$\text{Gross energy (MCal/kg DM)} = \frac{[4.15\times\text{carbohydrate (\%)}+5.7\times\text{CP (\%)}+9.4\times\text{Ethter extract (\%)}]}{1000}/4.184$$

$$\text{Carbohydrates} = 100 - \text{Ash (\%)} - \text{Ether extract (\%)} - \text{CP(\%)}$$

Chapter 6

Assessment of the potential of Grass-based organic dairies to reduce the carbon footprint of milk production using multiple functional units

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6.1 Abstract

With the need for agricultural intensification to supply food for a growing global population, meaningful assessments of environmental impacts are needed to guide best strategies forward. While life cycle assessment (**LCA**) provides an accepted means to evaluate systems, outcomes can vary depending on the functional unit (**FU**) used, especially in the assessment of livestock production and related products, where both crop and livestock production are considered. The objective of this study is to compare the three functional units (per ha, per cow, and per kg of energy-corrected milk, **ECM**) used to assess greenhouse gas (**GHG**) emissions from Wisconsin certified organic dairy farms. Data used to complete the LCA was obtained from a 2010 survey of organic dairy farms, from which farms were divided into four clusters based on their feeding strategies. Emissions from crop production, enteric fermentation, and manure management were included in the partial LCA. Analyses based on different functional units influenced the comparison of farm-level GHG emission between farms of different feeding strategies. Greenhouse gas emission per ha and per kg of ECM positively related with milk production per cow per yr in each cluster. Meanwhile, GHG emission per cow were negatively related with milk production per cow per yr in each cluster. Depending on resources available, different functional units provide different information which could impact policy and farm-level decision-making with respect to land use strategies and mitigation of environmental impacts, with combinations of mass-based and area-based units providing a more balanced assessment.

Keywords: feeding strategies, farm-level greenhouse house gas emission, grazing management

6.2 Introduction

Organic agriculture continues to expand, reaching a market value of $50 billion in the United States (**US**) in 2016 (Organic Trade Association (**OTA**), 2017). Organic dairy comprises a significant proportion of overall organic food sales, with 8% of all dairy products bought by US consumers produced organically (OTA, 2017). To obtain organic certification under the USDA National Organic Program (**NOP**), farmers must adhere to specific production practices that are verified through an inspection process. In the case of organic dairy farms, the cows' diets must confirm to specific standards, including that all feed (including concentrates and conserved forages) are produced as per NOP regulations, with cows obtaining a minimum of their 30% dry matter intake (DMI) from pasture during the grazing season (US Government Publishing Office, 2017). Organic farms vary, however, in the feeding strategies under this regulatory framework, using different amounts and combinations of concentrates and conserved forages to provide nutrition to their herds. Additionally, organic farms vary in the percent DMI which is derived from pasture, often exceeding the minimum standards set forth by the NOP.

Increasing attention has been focused on the integration of pasture into dairy feeding strategies, both within organic production and across the wider dairy industry. This interest is driven, in large part, by factors related to both market and environmental advantages. First, consumer interest in grass-fed products continues to expand, creating a high-value, niche-market opportunity for farmers (Cheung and McMahon, 2017). Second, policymakers have begun consider the awarding carbon credits for the conversion of working arable agricultural lands to pasture as a tool to mitigate greenhouse gas emissions (Victor and House, 2004).

Several studies have compared both the carbon footprint (**CF**) of conventional and organic diaries and confinement versus grass-based dairies. Outcomes drawn from these comparisons vary, with greenhouse gas (**GHG**) emissions from organic ranging from greater than conventional (Thomassen et al., 2008a; Kristensen et al., 2011), lower than conventional (Cederberg and Mattsson, 2000), and similar to conventional (Haas et al., 2001; van der Werf et al., 2009). In the case of confinement versus grass-based dairies, grass-based dairies tend to exhibit lower carbon footprints as compared to their confinement counterparts (Lewis et al., 2011; Flysjö et al., 2011). However, these types of comparisons have not been performed as extensively across the range of different management strategies employed by organic dairy farms, whose reliance on feed from row crops versus pasture varies.

Assessing the carbon CF of dairy farms is typically accomplished using a life cycle analysis (**LCA**) approach, which calculates GHG emissions generated from all stages associated with the generation, distribution, and disposal of a product (ISO, 2006). The functional unit (**FU**) used in these calculations can vary, the choice of which provides different perspectives on the relative impact of various related to production. Studies have demonstrated that the use of different FU can significantly impact the relative CF ranking among various types of production systems. For example, while kg of milk production is the recommended FU in LCA conducted within the dairy industry (International Dairy Federation (**IDF**), 2010; Opio et al., 2013), the functional unit of per ha of land may be the most appropriate FU in land resource efficiency studies. Per cow FU may provide support for the evaluation of the impacts of herd expansion on both on-farm and regional sustainability analysis, and most likely includes the GHG emission for both milk and meat, two major products in the dairy production system.

The objective of this study was to compare the GHG emissions from certified organic dairy farms in Wisconsin using different feeding strategies for their herds. Analyses were conducted using three different FU (per ha of land, per cow, and per kg of energy-corrected milk

(**ECM**) production) through a partial LCA integrating WI-based data within the models. With this information, farmers, industry, and policy makers can more accurately assess the impact of land use and feed choices on the overall carbon footprint of the organic dairy farm and better determine integrated strategies on organic dairy farms to optimize environmental performance with respect to GHG emissions.

6.3 Materials and Methods

This study is a follow-up study of Liang et al. (2017) that focused on the effect of feeding strategies on farm-level GHG emission per kg of ECM in Wisconsin certified organic dairy farms.

Four feeding strategies used by organic dairy farms were revealed by analyzing 2010 survey results that included general farm characteristics, management and feeding practices, crop land use, and grazing practices (Hardie et al., 2014; Liang et al., 2017). Cluster 1 was characterized by larger farms feeding the greatest amount of concentrate, utilizing the least amount of land as pasture, grazing the least number of days per year, and producing the highest volumes of milk. Cluster 2 fed the least amount of concentrate feed to cows and had the most days per year grazing, with 100% of the land used as pasture. Clusters 3 and 4 had the least number of cows and fed moderate amounts of concentrate. However, these two clusters differed in their productivity (cluster 3 characterized by greater milk production than cluster 4) and the degree to which pasture was utilized (cluster 4 utilizing more land managed as pasture and more days per year on pasture). Detailed description for herd management in each cluster are summarized in Table 6.1.

The partial LCA included GHG emissions from crop production (N_2O and CH_4), enteric fermentation (CH_4), and manure management (CH_4 and N_2O). The crop production yield and emission data was collected from the Wisconsin Integrated Cropping System Trial (**WICST**), a long-term cropping system experiment established in 1989 located in Arlington, Wisconsin. Land demand for feed production (corn, alfalfa, pasture, and soybean) was calculated based on cow feed requirement in each cluster and the crop yield from WICST (Table 6.1). Milk production per ha of land was 7,278, 5,819, 8,260, and 7,586 for cluster 1, 2, 3, and 4, respectively (Liang et al., 2017). Emission from cropland and pasture were calculated through Intergovernmental Panel on Climate Change (IPCC 2006) equations based on the 16-yr (1993-2008) period input and yield data in WICST pasture treatment and organic grain and forage rotations treatment. Changes in soil carbon quantities from cropland and pasture was calculated by comparing soil carbon (SC) concentrations in samples collected at the beginning of the trial (1989) to samples collected 20 years after its inception (Sanford et al., 2012).

Enteric fermentation CH4 emission was calculated based on the farm-reported dry matter intake (DMI) of each feed type (concentrate, corn silage, alfalfa haylage, vitamin and mineral) in each month of the year. Concentrate was assumed to be 75% corn grain and 25% soybean. The DMI from pasture during the grazing season was calculated as the difference between total DMI and supplemented feed DMI. Feed ingredient chemical composition was collected from Nutrient Requirements of Dairy Cattle (NRC, 2001). A model proposed by Moraes et al. (2014) was employed to estimate enteric CH_4 emissions in order to capture the variation resulting from diet formulation (gross energy (**GE**) intake, dietary NDF, and dietary ether extract).

GHG emissions associated with manure management included manure deposited on pasture during grazing, manure storage, and after manure applied to the field through mechanical spreading. Manure nitrogen (N) excretion was calculated as the difference between dietary N and milk N content. The proportion of manure N deposited on pasture was determined by the length of grazing season in a year, hours in a day on pasture during the grazing period, and cows' monthly DMI of each feed ingredient during grazing season (Table 6.1). In this partial LCA, all manure was handled in a liquid form, as the survey reported 85% of participated organic dairy farms handled liquid manure. Emissions of CH_4 and N_2O from manure management were estimated with IPCC (2006) equations.

Replacement heifer emission was based on percent of first lactation cow, herd size, and body weight. An emission factor of 11 kg eq. CO_2 per kg of body weight (Rotz et al., 2013) was assigned to replacement heifers. Three FU were reported in this study: per ha, per cow, and per kg of ECM. Allocation factors to milk were calculated with the IDF (2010) based on the annual amount of milk and meat sale for a farm. The allocation factors were only applied to the results using per kg FCM as the FU.

6.4 Results

Tables 6.2 to 6.4 report the GHG emissions as calculated using the three FUs from cropland and pasture, enteric fermentation, and manure management, respectively, with all results reported adjusted for allocation to milk. Rankings of clusters with respect to in-field nitrous oxide emissions associated with crop production varied with the functional unit used for assessment (Table 6.2). Overall, higher land emissions per farm per year (kg eq. CO_2) were associated with the clusters with greater proportions of land used for row crop and alfalfa production versus pastures (cluster 1 > cluster 3 > cluster 4 > cluster 2). These trends were particularly evident when soil carbon loss was considered, which markedly increased the annual land emissions per farm from clusters more dependent on row crops for the production of concentrate. Without soil carbon loss included in the calculation, land emissions per farm per year from cluster 1 was approximately 4X that of the other clusters. However, when the impacts of soil carbon loss were included, annual land emissions increased to approximately 5-6X that of the clusters which relied most heavily on pasture. On a per ha of land basis, rankings with respect to land emissions were the same as those on a per farm basis, with and without considering SC loss. Considered on a per cow basis, these same rankings were observed, with cluster 1> cluster 3 > cluster 4 > cluster 2, both with and without considering soil carbon loss. However, when annual emissions were considered on a per t ECM basis without considering soil carbon loss, rankings shifted, with cluster 1 > cluster 4 > cluster 2 > cluster 3 Accounting for changes in SC, the integration of pasture into land management strategies had a positive impact on GHG emissions, with rankings on a per t ECM basis shifting once again to cluster 1 > cluster 3 > cluster 4 > cluster 2 (Appendix 6.I, Liang et al., 2017)

Table 6.3 outlines the total enteric CH4 emissions from all lactating cows associated with each cluster. Here, choice of FU significantly shifts the rankings of the various clusters. On an annual per farm basis, emissions from farms of cluster 1 were greater than those of the other clusters, with cluster 2 > cluster 3 > cluster 4 due to the greater number of animals maintained on the farm. This trend was maintained when the FU of per cow were used in the calculations, as directly related to their total daily DMI intake (Table 6.7). Considered on a per ha of land basis, however, rankings of clusters with respect to enteric emissions shifted, with the 2 clusters more heavily reliant on pasture associated with higher levels of emissions (cluster 4 > cluster 2 > cluster 3 > cluster 1). Rankings shifted yet again where the FU of per t ECM was used as the functional unit, with cluster 2 > cluster 4> cluster 1 > cluster 3.

GHG emissions from manure deposited on pasture during grazing, including N_2O and CH_4 in kg, eq. CO2, are reported in Table 6.4. Rankings of clusters (cluster 1 >cluster 2 > cluster 4 > cluster 3) were related to both the number of cows and the amount of time the cows were on pasture. GHG emissions from manure deposited on pasture followed the same ranking among clusters as when considered on a per cow or per t ECM basis (cluster 2 > cluster 4 > cluster 1 > cluster 3). These rankings were related to the amount of time cows spent grazing on pasture, with farms from cluster 2 utilizing the greatest number of hours grazing per year, followed by cluster 4, cluster 1, and cluster 3 (Table 6.1 and 6.4). While the relative difference between clusters 2 and 4 were similar with respect to emissions contributed by manure deposited per cow, cluster 2 had much higher emissions (41-46%) than cluster 4 when considered on a per t ECM level, as cluster 4 was characterized by much greater ECM production than cluster 2 (5,495 vs. 3,587 kg per cow per yr, Table 6.1). On per ha of land level, emission from manure deposited on pasture had a similar trend as compared to the other two FU, although cluster 1 was lower than cluster 3. While clusters 1 and 3 had similar GHG emission from deposited manure per cow (888 vs. 884 kg per cow per year, Table 6.4), the greater land demand per cow in cluster 1 than cluster 3 (0.91 vs. 0.87 ha per cow per year, Table 6.1) reduced the emission per ha of land.

On a per farm basis, emissions of GHG from manure storage were greatest in cluster 1, followed by cluster 3, cluster 4, and cluster 2. Per-cow level emissions of GHG from manure storage followed these same rankings, with trends following the amount of DMI per cow fed by farms in each of the clusters. Emissions considered on a per t ECM level emission were again greatest from cluster 1, but rank shifts occurred among the remaining three clusters, with cluster 2 > cluster 4 > cluster 3 (Table 6.4). Per ha level emissions were greatest in cluster 3, followed by cluster 1, cluster 4, and cluster 2. As similar to calculations of emissions from manure deposited on pasture, the greater land demand needed for crop production associated with cluster 1 changed the ranking among clusters on per ha of land level as compared to the per cow level.

GHG emissions from manure spreading to the field were greatest from cluster 1, followed by cluster 3, with clusters 4 and 2 similar in emissions. Per-cow level GHG emissions after manure applied to the field followed the same ranking as DMI among clusters (cluster 1 > cluster 3 > cluster 4 > cluster 2) (Table 6.4). Per-ha level emission followed a similar ranking with per cow level emission, although cluster 3 was associated with greater emissions as compared to cluster 1. Rankings shifted once again on a per t ECM basis, with cluster 1> cluster 2 > cluster 4 > cluster 3.

A more nuanced picture emerged when GHG emissions were considered at the entire farm level with all three functional units and allocation factors considered (Table 6.5). The calculations of overall emissions, standardized as kg eq. CO_2, also considers emissions associated with replacement heifers and the appropriate allocation factor to milk (e.g., proportion of total GHG emission allocated to milk versus beef). Due to relatively higher beef sales, cluster 2 was associated with a smaller allocation factor, thus less of the overall emissions of the farm were associated with milk production. These differences in allocation factors between the clusters shifted rankings markedly When considering both the production of milk and meat, and without accounting for SCL, cluster 2 had the greatest GHG emission per ha land, followed by cluster 4, cluster 1, and cluster 3. When allocated only for milk production, these rankings changed, with cluster 4 > cluster 3 > cluster 1> cluster 2. With SCL included, rankings of GHG emission per ha land remained the same for cluster 2 and cluster 4, with cluster 1>cluster 3. However, when again only allocation to milk was considered, cluster 4 > cluster 3 > cluster 1> cluster 2. Allocated for milk and considering both milk and meat, farms from cluster 1 had the greatest emissions per cow, followed by cluster 3, 4, and 2, with the consideration of soil carbon changes not impacting the rankings. Calculated on a per t ECM basis and without considering changes in soil carbon, and including both milk and meat production, cluster 2 had the greatest annual GHG emission followed by cluster 4, 1, and 3. With soil carbon changes included in the calculation, cluster 2 still demonstrated the greatest annual emissions on a per t ECM basis, with cluster 1> cluster 4 > cluster 3. Rankings of GHG emissions on a per t ECM level with allocation factors included were cluster 2 > cluster 4 > cluster 1 > cluster 3 without soil carbon loss, and cluster 2 > cluster 1 > cluster 4 > cluster 3, both with soil carbon loss considering. Rank orders by these factors was driven by a combination of milk productivity and land under pasture management, depending on the consideration of loss of SC with feed production.

6.5 Discussion

While minimum standards for DMI from pasture have been established by the USDA NOP, organic dairy farms vary widely in the strategies with which they meet or surpass this standard, depending on their land base (both number of hectares and the appropriateness for row crop production), philosophical and practical management approaches, and farm financial strategies. With increasing attention turned to carbon sequestration and the role of pasture in GHG mitigation, an understanding of the broader impacts of pasture-based feeding strategies on the whole-farm carbon footprint of the organic dairy system is critical to anticipate the magnitude of change possible.

Accurately predicting benefits derived from the potential sequestration of carbon in pasture soils as related to the overall dairy carbon foot print is difficult, in part due to the uncertainty of carbon sequestration rates and saturation points across different soil types. The concept of SC saturation, and its longer-term impact on system carbon footprints, is recognized in the IPCC (2006) guidelines outlining LCA standards through their recommendation that carbon sequestration should be excluded from LCA calculations due to the assumption that soil's ability to store carbon reaches equilibrium after a fixed 20-year period. However, other scientists question whether this assumption can be broadly applied, as it has been documented in some studies that pastures and managed grasslands can permanently sequester carbon (Leip et al., 2010; Soussana et al., 2010). The uncertainty in predicting SC stability can be attributed to several factors, including lack of statistical power, insufficient time spans of studies, and incomplete understanding and documentation of carbon balances in soils (VandenBygaart and Angers, 2006; Sanderman and Baldock, 2010; Kravchenko and Robertson, 2011; Schmidt et al., 2011). While studies have shown the SC sequestration can occur under pasture-based management, the WCIST trial data upon which the analyses in this paper are based illustrate continued SC losses after 20 years of management at this specific location (Arlington, WI, USA), despite rotational grazing and no-tillage practices. In part, this may be explained by the derivation of these soils, which were historically native tallgrass prairies with deep, extensive root systems and large belowground C inputs (DeLuca and Zabinski, 2011; Sanford et al., 2012). In contrast to the deep roots of the tallgrass prairie, in the managed rotationally grazed pasture comprised of primarily of cool season grasses, fine roots (0–2 mm) contribute the majority of the belowground biomass, 80% to 90% of which is concentrated in the surface 30 cm of the soil (Jackson et al., 1996; Rasse et al., 2005). While Sanford et al. (2012) detected SC gains at the 0-15 cm depths in rotationally grazed pastures, soil carbon was lost at the 15-90 cm depths, resulting in a net loss of carbon across the entire soil profile (Sanford et al., 2012).

The inclusion of SCL in our analysis did demonstrate that the integration of a greater proportion of pasture into land management strategies resulted in overall reduction of SC loss as compared to management with a greater proportion of row crops. However, considered along with the other factors contributing to GHG emissions, the magnitude of these changes only led to rank shifts when the productivity of the farms reached a threshold value. While considering the reduced SC losses from pasture when calculating GHG per t ECM, farms of cluster 2 still contributed the greatest overall GHG emissions, despite managing more land as pasture. However, when SC was included in the calculation, the impacts of soil loss on the broader CF of the farm could be observed in the rank shift of clusters 1 and 4; despite high productivity, the degree of soil loss associated with the row crop hectares needed to produce the concentrate feed for farms in cluster 1 placed it behind cluster 4 with more moderate milk productivity but more land managed as pasture. The impacts of carbon sequestration on the CF rank shifts of different dairy management strategies has been observed in other studies. For example, in Obrien et al.'s study of the CF of grass-based versus highly intensive confinement dairies, the grass-based dairy system had the lowest CF per ton of ECM when carbon sequestration was included in the analysis; however, omitting sequestration resulted in the grass-based and confinement dairy systems having similar carbon footprints per ton of ECM (O'Brien et al., 2014). Similarly, Rotz et al. (2010) found in the carbon footprint per kg milk could be significantly reduced upon transitioning to pasture-based strategies when carbon sequestration in grassland was included.

Considering impacts solely from a land management perspective, even without carbon sequestration, transitioning row crop land to pasture may provide environmental benefits apart from GHG emission reduction. Greater exogenous nitrogen inputs associated with crop management can result in nitrogen losses to the environment in the forms of N_2O emissions and nitrogen leaching into ground and surface water (Monteny et al., 2006). Although the magnitude is less than what might be anticipated from conventional cropping systems in which N is applied more frequently both within and across crop rotation phases, N inputs are still applied to organically managed corn in the form of NOP-approved amendments or manure. Comparisons of LCAs of conventional dairy systems have found that feeding more corn silage to the cows increased GHG emission per ha of land due to higher land demand and fertilizer input (Basset-Mens et al., 2009; Salou et al., 2017). Similarly, our study found that the production of organic corn as a primary source of feed concentrate can increase the overall carbon footprint associated with land use for feed production. However, in organic management, practices mandated by the NOP, including the requirements for diverse, multi-year crop rotations and use of cover crops, reduce the need for N inputs over the entire course of the crop rotation. As these practices typically include the more frequent use nitrogen-fixing legumes, potential opportunities to further decrease N inputs in the production of organic concentrates are possible.

6.5.1 Functional Units

Depending on the functional unit (per ha land, per cow, and per t ECM) used in the calculations, rankings of clusters shifted with respect to GHG emissions. When considered on a per ha of land and per t ECM FU, GHG emissions appeared less from farms with greater milk production. The finding that greater milk production resulted in lower GHG emission per t ECM was in agreement with previous findings (Liang and Cabrera, 2015; O'Brien et al., 2016). The increased production of cows in modern dairies, along with the fewer cows needed to produce the same volume of milk, has led some researchers to assert that present dairy production has less environmental impact than past production methods and/or less intensive systems (Sevenster and Jong, 2008; Capper et al., 2009). For example, in a study investigating the carbon footprint of different dairy systems in Georgia, pasture-based systems with lower milk production contributed 4% greater carbon footprints as compared to confinement systems (Belflower et al., 2012). However, when models increased milk production by 22%, CF was reduced by about 15% in pasture-based systems, whether the increased production was obtained through animal management or feeding more corn (Belflower et al., 2012).

Considered on a per cow basis, however, GHG emission were not related to the average milk production of the cluster, with low input farms (cluster 2 and 4) demonstrating lower per cow emissions as compared to the more intensive farms (cluster 1 and 3). This may be due to several factors. Cluster 1 performed particularly poorly with respect to total land emissions with soil carbon loss included, and, to a lesser degree, emissions related to manure storage. On low input farms, fewer emissions associated with crop production, along with fewer emissions associated with manure storage, contributed to the overall less emissions considered on a per-cow basis, despite fewer animals over which emission burdens were distributed. Enteric CH4 emission largely depended on DMI or energy intake level (Ramin and Huhtanen, 2013; Moraes et al., 2014). Cows in low input farms had much lower intake level (Table 6.1 and Appendix 6.I), which resulted in lower enteric CH_4 emission per cow.

Greenhouse gas emissions per ha of land trended negatively with greater cow supplement feed intake (corn, alfalfa, and soybean) and with greater concentrate production. This could be a function of two factors. First, the overall land-base for the less-pasture intense farms were greater to allow for the production of concentrates as well as dry hay and silage, distributing whole-system emissions over a larger land base. Second, on a per-ha basis, energy derived from land under row crop and alfalfa hay production likely produced more digestible feed, reducing enteric emissions, which is a major contributor to the GHG emissions on dairy farms. Indeed, calculated enteric emissions were greater from the systems more reliant on pasture on a per land and per t ECM basis. This is in agreement with Sutter et al. (2013), who noted that the high CH_4

emissions per kilogram of ECM is the weakest aspect of pasture feeding strategies on system carbon footprint, with increased use of forages from pasture results in higher CH_4 emissions (Boer, 2003; Takahashi and Young, 2002).

While enteric emissions from grazing herds could be reduced by substituting concentrate feed for forage, improving forage quality, and the nutrient efficiency of pastures could also contribute to the mitigation of these impacts (Hietala et al., 2014). These improvements could include increasing pasture quality through forage composition, breeding improved pasture grass and legume varieties, fertility management, grazing practices, and management of the harvest and storage of conserved feeds. Also, breeding cows for greater genetic merit for milk production on pasture could contribute to emission abatement (Wall et al., 2010).

6.5.2 Consideration of allocation factors

On many farms raising both crops and livestock, more than one product (including those that may be value-added) are often generated and brought to market through inter-related processes. To accurately assess the carbon footprint of each individual product, the LCA must disaggregate the GHG contributions associated with each separate enterprise, so that the burdens and impacts of production are “allocated” appropriately across all outputs (ISO 14041, 1998). While, on the dairy farm, milk is the primary output, other products can be considered, such as beef, surplus replacement heifers, and other specialty items such as products from manure. The process of allocating impacts to the individual products ensures that the analysis does not overstate the environmental burden of dairy production and ignore the contributions of the co-products produced (Casey and Holden, 2005; Cederberg and Stadig, 2003).

Methods to allocate GHG emissions among the coproducts of multifunctional systems vary by different LCA and carbon footprint guidelines (International Organization for

Standardization, 2006b; Institution, 2011; International Dairy Federation, 2010). Depending on the methodology selected, significant differences can result in the proportion of dairy system GHG emissions that are allocated to milk and can change rankings of systems with respect to GHG emissions (O’Brien et al., 2014; Flysjö et al., 2011). Other published studies have demonstrated that the results of LCA derived from comparisons of grazing versus confinement systems can vary with consideration of different allocation factors. For example, an Iowa-based study found that while whole-farm GHG emissions of a dairy grazing system was higher than the conventional system by 2.0%, after considering allocation to co-products, emissions from the grazing system were 9.2 percent below the conventional system (Duffy and Herringshaw, 2011).

In our analysis, the co-products that were considered are limited to milk and meat. Farms with a higher level of pasture feeding tended to have greater allocation to meat, which lowered overall carbon footprint significantly from these farms; this resulted in a lower carbon footprint of grazing systems when considered on a per ha land as well as on a per cow basis. With consumer demand for grass-fed meat products increasing, the integration of beef production into organic dairy farms, particularly those with an emphasis on pasture-based feeding strategies, could offer an economic opportunity for farms, in addition to providing environmental benefit through the distribution of emissions over a wider range of co-generated products. However, on the farms included in this study, the lower milk production associated with the clusters with greater emphasis on pasture created a disadvantage when evaluating the GHG emissions on a per t ECM basis.

6.5.3 Other considerations

Although the partial LCA focused on GHG emissions allows for one tool to assess the possible impacts of feeding strategies and land use on organic dairy farms, other environmental trade-offs must be considered, including soil erosion, water quality and resource consumption (Boer, 2003). Over the past decade, grazing and confined dairy operations have been compared to examine their carbon footprint, extent of nitrate leaching, and ammonia volatilization (Belflower et al., 2012). Additionally, these same types of evaluations have been conducted for organic versus conventional milk production, with organic milk production typically demonstrating a more positive impact on environmental indicators including energy saving, acidification, eutrophication, photo-oxidant formation, ecotoxicity, and ozone depletion, which are the other great concerns of intensive dairy production (Cederberg and Mattsson, 2000; Haas et al., 2001; Thomassen et al., 2008b; Nemecek et al., 2011)

While consideration of these other factors related to environmental sustainability is critical in the development of a more holistic strategy in the development of sustainable agricultural systems, the relative prioritization of these additional factors in comparison to GHG emissions remains challenging. For example, in the determination of the percentage of land to manage as pasture, the suitability of the land associated with an individual farm for row crop production may play an equally important role in decision making as compared to greenhouse gas emissions. The impacts of annual crops on sloping land includes loss of soil and nutrients to runoff and erosion, eutrophication of local water bodies (Arsenault et al., 2009). Other studies have demonstrated the importance of this consideration in Wisconsin, USA (Reinemann et al., 2013a), in their comparison environmental impacts of dairy farms with varying emphasis on grazing, illustrated that the corresponding environmental benefits of management intensive grazing versus row crop production on less productive lands (which also tended to be environmentally sensitive) (continuous crop cover versus annual harvest and tillage) is much more pronounced than on less sensitive lands (Reinemann et al., 2013b).

Furthermore, it is important to consider the feedbacks between the different categories contributing to overall farm emissions when considering the decision to change management associated with any single category. For example, when evaluating the decision to increase concentrate use to lower enteric emissions, other environmental impacts must be considered, including the type of land that would contribute to additional hectares required for production, the impacts of shipping that product, and the associated energy inputs and GHG emissions related to the production of those row crop hectares (Schader et al., 2012). When these additional factors are considered, it becomes apparent that while greater proportion of concentrate in the ration can decrease enteric emissions, it can concomitantly result in higher additional GHG emissions from a land use perspective (Hörtenhuber et al., 2010; O'Brien et al., 2012) .

Improvements in management strategies can offer positive contributions to mitigate the impacts of these trade-offs. For example, better quality and productivity of pastures could yield marked benefit not only to the milk productivity and profitability of organic dairy farms, but also to GHG emissions (Lizarralde et al., 2014; Lovett et al., 2006; Casey and Holden, 2005; Beukes et al., 2010; Yan et al., 2013). Poor grazing management practices, such as over-grazing on poor pastures with high stocking rates, can lead to low forage intake and suboptimal herd nutrition. While greater supplemental feeding with concentrate can compensate for poor grazing management, this leads to an inefficient use of resources, particularly in organic production where access to pasture is mandatory. Research and education to provide farmers with tools to provide efficient technologies and strategies to improve pasture productivity, quality, and management intensive grazing practices could lead to an increase in milk productivity on farms with a high degree of pasture-based feeding, further leading to an overall reduction in the CF of these grazing based farms. However, as discussed above, these changes must be considered in the context of the broader management trade-offs. Increasing pasture intake will more likely and reliably result in net positive benefits when the forage consumed is high quality feed with high energy content and relatively low fiber content, which simultaneously reduces the feed demand per kilogram of milk and enteric emissions (Lovett et al., 2008).

6.6 Conclusions

Choice of FU changes the LCA results of dairy production systems. Different functional units interpret the results in various ways: intensification, land resource efficiency, or production efficiency. In addition to the FU, allocation factor is important. Reconciling the relative environmental impacts and productivity is difficult, and likely differs on a regional basis. While mass-based FU is the dominant practice in LCA studies, these studies may well ignore environmental impacts of intensification of dairy systems and likely of other agricultural production systems. We recommend using both mass-and area-based FUs in LCA studies of agri-food products to ensure more balanced assessment results.

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Table 6.1. Descriptive statistical results of 4 clusters[1] and the total sampling farms from Hardie et al. (2014). Energy-corrected milk production (ECM), feed efficiency, and grazing time on pasture in a year were calculated based on data from Hardie et al. (2014). Other results were calculated based on survey results from Hardie (2013).

	C1	C2	C3	C4
Number of farms	8	5	32	24
Number of cows per farm	129	50	41	43
Rolling herd average milk production (kg per cow per year)	6,878	3,632	7,457	5,417
Energy-corrected milk production (kg per cow per year)[2]	6,657	3,857	7,164	5,495
Percent of purebred Holstein cows	90	0	89	6
Percent of first lactation cows	31.6	32.7	29.7	26.1
Number of bull calf sold per yr	39	19	15	16
Concentrate fed per cow per day (kg per day)	8.0	2.0	6.0	6.0
Dry matter intake (DMI, kg per cow per day)	22.1	15.2	20.9	18.1
Percent of Land used as pasture	22	100	31	49
Grazing period starting and ending time	Apr. 19 Nov. 7	Apr. 26 Nov. 28	May 1 Oct. 21	Apr. 21 Nov. 8
Grazing period length (days)	203	216	176	199
Average hours per day on pasture during grazing season	17	22	19	21
Grazing time on pasture (days per yr)[3]	143	194	141	174
Allocation factor to milk[4]	0.82	0.71	0.85	0.84
Land demand per cow per year (ha)	0.91	0.66	0.87	0.72

[1] Cluster 1 = C1, cluster 2 = C2, cluster 3 = C3, and cluster 4 = C4.

[2] ECM = [0.25 + 0.122 × fat (%) + 0.077 × protein (%)] × milk production (kg) (Sjaunja et al., 1990).

[3] Grazing time on pasture in a year is the actual time (days) cows graze on pasture during one-year period, calculated as grazing period length × (average hours per day on pasture during grazing season÷ 24).

[4] Allocation factor to milk is the proportion of total GHG emission allocated to milk. It is calculated as 1-5.7717 × (M_{meat} /M_{milk}) (IDF, 2010).

All four clusters – relatively same amount of replacement rate - meat sales not much more, but more related to lower milk – greater proportion of what is being produced on farm is meat, - less of carbon footprint allocated to milk

Table 6.2. Nitrous oxide emissions from row cropland (corn, soybean, and alfalfa) and pasture with or without soil carbon loss (SCL) for each feeding strategy cluster[1] under different concentrate scenario[2], reported in 3 units: farm-level total land emission (kg eq. CO_2), per-cow level (kg eq. CO_2 per cow), per-t of energy corrected milk (ECM, kg eq. CO_2 per t ECM). Concentrate scenario of 75% corn and 25% soybean was the baseline scenario (BASELINE); the other 2 scenario results were represented as the difference from the baseline scenario.

	C1	C2	C3	C4
Total land emission without SCL (kg eq. CO_2 per farm per yr)	114,456	26,936	33,702	28,808
Total land emissions with SCL (kg eq. CO2 per farm per yr)	334,949	55,156	93,928	71,241
Land emission per ha of land without SCL (kg eq. CO_2 per ha of land per yr)	975	817	945	931
Land emission per cow without SCL (kg eq. CO_2 per cow per yr)	887	539	822	670
Land emission per t ECM without SCL (kg eq. CO_2 per t ECM)	109	99	97	102
Land emission per ha of land with SCL (kg eq. CO_2 per ha of land per yr)	2,809	1,642	2,592	2,264
Land emission per cow with SCL (kg eq. CO_2 per cow per yr)	2,556	1,084	2,255	1,630
Land emission per t ECM with SCL (kg eq. CO_2 per t ECM)	322	204	271	254

[1] Cluster 1 (C1) fed the greatest amount of concentrate; Cluster 2 (C2) grazed longest time and fed the least concentrate; Cluster 3 (C3) and Cluster 4 (C4) were moderate between C1 and 2. Details summarized in Table 1.

[2] BASELINE = using 75% corn grain and 25% soybean seed; ALLCORN = using all corn grain; HALFCORN = using 50% corn grain and 50% soybean.

Table 6.3. Total enteric CH4 emission from all lactating cows in the herd for each feeding strategy cluster1, in the dominators: kg of CH4, kg of eq. CO2, kg eq. CO2 emission per cow, and kg of eq. CO2 emission per t of energy corrected milk (ECM). Concentrate scenario of 75% corn and 25% soybean was the baseline scenario (BASELINE); the other two scenario results were represented as the difference from the baseline scenario.

	C1	C2	C3	C4
Enteric fermentation CH_4 emission (kg CH4 per farm per yr)	17,320	5,325	5,272	5,073
Enteric fermentation equivalent CO_2 emission (kg eq. CO_2 per farm per yr)	588,888	181,038	179,236	172,488
Enteric fermentation emission per ha of land (kg eq. CO_2 per ha of land per yr)	5,016	5,486	5,025	5,571
Enteric fermentation emission per cow (kg eq. CO_2 per cow per yr)	4,565	3,621	4,372	4,011
Enteric fermentation emission per t ECM (kg eq. CO_2 per t ECM)	565	670	518	614

[1] Cluster 1 (C1) fed the greatest amount of concentrate; Cluster 2 (C2) grazed longest time and fed the least concentrate; Cluster 3 (C3) and Cluster 4 (C4) were moderate between C1 and 2. Details summarized in Table 1.

Table 6.4. Nitrous oxide and CH_4 emission from manure management (manure deposited during grazing, manure storage, and manure spreading) for each feeding strategy cluster[1], in the dominators: kg of CH_4, kg of eq. CO_2, kg eq. CO_2 emission per cow, and kg of eq. CO_2 emission allocated to per t of energy-corrected milk (ECM). Concentrate scenario of 75% corn and 25% soybean was the baseline scenario (BASELINE); the other two scenario results were presented as the difference from the baseline scenario.

	C1	C2	C3	C4
Manure deposited during grazing				
N_2O (kg N_2O per farm per yr)	359	166	114	142
CH_4 (kg CH_4 per farm per yr)	223	82	66	72
Total equivalent CO_2 (kg eq. CO_2 per farm per yr)	114,501	52,372	36,226	44,708
Equivalent CO_2 per ha of land (kg eq. CO_2 per ha of land per yr)	976	1,586	1,016	1,444
Equivalent CO_2 per cow (kg eq. CO_2 per cow per yr)	888	1,047	884	1,040
Equivalent CO2 per t ECM (kg eq. CO_2 per t ECM)	110	194	105	159
Manure storage				
N_2O (kg N_2O per farm per yr)	131	33	40	33
CH_4 (kg CH_4 per farm per yr)	3,442	707	1,065	821
Total equivalent CO_2 (kg eq. CO_2 per farm per yr)	156,001	33,892	48,037	37,836
Equivalent CO_2 per ha of land (kg eq. CO_2 per ha of land per yr)	1,329	1,027	1,347	1,222
Equivalent CO_2 per cow (kg eq. CO_2 per cow per yr)	1,209	678	1,172	880
Equivalent CO2 per t ECM (kg eq. CO_2 per t ECM)	150	125	139	135
Manure spreading				
N_2O (kg N_2O per farm per yr)	260	66	80	66
CH_4 (kg CH_4 per farm per yr)	30.1	6.4	9.5	7.4
Total equivalent CO_2 (kg eq. CO_2 per farm per yr)	78,595	19,800	24,117	19,829
Equivalent CO_2 per ha of land (kg eq. CO_2 per ha of land per yr)	669	600	676	640
Equivalent CO_2 per cow (kg eq. CO_2 per cow per yr)	609	396	588	461
Equivalent CO2 per t ECM (kg eq. CO_2 per t ECM)	75	73	70	71

[1] Cluster 1 (C1) fed the greatest amount of concentrate; Cluster 2 (C2) grazed longest time and fed the least concentrate; Cluster 3 (C3) and Cluster 4 (C4) were moderate between C1 and 2. Details summarized in Table 1.

Table 6.5. Emission source and total farm carbon footprint (kg eq. CO_2 per t ECM and kg eq. CO_2 per ha of land) for each feeding strategy cluster[1]. Concentrate scenario of 75% corn and 25% soybean was the baseline scenario (BASELINE); the other two scenario results were represented as the difference from the baseline scenario.

	C1		C2		C3		C4	
N_2O (kg eq. CO_2 per t ECM)[2]	***Milk and meat***	***Only milk***	***Milk and meat***	***Only milk***	***Milk and meat***	***Only milk***	***Milk and meat***	***Only milk***
Crop land and Pasture (without SCL included)	133	109	140	99	115	97	122	102
Grazing manure deposit	125	102	257	183	116	98	179	150
Manure Storage	45.4	37	51.0	36	40.7	35	41.6	35
Manure Land Application	90.3	74	101.5	72	81.0	69	82.9	69
CH_4 (kg eq. CO_2 per t ECM)[2]								
Enteric fermentation	686	562	939	667	610	519	730	613
Grazing manure deposit	8.8	7.2	14.5	10.3	7.6	6.5	10.4	8.7
Manure Storage	136	112	125	89	123	104	118	100
Manure Land Application	1.2	1.0	1.1	0.8	1.1	0.9	1.1	0.9
Soil carbon loss (SCL, kg eq. CO_2 per t ECM)[2]	254		145		190		177	
Replacement heifer emission (kg eq. CO_2 per t ECM)	293	240	470	240	249	211	256	215
GHG emission without SCL (kg eq. CO_2 per ha land)	11,107	9,108	12,265	8,708	11,056	9,398	11,762	9,880
GHG emission with SCL (kg eq. CO_2 per ha land)	12,985	10,648	13,120	9,315	12,745	10,833	13,133	11,031
GHG emission without SCL (kg eq. CO_2 per cow)	10,107	8,288	8,095	5,747	9,619	8,176	8,469	7,114
GHG emission with SCL (kg eq. CO_2 per cow)	11,816	9,690	8,659	6,148	11,088	9,425	9,455	7,943
GHG emission without SCL (kg eq. CO_2 per t ECM)[3]	1,518	1,245	2,099	1,490	1,343	1,141	1,541	1,295
GHG emission with SCL (kg eq. CO_2 per t ECM)[3]	1,775	1,456	2,245	1,594	1,548	1,316	1,721	1,445

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[1] Cluster 1 (C1) fed the greatest amount of concentrate; Cluster 2 (C2) grazed longest time and fed the least concentrate; Cluster 3 (C3) and Cluster 4 (C4) were moderate between C1 and 2. Details summarized in Table 1.

[2] Nitrous oxide and CH4 emission and soil carbon loss values in the table were the total emission for both milk and meat. Greenhouse gas emission per t ECM (kg eq. CO_2 per t ECM) was GHG emission allocated to milk adjusted with allocation factor to milk

Appendix 6.I. Daily lactating cow DMI (kg per cow per d) of different feed type for each cluster[1] from Hardie et al. (2014). Daily corn grain and soybean DMI (75% corn grain + 25% soybean) were calculated based on daily concentrate intake from each cluster (Liang et al., 2017).

Cluster	Concentrate feed ingredient		Total concentrate	Corn silage	Hay	Alfalfa haylage	Vitamin and mineral	Grazing[2]	Total DMI
	Corn grain	Soybean							
1	3.72	1.24	5.0	2.7	2	7.9	0.5	4.2	22.1
2	1.52	0.51	2.0	0	3.2	0	0.1	9.8	15.2
3	3.02	1.01	4.0	2.0	3.1	6.0	0.3	5.5	20.9
4	1.32	0.44	1.8	1.3	3.1	4.7	0.2	7.0	18.1
Average			3.2	1.5	2.9	4.7	0.3	6.6	19.1

[1] Cluster 1 fed the greatest amount of concentrate; Cluster 2 grazed longest time and fed the least concentrate; Cluster 3 and cluster 4 were moderate between clusters 1 and 2.

[2] Grazing DMI was calculated as the difference between the total DMI and other feed intake (concentrate, corn silage, hay, haylage, and vitamin and mineral).