MANAGING TODAY'S DAIRY HERD FOR A SUSTAINABLE FUTURE

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ABSTRACT

Sustainability has become an important word throughout agriculture, yet it is often overused and misinterpreted. Sustainability has three pillars: environmental, economic, and social. For a project or business to achieve optimal sustainability it must mix these 3 components. Research is being conducted in each of these areas to aid dairy producers in making sustainable decisions for their operations. To further this research, this thesis primarily focused on economic and environmental sustainability through two different projects.

The first project, which primarily focused on economic sustainability, investigated whether Jersey or Holstein dairy cattle are more profitable when housed on the same farm in a North Central U.S. climate. The study included 3 case study farms that milked both Jersey and Holstein dairy cattle and found that Holstein cows were on average $456 more profitable annually across the 3 farms. Based on sensitivity analysis, it is unlikely that Jerseys can surpass Holstein profitability. The second project focused on providing a fuller understanding of greenhouse gas (GHG) footprints on dairy farms. GHG footprints can be impacted by management practices. We evaluated whether small dairies could approach net zero emissions, by assessing the GHG footprints of four small and mid-sized dairy farms throughout the United States with Farm ES and Comet models. Longitudinal soil samples were also analyzed to determine carbon sequestration rates. Evaluating these 4 farms allowed comparison across regions, management practices, and prediction models and revealed that small dairy farms can approach carbon neutrality today when accounting for soil carbon sequestration.

Although vastly different, both studies provide valuable insight into questions the dairy industry has asked for years. As an industry, being able to quantify what is currently happening on dairies opens opportunities to improve decision-making in the future and create solutions that are economically, environmentally, and socially sustainable.

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LIST OF ABBREVIATIONS

AI	Artificial insemination
BCS	Body condition score
BRD	Bovine respiratory virus
BVDV	Bovine viral diarrhea virus
CH_4	Methane
CNMP	Comprehensive nutrient management plan
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DA	Displaced abomasum
DIM	Days in milk
DM	Dry matter
DMI	Dry matter intake
F1	First filial generation
FPCM	Fat and protein corrected milk
GA	Georgia
GHG	Greenhouse gas
IgG	Immunoglobulins
IOFC	Income over feed costs
LCA	Life cycle analysis
MCR	Methyl-coenzyme M reductase
MI	Michigan
NASEM	National Academies of Sciences, Engineering, and Medicine

NEFA	Non esterified fatty acids
N_2O	Nitrous oxide
3-NOP	3-nitrooxypropanol
OM	Organic matter
PA	Pennsylvania
PMR	Partial mixed ration
PPD	Producer price differential
SCC	Somatic cell count
SOC	Soil organic carbon
SNFP	Solids nonfat and protein
S/P	Sample to positive ratio
THI	Temperature humidity index
TMR	Total mixed ration
U.S.	United States
USDA	United States Department of Agriculture
WA	Washington

CHAPTER 1:

INTRODUCTION

Dairy producers across the country must continually make decisions to maintain or improve their dairy operations. Sustainability is one of many things considered when making decisions throughout the industry. A robust dairy farm must consider economic, environmental, and social implications of their business and management decisions. Research has been and continues to be used to aid producers in considering these implications of management strategies on dairy farms.

Over the last 30 years the demographics of the U.S. dairy herd have changed drastically. As the dairy herd across the country slightly declines, the proportion of Holstein cows within the U.S. herd has diminished as Jersey and crossbred dairy cattle grow in popularity (USDA, 2000, 2020). Cattle breed is a factor that impacts the economic sustainability of a dairy farm and many producers across the country have differing perceptions on which breed results in greater profitability.

Furthermore, there has been a recent push to better understand impacts of decisions made around environmental sustainability. Much focus has been placed on greenhouse gas (GHG) emissions and reducing the carbon footprint on dairy farms. Recent research has focused on understanding the emissions from large dairy farms and strategies to mitigate emissions (De and Il Ver, 2014; Rotz, 2018; Place et al., 2022). Yet limited research has quantified GHG emissions from smaller dairy farms and economically sustainable practices to reduce environmental impacts on these farms.

Therefore, we were interested in investigating two of the questions dairy producers must face when considering strategic decisions for the profitability and environmental impact of their operations. From an economic sustainability perspective, we evaluated whether Jersey or Holstein dairy cattle were more profitable in a North Central U.S. climate by evaluating performance of cattle from both breeds managed on the same farms. Understanding this topic can lead producers to optimize profitability and thereby remain economically competitive within the industry. Furthermore, we were interested in understanding questions around environmental sustainability, to look at sustainability from a holistic approach when it came to small to mid-size dairy farm emissions. Therefore, we quantified GHG emissions on 4 small and mid-sized dairies throughout the U.S. using 2 different estimation models. Comparing these estimates allowed evaluation of management practices that help farms reduce emissions. By documenting optimal breed choice and environmental practices, this research can contribute to ongoing efforts to enhance the sustainability of dairy farms.

CHAPTER 2:

APPROACHES TO ENHANCE DAIRY INDUSTRY SUSTAINABILITY LITERATURE REVIEW

SUSTAINABILITY INTRODUCED

Consumers are the driving force behind food production across the world. As consumers further their demand for food that is sustainably sourced, the agricultural industry must understand what constitutes sustainable agriculture. Sustainable agriculture is created through economic, environmental, and social sustainability (Velten et al., 2015). Sustainable agriculture applies to farmers and producers as well as to all input suppliers and post farm-gate players. Post farm-gate value-adding supply chain members include processors, manufacturers, transporters, wholesalers, and retailers. This is where much of the economic value is captured within the food industry, and these steps can also be sources of greenhouse gas emissions and water use (Yi et al., 2021). Therefore, as a food industry all members of the supply chain must strive for economic, environmental, and social sustainability.

Economic sustainability on dairy farms requires an understanding of management practices and decisions that take place throughout the farming operation. As input costs such as feed, labor, and land increase, paired with volatile revenue, the goal of economic sustainability becomes critical. Due to the uncertainties within production agriculture, economic sustainability requires that farms have the financial ability to survive a negative profit year and still maintain their presence within the industry (Nabil, 2016). Economically sustainable producers focus on long-term profitability. Producers can strategically use risk management practices to help maintain this long-term profitability. Cattle genetics, reproductive decisions, facility style, labor needs, and cropping systems are all management decisions and practices that could impact profitability and overall economic sustainability.

Environmental sustainability has become a greater concern for dairy producers as the industry strives for carbon neutrality to aid in efforts to reduce global warming. Furthermore, water and air quality continue to be more intensely regulated. Although environmental sustainability has been at the forefront recently, it is not a new concept and goes far beyond carbon footprinting. It ensures that businesses are practicing environmental stewardship through responsibly using the assets of the earth. Environmental sustainability can be broken down into production (including natural resource conservation and productive capacity) or non-production factors, which include animal welfare and environment improvement (Velten et al., 2015). Within production agriculture, efficiency in using environmental resources such as land, water, and fuel while reducing greenhouse gases (GHG) emissions is a key goal. Life cycle analysis has been used as a tool for quantifying the resources used and emissions within the dairy industry (Mc Geough et al., 2012).

Social sustainability is determined through the impact a dairy farm has on people, including employees, neighbors, or consumers (United Nations Global Compact). As the world population continues to increase, reaching between 8 and 10 billion people in 2050, social sustainability will become increasingly important (Lutz and KC, 2010). What consumers perceive to be happening on farms and to animals can be felt both positively and negatively and greatly determine a person’s perception of a product, business, or industry. Consumer demand for food drives the agriculture industry. Therefore, helping consumers understand where their food comes from and that it is safe is critical for society and begins with industry leaders building relationships with consumers. All three pillars of sustainable agriculture are important to the dairy industry as it continues to grow, producing the food needed to fuel future generations.

ECONOMIC SUSTAINABILITY

Dairies across the country operate businesses with millions of dollars of cash flow, leading to the dairy industry's total economic impact of $753 billion annually within the U.S. economy (Dykes, 2021). Even with a $753 billion dollar industry, the number of dairy farms in the U.S. continues to decline as average herd size and milk production per cow increases (Wolf, 2003). This leads us to consider which factors make a dairy operation profitable. When it comes to measures of profitability within the dairy industry, most profitability measures are analyzed per cwt of milk. As markets have evolved to a heavier emphasis on fat and protein component production, financial data have been analyzed per pound of fat and protein corrected milk. Research has determined that larger dairy farms typically are more profitable per cow than smaller dairy farms (Wilson, 2011; Connolly, 2022). A USDA publication found that in 2005, only operations over 500 cows had positive mean net returns per cwt milk (MacDonald et al., 2007).

When considering economic differences between small and large farms, it comes down to economies of scale advantages that large farms can capture (Wolf, 2003). Large farms can spread their fixed costs across more cows and greater cwt of milk, leading to less average fixed costs per cwt of milk on large farms compared to smaller farms. Furthermore, feed is the largest expense on all dairy farms (MacDonald et al., 2007) and location has a large impact on the feed bill on dairies throughout the U.S. (Wolf, 2003). Areas of the country such as the Midwest, which can generally grow much of their own crops, incur less purchased feed costs and more grown feed costs compared to the western U.S. Yet there are benefits and costs when it comes to purchasing feed. Although purchased feeds incur freight costs that home grown feeds do not, purchasing feed allows producers to assure consistently high feed quality for their herds every year, given there are no crop shortages (Wolf, 2003). In years of crop shortage, the prices for purchased feeds will be much higher and impact profitability in those parts of the U.S. purchasing more feed compared to the farms that are not. Dairy location not only can impact their costs of production but also their revenue. With milk being the largest revenue source, location can impact profitability on a dairy due to the environmental and weather impacts on milk production (Dartt et al., 1999). Weather and environmental impacts will be considered in more detail later in this review, but impact profitability differently between regions, along with milk price variations (Wolf, 2003). Transportation costs of both feed commodities and milk are also impacted through operation location and local supply and demand requirements.

Economic sustainability greatly determines an operation's long-term viability and risk of selling out. Because farms are businesses, if a dairy is not making a profit, it is nearly impossible to continue operation, as observed throughout the industry with recent shifts in herd sizes. Nearly all decisions that are made on dairy farms ultimately have some impact on long-term profitability and sustainability of the business. Therefore, the following factors can be considered when assessing economic sustainability on current dairy operations.

Breed Impact on Economic Sustainability

It seems like a debate that never ends: are Jersey or Holstein cows the better choice for profitable dairy production? With dairy herd size increasing and dairy farm numbers decreasing, the demographics of the dairy industry continue to change, yet this topic remains at the forefront as producers strive to maintain optimal profitability (Macdonald et al., 2020). Holstein cows have been the predominant breed in the U.S. dairy population for many decades. Yet from 2000 to 2020 the U.S. Holstein dairy herd declined 12.4% while the Jersey dairy herd increased 4.1% (USDA, 2000b, 2020). Although the Holstein breed dropped in their proportion of the U.S dairy herd, they remain the most popular breed. The question of breed profitability and efficiency has again come to the forefront as producers face increasing feed costs and volatile milk prices. This decision may have significant impact on the economic sustainability of an operation given the milk solids pricing market U.S. producers operate in. The following factors should be considered to optimize economic sustainability.

Regional Distribution and Heat Stress

Of the Jersey cows included in the study of Garcia-Peniche et al. (2005), 61% were in the Southwest U.S. The purported heat stress resilience of the Jersey breed compared to Holstein supports their growing footprint in the warmer southern and western regions of the U.S. (Garcia-Peniche et al., 2005). A study evaluating the impact of heat stress on 8 Jersey and 6 Holstein steers found significant increases in basophil and eosinophil concentrations in Holstein steers under heat stress conditions. No significant changes in Jersey eosinophil and basophil concentrations were found when impacts were evaluated at $P < 0.05$, although Jersey steers had greater blood basophil and eosinophil populations in both normal and heat stress conditions (Park et al., 2021). A 2021 study reported a significant difference in dry matter intake (DMI) by season for both breeds when age was balanced across season. Jersey steers consumed more dry matter in the summer compared to winter and spring, whereas Holstein steers consumed more dry matter in the spring compared to winter and summer (Islam et al., 2021b). In the summer, Holstein steers consumed the least DM whereas Jersey steers consumed the least in the winter (Islam et al., 2021b). This could be due in part to the Jersey breed's better ability to handle extreme weather conditions (Tarr et al., 2007).

Production responses to heat stress also differ between the breeds. In a study examining responses to the onset of heat stress (THI > 72) in 586 Holstein and 142 Jersey cows, milk yield significantly increased for Jersey cows by 2.70%, whereas Holstein milk yield significantly decreased by 3.93%. However, Jersey milk production still did not surpass Holstein production in heat stress conditions (Smith et al., 2013). Other studies found a reduced milk production for Jersey vs. Holstein cows, but the onset of heat stress for Jersey cows occurred at a greater THI than for Holstein cows (West, 2003). As dairy producers continue to face climate change, the U.S. Jersey population may continue to increase their presence due to the seasonal resilience they demonstrate.

Milk and Component Production

Most research comparing Jersey and Holstein cows has contrasted the breeds using data from different farms with different management and different environments. Furthermore, past research focused heavily on differences in milk production, feed consumption, and costs between the breeds, along with seasonality differences, to estimate the economic returns for the two breeds. On a fluid milk basis, Jersey cows were reported to produce 23% less milk than Holstein cows (White et al., 2002). This difference in milk production can be accounted for in part by smaller body size, resulting in reduced capacity for dry matter intake compared to Holstein cows (White et al., 2002). Furthermore, a study comparing Jersey x Holstein crossbred cows to Holstein cows found that the crossbred animals produced 5.5 kg/d less milk than Holstein cows, with significantly greater component concentrations. These findings suggest that first filial generation (F1) daughters are intermediate between Holstein and Jersey milk production performance (Anderson et al., 2007). Jersey cows do have an advantage when it comes to fat and protein concentrations, but the greater concentrations do not overcome the lesser milk yield, resulting in lesser fat and protein yields for Jersey cows (Palladino et al., 2010). In evaluating breed selection for optimal profitability, it is important to understand the milk pricing system within the U.S. Most U.S. dairy producers are paid for component yields rather than on a fluid basis; lactose and other non-fat and non-protein solids have very little value in most U.S. markets (USDA, 2022).

Therefore, it is important to determine yields of fat, protein, and solids nonfat and protein (SNFP) sold to overcome biased perceptions based on component concentrations. Furthermore, past research has not accounted for bonuses and discounts that are paid on a fluid basis (Bailey et al., 2005), including producer price differential (PPD), bonuses for milk quality, and milk hauling costs. Overall, the market in which milk is being priced plays an important role in determining the relative profitability of dairy breeds.

Reproduction

Jersey cows have been perceived by the U.S. dairy industry to be more fertile (Norman et al., 2009). Achieving pregnancy more quickly after the voluntary waiting period enables cows to return to the beginning of the lactation curve more quickly, a key to dairy profitability (Gröhn and Rajala-Schultz, 2000). Reproductive inefficiencies can also lead to increased culling, requiring more replacements to maintain a herd, further reducing overall profitability (Congleton and King, 1984). In a 2009 study comparing the reproduction of over 5 million Jersey and Holstein cattle, conception rate was analyzed by parity and breeding number, revealing that conception rate averaged 5% greater for Jersey cows compared to Holstein cows across parities (Norman et al., 2009). For the first 4 inseminations in every parity, Jersey cows had a greater conception rate than Holstein cows, with the difference between Jersey and Holstein cows ranging from 1% to 11% (Norman et al., 2009). Genetic improvements have been made within both breeds in the last 10 years. Comparing the Dairy Records Management System (DRMS) 2022 U.S. Jersey herd reproduction metrics to those of the Holstein herd, Jersey cows had a 2.7% greater conception rate across 417 Jersey and 6,821 Holstein herds (Dairy Records Management Systems Dairy Metrics, 2022).

Comparing reproduction of Jersey and Holstein cows in pasture or confined housing systems with seasonal calving revealed additional Jersey reproductive advantages. In both the confined and pasture systems, Jersey cows had a significantly greater first service conception rate, all service conception rate, and percent of cows pregnant in 75 days post calving compared to Holstein cows (Washburn et al., 2002). In a 1989 study, Jersey cows had a 9-day shorter calving interval within parity, on average, compared to Holstein cows (Nieuwhof et al., 1989). Furthermore, Jersey cows had a significantly shorter first calving interval than Holstein cows after calving in the spring or summer (Garcia-Peniche et al., 2005). Animals calving in spring and summer would reach their voluntary waiting period in the warmer months, pointing to likely involvement of seasonal resiliency in the Jersey breed.

Heat detection is critical to creating pregnancies in eligible cows. In a study of 212 cows, Jersey cows expressed estrus at 37.2 days post-calving on average, whereas Holstein cows had their first detected estrus at 66.9 days post-calving, on average (Fonseca et al., 1983). Overall, Jersey cows are found to be more reproductively efficient, seasonally resilient, and fertile than Holstein cows. Greater reproductive differences between breeds are evident in warmer months. The research reviewed does include some very old data and we acknowledge that both genetics and reproductive management have changed dramatically over the past 50 years.

Nutrition and Feed Costs

Nutrition is the key driver for milk production and would be important in reducing the productivity gap between Jersey and Holstein cows. Optimal nutrition of Holstein cows has been studied in great detail, which is not the case for Jersey cows. Many of the formulas in NASEM (2021) only take Holstein data into account, including the DMI equations. Genetic improvements are being used to achieve greater feed efficiency within dairy breeds, contributing to reduced environmental footprints. Although there are few direct comparisons of Jersey vs. Holstein cow energetics, one study evaluated maintenance energy requirements between Holstein Friesian and cross bred Jersey-Holstein cows. No significant difference in maintenance requirement between those genetically different animals was found (Dong et al., 2015). The study did not evaluate maintenance requirements between purebred Holstein and Jersey cows, but F1 Jersey-Holstein crossbred cows have a mean body weight and DMI less than Holstein and greater than Jersey cows (Olson et al., 2010).

A potential challenge to reducing this gap is the size of a Jersey cow and their gut capacity. On average, Jersey cows are genetically smaller animals than Holstein cows, and differ in feed efficiencies and maintenance requirements (Kristensen et al., 2015). A 2015 study including 508 Holstein and 100 Jersey herds revealed that Jersey cows are more efficient at converting energy into milk solids than Holstein cows (Kristensen et al., 2015). Jersey cows consume less dry matter than Holstein cows, which can be attributed to their smaller gastrointestinal capacity (Beecher et al., 2014). Beecher et al. (2014) found that every component of the Jersey gastrointestinal tract is smaller than that of a Holstein, providing less space for feed to be stored and digested. This drives the importance of getting the most out of the ration that is consumed, as nutritionists have less dietary dry matter to work with when formulating for Jersey cows. The lesser feed consumption of Jersey cattle also lowers feed costs, impacting overall profitability of the breed. Furthermore, when investigating the rumen microbiome of Jersey and Holstein steers, it was found that Holstein steers have a significantly higher rumen pH compared to Jersey steers (Islam et al., 2021a), contributing to different rumen microbiome populations in each breed (Russell, 1998). Therefore, further research should be done to identify how to more precisely feed Jerseys based on their unique microbiome situation to optimize efficiency, production, and sustainability, with a goal of reducing the gap between breeds.

Nutrition alters milk component yield. To maximize milk solids production, it is important to understand that 55% is determined by genetics, while the other 45% is due to environmental factors such as nutritional inputs (Grant and Kononoff, 2007). In general, to maximize solids production, producers should maximize feed intake. In further striving to alter milk protein within a current herd through environmental factors, focus should be placed on feeding adequate crude protein (between 16 and 18% of DM) and maintaining adequate bypass protein (between 33 and 40% of crude protein; Grant and Kononoff, 2007). As producers strive to create a product that is demanded by processors and customers, understanding how nutrition impacts milk production and quality for both breeds is critical.

Health

Animal health plays a role in the economic sustainability of dairy farms. If a breed is prone to numerous health disorders, their risk of leaving the herd early increases. Production and reproduction outcomes may also be impacted over a long period of time (Pritchard et al., 2013). Within the U.S. in 2007, 56.5% of the deaths in pre-weaned calves were due to digestive problems whereas 46.5% of the deaths in post weaned heifers were due to respiratory disease (USDA, 2010). Management and type of housing for calves play a large role in their risk of disease. A 2015 review reported that research has produced mixed results as to whether individual calf housing benefits calf health compared to group housing, but concluded that management practices significantly impact transmission and prevalence of disease (Costa et al., 2015). Ventilation, health monitoring and treatment, feeding methods, group size and age, as well as cleaning practices all should be managed properly to ensure optimal calf health in both individual and group housing situations (Costa et al., 2015).

Within the industry, Jersey calves are perceived to be less resilient. Research indicates that Jersey cows produce colostrum with greater IgG concentrations which leads Jersey calves to have a greater total serum protein concentration than Holstein calves (Quigley et al., 1994). This provides Jersey calves with greater passive transfer of immunity in early life. Considering calf health differences between breeds around the weaning period, Jersey bulls had a significantly lesser change in bovine viral diarrhea virus (BVDV) antibody sample to positive ratio (S/P) from 14 days prior to weaning to 14 days after weaning (Murray et al., 2018). This could lead Jersey calves to being more susceptible to bovine respiratory disease (BRD) than Holstein calves in the post weaning period. A 2002 study looking at glucose metabolism with differing milk replacer feeding methods found that for both 2× and 1× daily feeding, Holstein calves had greater plasma and urine glucose concentrations, but lower plasma NEFA concentrations and less insulin sensitivity compared to Jersey calves (Stanley et al., 2002). Because Jersey calves have greater insulin sensitivity, this may decrease blood glucose concentration more quickly after feeding compared to Holstein calves, leaving them at risk for hypoglycemia and potentially impaired immune function. Therefore, research suggests that Jersey calves have lesser resilience to disease compared to Holstein calves despite greater passive transfer.

Cow health and disease traits have become of increasing interest in breeding programs due to the impact of cow health on production, reproduction, culling risk, and profitability. In a 2014 study comparing culling risk of Jersey and Holstein dairy cattle from over 200,000 lactations in Texas, Jersey cattle had a 7% lesser culling risk for economic reasons and a 2.9% lesser culling risk for disease or injury compared to Holstein cattle (Pinedo et al., 2014). Metabolic diseases may play a factor in culling decisions; these diseases are heavily influenced by the environment and management practices and have heritability estimates less than 5% (Pryce et al., 2016). Understanding that health incident monitoring and recording is not universal across herds, there is an opportunity to capitalize on differences between breeds. Milk fever is of interest to dairy producers as it has been positively related to other metabolic diseases and reduced lactation performance (Pryce et al., 2016). Ballantine and Herbein (1991) found that Jersey cows had lesser total and ionized calcium concentrations compared to Holstein cows at calving, but did not identify a mechanism underlying these lower concentrations. A 2018 study of 27,297 Jersey cows and 29,549 Holstein cows found a milk fever incidence rate of 6.84% for Jersey cows and 4.34% for Holstein cows, with higher incidence as parity increased (Saborío-Montero et al., 2018). Further, among crossbred cows, the risk of milk fever was progressively reduced as the proportion of Holstein genetics increased (Saborío-Montero et al., 2018). Although Holstein cows have a lesser estimated risk of milk fever compared to Jersey cows, the heritability (between 0.01 to 0.07) and repeatability (between 0.04 to 0.07) measures of milk fever are very low (Kadarmideen et al., 2000).

Somatic cell count across 1,924 Holstein herds and 123 Jersey herds showed that Holstein cows had a 203,000 cells/mL weighted average somatic cell count compared to 235,000 cells/mL for Jersey cows (Ag Source, 2021). The environment plays a critical role in somatic cell count. Further investigation could be done to determine the impact of heat stress on somatic cell count within the breeds. Additionally, well-managed dairies that emphasize cleanliness and practice exemplary milk preparation procedures in the parlor benefit from lesser somatic cell counts (Kelly et al., 2009). Even on well-managed dairies, somatic cell counts vary based on environmental factors such as weather stressors. A 1982 study of 27,009 cows found that somatic cell count was least in the month of May and greatest in December (Kennedy et al., 1982). Somatic cell count not only impacts the quality of milk but is negatively associated with the health and productivity of the herd. Therefore, maintaining low somatic cell counts remains a goal.

Mastitis is also a costly disease, primarily due to milk production loss, with an estimated cost per case of mastitis in the first 30 days post-fresh of $444 (Rollin et al., 2015). A study comparing Jersey vs. Holstein mastitis cases in pasture and confined management systems with 36 cows in each system revealed that Jersey cows had a 37% lesser mastitis incidence than Holstein cows in both the confined and pasture systems (Washburn et al., 2002). The same study revealed greater longevity among Jersey cows, with 30% more of the Jersey cows in the confined system remaining in the herd for their next lactation and 21% more of the Jersey cows in the pasture-based system remaining (Washburn et al., 2002). Furthermore, there was significantly greater incidence of mastitis in the confined system than the pasture system; none of the pasture Jersey cows were infected with mastitis (Washburn et al., 2002). Although there is currently limited research comparing the risk of mastitis between the two breeds, Berry et al. (2007) revealed similar findings that Jersey cows are at lesser risk of mastitis than Holstein cows. High somatic cell milk (greater than 100,000 cells/mL) reduces the quality, quantity, and shelf life of cheese while increasing moisture content (Barbano et al., 1991). Holstein cows have an average somatic cell count 32,000 cells/mL less than Jersey cows (Ag Source, 2021).

Product Use- Quality and Characteristics

As consumer tastes and preferences change, the optimal use of milk for production of dairy products may shift. Although fluid milk consumption in the U.S. continues to decline, total dairy consumption is on the rise due to increasing demand for cheese and butter (Bentley, 2014). Milk coagulation is an important property for cheese production and is measured through curd firmness and the rennet clotting time of milk (de Marchi et al., 2007). Quality and quantity of cheese are dependent on the milk coagulation property and can be impacted by somatic cell count, milk concentrations of calcium and phosphorus, and protein and casein content (de Marchi et al., 2007). Recognizing that somatic cell count is greatly influenced by the environment, it is an important factor to manage and monitor on dairies to ensure ample quality, quantity, and shelf life of all dairy products.

Milk proteins in the form of whey and caseins are important in facilitating the curding and coagulation process. Additionally, calcium and phosphorus are essential nutrients in coagulation and increase the rate of curd formation and firmness in curds (Lim et al., 2020). A 2020 study found that Holstein cows produce milk with greater milk calcium and phosphorus concentrations at 3 days in milk (DIM), but Jersey cows produced greater calcium and phosphorus concentrations at 30 DIM. Jersey cows have greater milk calcium and phosphorus concentrations over the course of a lactation (Linn, 1988). According to a 2015 study, Jersey cows have greater cheese yield in kg/100 kg of milk due to their high component concentrations compared to Holstein cows (Bland et al., 2015). Jersey cows' greater total solids, calcium, and phosphorus concentrations throughout their lactation provide greater milk coagulation potential, higher quality cheese, and more desirable moisture content. However, it takes a greater number of Jersey than Holstein cows to make a given amount of cheese.

Jersey vs. Holstein Economics

A few studies have evaluated income over feed costs (IOFC) differences between Jersey and Holstein breeds, but they failed to account for all financial implications of the breeds. A 2002 study with 222 Jersey and 282 Holstein cows in pasture and confined housing systems revealed that Holstein cows had a $1.45 per day greater IOFC than Jersey cows, which was significant (White et al., 2002). Although the study found lesser feed costs for Jersey cows within both housing systems, Holstein cows generated more milk revenue compared to Jerseys, overcoming the greater feed costs (White et al., 2002). In contrast, Anderson et al. (2007) found that Jersey-Holstein crossbred cows have a $0.21 per cow per day advantage in IOFC over Holstein cows. This study lacked a broad scope of inference, drawing conclusions from just one farm and including around 200 animals labeled Jersey-Holstein crossbred and 800 Holstein cows. In the Jersey-Holstein crossbred pen, many different genetic backgrounds were represented, including full Jersey breed cows, half Jersey/half Holstein, and one-quarter Jersey.

A variety of other research across the world has investigated how the value of fat and protein impacts the profitability of Jersey and Holstein cows. However, these studies fail to account for many of the economic opportunity costs and revenues. Edwards et al. (2019) suggested that a higher fat price in comparison to protein price is a key factor to Jersey profitability and should be considered when making breed decisions. Further research should be done to identify the full profitability differences between the breeds, accounting for economic and financial revenue and expenses.

ENVIRONMENTAL SUSTAINABILITY

Mature dairy cattle produce roughly 12 gallons of manure for every 454 kg of live body weight, which equates to approximately 18 gallons of manure per day for a 680-kg Holstein cow (Chastain and Camberato, 2004). This manure is a combination of feces and urine and contains about 15% dry matter, including nutrients that can be used to fertilize crops (National Academies of Sciences, Engineering, and Medicine: Nutrient Requirements of Dairy Cattle, 2021). Yet manure has the potential to harm air and water quality if not properly managed. Managing runoff risks on farms as well as manure application rates and timing can positively impact water quality (Aillery et al., 2005). Regarding greenhouse gases and climate change, methane emissions from the rumen and manure lagoons have potential climate effects. To account for these emissions across an entire supply chain for any resource or pollutant, industries including the dairy industry have utilized life cycle analysis (LCA). Life cycle analysis has allowed the dairy industry to quantify aspects of environmental sustainability and identify areas of opportunity (International Organization of Standardization, 2006; Chen and Corson, 2014; Goglio et al., 2018; Berton et al., 2021).

Greenhouse Gases

About 11% of the total GHG emitted globally is attributed to animal agriculture (EPA, 2022a). Methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) are the three major GHG that the dairy industry contributes. Methane is considered a flow gas, as it is short-lived, with an estimated half-life of 10 years in the atmosphere. As a result, CH_4 does not necessarily build up over time, as it is created as quickly as it leaves the atmosphere if methane production remains stable. On the other hand, CO_2 is considered a stock gas because the rate of degradation is far slower (half-life of about 1000 years), causing the gas to accumulate within the atmosphere

(Place and Mitloehner, 2021). Because methane has more warming potential over 10 years than CO_2, it is more important in the near term. Yet CO_2 is a stock gas, and therefore its impact over hundreds of years is greater. On a dairy farm, GHG are emitted from three primary sources. Of the total GHG emissions on a dairy farm, roughly 50% comes from enteric CH_4 emissions (Mc Geough et al., 2012). Enteric CH_4 is produced within the cow's rumen and is released into the atmosphere through belching. Although enteric methane production will never be eliminated, it presents an opportunity for the dairy industry to alter feeding methods to improve feed efficiency and reduce enteric emissions. A large amount of CH_4 and N_2O emissions come from manure, whereas CO_2 and N_2O are also emitted through feed production. Emissions of N_2O from crop production represent approximately 26% of the total farm GHG emissions, whereas manure methane and manure N_2O represent about 8% and 7%, respectively (Mc Geough et al., 2012). Manure contributions depend on the handling system and therefore its impact on emissions varies widely between farms. Therefore, the cow, manure, and feed production are the primary emission sources that contribute to a dairy farm's GHG footprint. By focusing on these 3 sources, there is potential to reduce GHG emissions from dairies.

Life Cycle Analysis

Life cycle analysis is a modeling method that is used to identify environmental impacts of agricultural production. Application of LCA has been increasing in the last 25 years due to the increasing governmental and consumer push the agricultural industry has faced for reducing emissions (Matlock et al., 2022). Life cycle analysis provides transparency and understanding of emissions and processes that contribute. It attempts to account systematically for all potential contributions by segment of the system in which emissions (for example GHG) are produced or released in the process of generating a single unit of product. Production could be defined by milk production, cows, or monetary figures. For example, researchers can account for the GHG emissions and impact from one pound of milk produced. It is important to define the industry scope over which measures will be accounted for to compare emissions accurately. Many LCA studies have investigated emissions related to milk from cradle to farm-gate, or from feed crop production to milk leaving the farm (Mazzetto et al., 2020).

There are two potential aims for LCA studies. Comparative studies work to compare different systems which are being studied, such as dairy cow milk vs. plant-based alternatives (Grant and Hicks, 2018). Descriptive studies investigate the environment of a system and the benefits and costs associated with a particular system (Baldini et al., 2017). Figure 2.1 demonstrates the emissions that would be quantified in a descriptive LCA of milk.

Assigning GHG emissions to specific stages of a process and to the products produced is important. Developing and implementing allocation rules within an LCA project is critical for accurate allocation and environment impact calculations (Baldini et al., 2017). Differing allocation methods between studies impact the consistency of measurements from study to study, making it difficult to compare across studies. The LCA work that has been done in the dairy industry focuses on GHG emissions and carbon footprinting of milk and meat production at the cradle to farm-gate level. Other LCA have been conducted post farm-gate, and covering the dairy supply chain until the product reaches the consumers. Studies differ in their measurement of milk production and carbon footprints (Rotz et al., 2010; Mc Geough et al., 2012; Cates et al., 2013; Thoma et al., 2013a; Chen and Corson, 2014; Meul et al., 2014; Baldini et al., 2017, 2018; Grant and Hicks, 2018; Berton et al., 2021).

Breed Impact

Dairy cattle enteric methane emissions are directly related to an animal's DMI (Place and Mitloehner, 2021). Therefore, Jersey cows' lesser DMI compared to Holstein cows (Islam et al., 2021) results in a lower carbon footprint per cow for the Jersey breed. Jersey cows' lesser DMI also reduces CO_2 and N_2O emissions created from feed production, since less feed needs to be produced to feed a Jersey cow. However, as milk production increases, the enteric methane emissions per volume of milk decrease (Place and Mitloehner, 2021). In a 2021 study, Jersey cows had a 4.4% lesser milk GHG emissions intensity [kg CO_2-e/kg FPCM (fat and protein corrected milk)] than Holstein cows but produced 7% more enteric CH_4 (/kg FPCM) than Holstein cows. Manure management related emissions were 29% less (kg CO_2-e/kg FPCM) for Jersey cows which overcame their slightly greater enteric CH_4 emissions (Uddin et al., 2021). Uddin et al. (2021) attributed the difference in manure management emissions to differences in feed efficiency, manure volume, and manure characteristics. Consistent with the reported greater enteric methane production in Jersey cows, a study found that Jersey steers produced 46% more methane per kg DMI, on average, than Holstein steers. Both breeds produced less methane in the summer compared to any other season (Islam et al., 2021b). A study comparing Jersey and Holstein milk production resulting in 500,000 t of Cheddar cheese found that Jersey cows produced 17,234 t less manure nitrogen and 1,492 t less manure phosphorus compared to Holstein cows (Capper and Cady, 2012). This was largely due the ability to convert Jersey milk protein to cheese more efficiently than Holstein cows (Auldist et al., 2004; Bland et al., 2015). Jersey cow's lesser milk yield requires more animals to produce the same amount of cheese as Holstein cows, yet because Jersey cows have lesser DMI, the total mass of feed intake required for a kg of Jersey cheese is less than the feed required for a kg of Holstein cheese. This resulted in a lesser GHG footprint per t of cheese production (Capper and Cady, 2012). As both breeds become more efficient through genetics and management practices, nutrient excretion and GHG emissions may be further decreased.

Methods for Reducing Environmental Impacts

Dairy producers throughout the U.S. have reduced the environmental footprint and resources needed to produce dairy products over the last 100 years. A 2020 study revealed that from 1964 to 2014, California dairy producers reduced CO_2-equivalent emissions associated with producing 1 kg of energy-corrected milk by 45% (Naranjo et al., 2020). Much of this reduction was attributed to reduced enteric and feed production emissions, as the focus on investing in manure management emissions reduction did not begin until 2015 (Rocha, 2020). Research leading to more feed-efficient cows through genetic advancements has helped to reduce GHG emissions intensity of milk during those 50 years. Modern dairy practices and efficiencies, including getting more milk from an average cow, has led to today's milk having lower GHG, land, and water footprints than in previous decades. Today's farmers use 90% less land and 65% less water per unit of FPCM compared to 1944 (McCabe, 2021).

Nitrogen loss through fertilizer application is one contributor to dairy's GHG footprint. A 2002 study determined that when nitrogen fertilizer is applied, at least 1% is released as N_2O into the atmosphere (Bouwman et al., 2002). Legumes, such as soybeans, are nitrogen-fixing crops, whereas corn is a nitrogen-depleting crop. Rotating these crops allows producers to apply less fertilizer, reducing the environmental impact (Behnke et al., 2018). Therefore, crop rotation is a method being used to reduce the dairy industry's GHG footprint. Fixing nitrogen into the soil through crop rotation including legumes also leads to more cost-efficient crop production and can increase crop yields. A University of Illinois study found a 35% reduction in N_2O emissions and a 20% increase in yield when comparing corn grown with a soybean rotation to corn grown with no crop rotation (Behnke et al., 2018). When nitrogen fertilizer is applied, crops utilize less than 50% of the nitrogen, leaving the rest to be lost to the environment (Millar et al., 2010). Crop rotation is not only an effective method to optimize environmental quality through reducing nutrient runoff and GHG emissions, but also increasing efficiency and saving producers money.

Today's cows are more environmentally sustainable compared to cows managed by previous generations of dairy farmers, producing 29% more milk per cow annually in 2007 compared to 1944, with a 63% lesser GHG footprint per unit of FPCM (Capper et al., 2009). Dairy genetics research may continue to uncover which traits lead to more feed-efficient cows and animals who produce less enteric methane, a major GHG emissions source, all while continuing to increase milk production efficiencies. Research may also identify feeds effective in reducing enteric methane emissions in dairy cattle, such as red seaweed (Kinley et al., 2020). Better understanding nutrition, genetics, and biology of dairy cattle and improving these areas of the dairy industry would continue to allow the industry to reduce emissions while remaining productive.

Earthen storage lagoons, which have been a common manure storage system on dairies in northern climates, are exposed to air and release GHG when microbes break down organic matter (Rocha, 2020). Biodigesters are being utilized as a method to reduce these GHG emissions. Through biochemical processes, anaerobic digesters produce biogas, which is ~ 40% CO_2 and 60% CH_4 (Rocha, 2021). In turn, biogas can be used to fuel cars, heat homes, and generate electricity. Methane is converted to CO_2 before the biogas enters the atmosphere, avoiding the greater global warming potential of CH_4. This process reduces GHG emissions from the dairy industry while generating additional revenue for dairies and displacing use of fossil fuels (Wright, 2001).

Carbon Sequestration

Manure from dairy operations has value. Whether that is captured using digesters, conversion to bedding, or more traditionally, spread onto fields for nutrients, managing manure plays a substantial role in the sustainability of a dairy farm. Manure used on fields as fertilizer is important for building organic matter in soil, which promotes healthy crop production (Min et al., 1999). A 2003 study that compared soil quality from fields that were fertilized with dairy slurry or inorganic fertilizer. Researchers found that fields with continuous dairy slurry showed greater soil aggregate stability and carbon sequestration compared to the inorganic fertilizers (Min et al., 2003). Aggregate stability of soil is the main measurement of soil structure and is directly related to organic matter content and the soil's ability to sequester carbon while increasing productivity (Beare et al., 1994). Forages make up more than half of a typical dairy diet, but the type of forage produced has a large impact on its carbon sequestration impact, as sequestration rates vary across forages (Neal et al., 2012). An Australian study found that C4 perennial forages have the greatest rate of carbon sequestration, leading to high soil organic matter (Neal et al., 2012). Furthermore, the nitrogen cycle and carbon sequestration within the soil interact with each other and are impacted through farm management practices such as manure and fertilizer application and method, tilling practices, and irrigation (Lal and Stewart, 2018). When it comes to tillage, there are benefits and shortcomings of both conventional tilling and 'no till' practices. From a soil organic matter perspective, no till keeps organic matter and carbon intact near the surface of the soil where it can be utilized (Haddaway et al., 2017). Although no till may promote soil organic matter, it challenges producers when it comes to weed management, yield reductions, and potential long term soil health reductions through greater soil density (West and Post, 2002). Tillage practices continue to be an intense discussion within the industry to determine which methods are most sustainable in the long run. Yet research internationally has shown that carbon sequestration not only aids in reducing the GHG footprint of the dairy industry, but it also aids in crop productivity and health of soils (Barrios, 2007).

Application of LCA on Dairy Farms

Life cycle analysis is being applied on dairy farms throughout the U.S. for multiple reasons. Throughout the food chain, consumers are striving for greater transparency. A recent report indicates that 69% of consumers want to know what sustainability practices are taking place to ensure that their food is sustainably sourced (Wells, 2017). This increased need for transparency has propelled large grocery providers such as Walmart to ensure farms who supply their groceries are utilizing sustainable practices. Therefore, milk cooperatives have created sustainability divisions to ensure the milk they receive is being produced in an environmentally sustainable manner. Milk cooperatives across the country are aiding producers by performing LCA annually to ensure the dairy industry is meeting supplier and consumer standards. Farms who participate in these annual reviews not only improve their farming operations and benefit from quantifying their emissions, they also ensure their milk will be purchased through their cooperative and remain in good standing. Additionally, milk marketing organizations such as the United Dairy Industry of Michigan may encourage dairy farms to participate in annual sustainability evaluations, as these aid in the story they can promote to consumers.

Ultimately, consumers are the driving force behind the dairy industry. The industry must strive to produce a product that consumers will purchase and enjoy. Utilizing LCA on farms to quantify the emissions impact of dairy production is one way the dairy industry is striving to meet consumer needs.

SOCIAL SUSTAINABILITY

With fewer Americans growing up involved in the dairy industry, the social aspect of sustainability becomes of growing importance for the U.S. The agriculture industry must pursue positive relationships with consumers, ensuring them their food is safe for their families and the environment. Not only does social sustainability include farm outreach and education events that help consumers understand where their food comes from, but it also relates to the practices dairy farmers implement daily. Practices such as fertilizer application and manure storage have direct impacts on communities. If fertilizer is not managed and applied appropriately, it could lead to nitrogen and phosphorus runoff ending up in rivers and lakes (Altamira-Algarra et al., 2022). These excess nutrients will not only negatively affect community recreation such as fishing, swimming, and tourism, but also have the potential to impact public health through drinking water.

The dairy industry also contributes to social sustainability through the creation of jobs and providing consistent access to safe dairy products. The dairy industry provides 3.3 million jobs within the U.S (Dykes, 2021), including on-farm, processing, consulting, marketing, education, and other roles, all providing the community with opportunities to make a living and provide their families with a comfortable life. In addition, through the generation of biogas in manure digesters, the dairy industry is producing a renewable energy source to generate electricity, heat homes, and fuel cars for their communities (Wright, 2001).

Social sustainability emphasizes improving the quality of life for people including farmers, employees, neighbors, and consumers (SARE, 2021). With so many individuals building a career within the dairy industry, it is important that owners and managers keep in mind Maslow's hierarchy of needs and human rights, to ensure that employees' quality of life in the workplace adds value to their lives (Maslow, 1943). Larger farms have allowed for greater work-life flexibility on many farms in recent years due to larger workforces and greater specialization compared to smaller farms. Work-life balance has been a major push throughout the professional world as mental health has become a greater focus, and this applies to the agricultural industry (Janker et al., 2019). Social sustainability ensures that employees have adequate resources to be successful and to maintain a balanced life.

The concept of social licensing plays a critical role in the social sustainability of a dairy operation due to the trust built within a community. Social licensing refers to the relationship of the community with a business or industry. Although not regulatory, the community informally acknowledges that the businesses has a "social licensing to operate" under the expectation that the business is beneficial and accepted (Moffat et al., 2015). Within the dairy industry, for a farm to secure social licensing, they must gain legitimacy, credibility, and trust from stakeholders and community members (Rooney et al., 2014). These 3 characteristics are not granted, yet are earned through decision making, communication, and practicing accepted management styles. Society consistently changes expectations of businesses and industries and therefore they must adapt to maintain their social licensing within a community and cultivate flourishing relationships (von Keyserlingk et al., 2013).

Social sustainability is more difficult to measure than economic sustainability. Employee turnover rate, community interaction, and product salability all could be indicators of whether industries are succeeding in investing in people and improving society's quality of life. Although there is little research on social sustainability specifically for the dairy industry, connecting psychology to the people impacted by dairy can help us to build a more sustainable industry (Janker et al., 2019). Ultimately, social sustainability is about building flourishing relationships that allow people to succeed while operating in a manner that meets expectations of the community and ensures employees find value in being involved in the dairy industry.

CONCLUSIONS

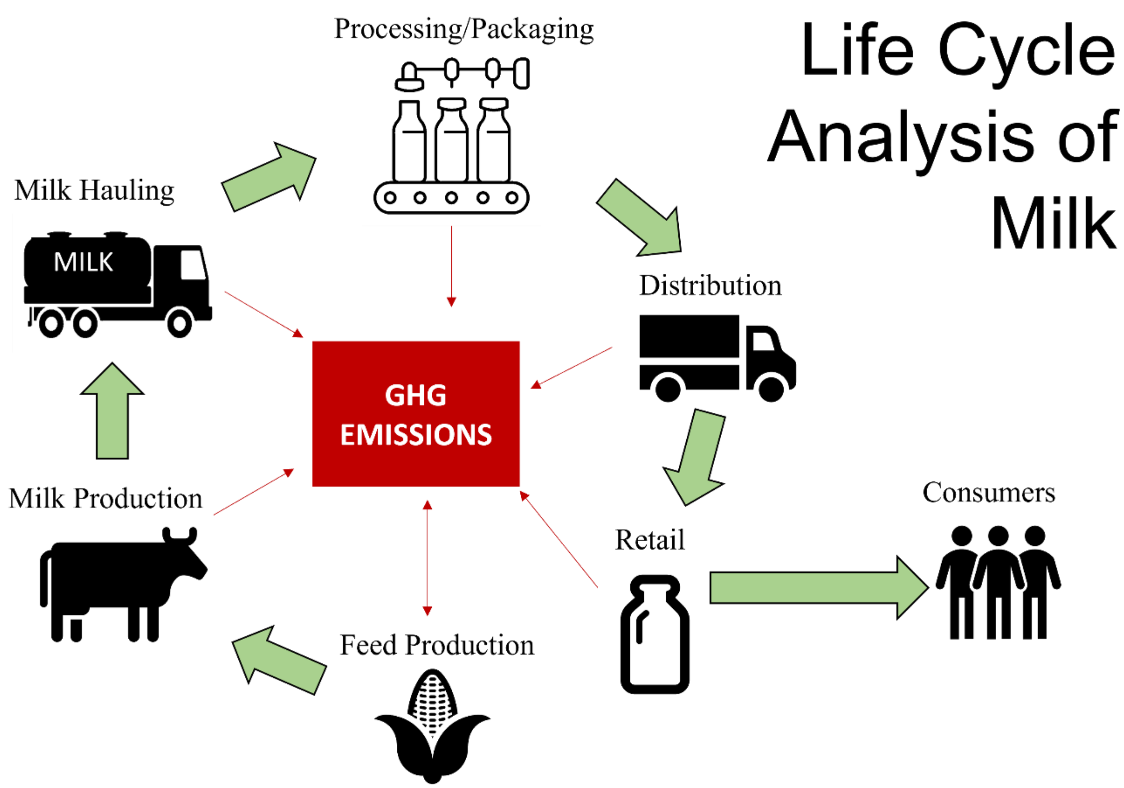
Sustainability drives the U.S. dairy industry, ensuring economic profit, environmental conservation, and social wellbeing. Producer decisions must be made based on all three of the sustainability pillars to ensure longevity of an operation. Although the dairy industry, like all industries, has areas of opportunity, research advancements in many domains should continue to elevate the industry to become more efficient and sustainable.

To ensure economic sustainability, dairy farms will continue to take advantage of economies of scale opportunities while making decisions that set their operations to have a positive return on investments. Increasing Jersey productivity through genetic gains or more targeted management strategies would aid in reducing the productivity gap with Holsteins and change profitability outlooks for farms utilizing Jerseys.

The dairy industry will likely continue to improve environmental sustainability through investments in technology to reduce GHG emissions from manure storage and to better control nutrients applied to cropland. Further research to reduce enteric methane production could also drive a reduction in GHG footprints while potentially making cows more efficient and productive. Lastly, as societal expectations continue to change for businesses and farms, the dairy industry must strive for social trust to build relationships within communities, leading to a socially sustainable future. Admittedly, social decisions cannot be isolated from those involving economics and the environment.

FIGURES

Figure 2.1 *Life cycle analysis (LCA) of milk.* The graphic represents all the supply chain activities that would contribute to the GHG footprint of milk (Baldini et al., 2018).



CHAPTER 3:

ANALYSIS OF JERSEY VS. HOLSTEIN BREED PROFITABILITY ON NORTH CENTRAL U.S. DAIRIES

ABSTRACT

With over 9 million cows in the United States (U.S.), Holstein is the dominant breed in the U.S. dairy population; however, the U.S. Jersey population is growing. The objective of this study was to determine the profitability of Holstein and Jersey cows managed similarly on the same farms. Holstein and Jersey economic performance was compared within 3 north central U.S. dairies, each milking more than 500 cows. The herds' average distribution was 21% Jersey (27 ± 0.67 kg/d milk, 4.92% ± 0.24 fat, 3.72% ± 0.03 protein) and 79% Holstein (37 ± 1.98 kg/d milk, 3.85% ± 0.21 fat, 3.17% ± 0.17 protein). A comparative budget approach was used to assess economic factors that differed between the breeds on a per-cow annual basis, based on the assumption that an existing farm would be constrained by stalls and parlor to an equal number of Jersey and Holstein cows. Data from 2020 were gathered from farm management software, on-farm evaluations, and producer interviews. Sensitivity analysis was performed to determine which conditions would lead to different conclusions. Factors considered in the analysis included milk and component production, milk bonuses, ration prices, and dry matter intake (DMI). In a 2021 price scenario, Holstein cows ranged from $345 to $601 more profitable than Jersey cows on a per-cow annual basis. Although Jersey cows had an advantage in component concentration, Holstein cows produced 13 ± 4.7% more fat and 22 ± 6.6% more protein annually due to greater milk yield. This accounted for most of the profitability advantage for Holsteins; 78% of the revenue advantage for Holstein cows came from increased component production. Few health and reproductive differences were found. The sensitivity analysis revealed, if all other factors

remained the same, Jersey profitability would equal that of Holstein if any of the following changes occurred (assuming no change in Holstein metrics): mean Jersey milk production increased to 31 kg/d; milk price adjustments decreased from -$0.008 to -$0.11 per kg fluid milk; lactating cow ration price increased from $0.27 per kg DM to $0.53 per kg DM; or Jersey DMI decreased from 20 kg/d to 15 kg/d. The study did not consider crossbred profitability nor new infrastructure investments. In conclusion, Holstein cows were more profitable than Jersey cows on these 3 north central U.S. dairies.

Key words: economics, breed, case study

INTRODUCTION

Dairy farms continue to strive for ways to improve profitability and thereby sustain their business. The question of whether Jersey or Holstein cows are more profitable has remained relevant, particularly as producers face increasing feed input costs and volatile milk prices (Endres, 2018). According to the Council on Dairy Cattle Breeding, in 2000, Holstein cows made up 92.3% of the U.S. dairy herd and Jersey cows made up only 3.8%. In 2020, Holstein made up 79.9% and Jersey made up 7.9% of the U.S. dairy herd, with 11.8% constituted by crossbred animals (USDA, 2000b, 2020). Although Holstein clearly remains the dominant dairy breed in the U.S., the Jersey breed has a growing population, particularly in the Southwest region (Garcia-Peniche et al., 2005).

In evaluating the economics of breed selection, the milk pricing system can influence the outcome (Schmidt and Pritchard, 1988). Most U.S dairy producers are paid for component yields rather than fluid milk; therefore, economic analyses need to focus on yields of fat, protein, and solids nonfat and protein (SNFP) rather than fluid yield or component concentrations alone. On a fluid milk basis, Holstein cows were reported to produce 23% more milk than Jersey cows

(White et al., 2002). Jersey cows produce milk with greater fat and protein concentrations, but these do not fully overcome the lesser milk yield, resulting in lesser component yields for Jersey cows (Palladino et al., 2010). On the cost side, Jersey cows consume less feed than Holstein cows (Beecher et al., 2014), and reproductive differences may also exist. In an analysis of over 5 million cows, Jersey cows had 1% to 11% greater conception rates than Holstein cows (Norman et al., 2009). These lesser costs could allow Jersey cows to match Holstein profitability despite lesser milk component yields.

Previous research comparing Jersey and Holstein cows often contrasted the breeds using different farms with different management and environments (Bailey et al., 2005; Norman et al., 2009; Xue et al., 2011; Kristensen et al., 2015; Lim et al., 2020). Research also has not accounted for bonuses and discounts that are paid on a fluid milk basis (Bailey et al., 2005b) or for potential differences in health outcomes. The objectives of this study were to identify whether Jersey or Holstein cows are more profitable in existing North Central region dairy facilities and to determine which conditions might influence this conclusion.

MATERIALS AND METHODS

Commercial dairy farms were recruited for participation using the following criteria: measurement of individual cow milk yields and component concentrations at least 8 times per year; at least 5% of the farm's herd and one pen representing each breed; both breeds located on the same farm but generally housed in separate pens; and both breeds comprised of mature populations with a stable parity distribution. Three North Central region dairies were identified for the study. All 3 farms provide free stall housing with sand bedding and concrete floors, and milk 2 or 3 times per day. Animals on the same farm received the same management and environment unless otherwise noted. Table 1 provides an overview of the characteristics of the 3 farms. On average, the study herds were comprised of 21% Jersey and 79% Holstein cows. All 3 farms added Jersey cows to their herds over the past decade for a variety of reasons, including adding revenue from dairy sales and increasing milk components shipped within a limited volume quota.

Data were collected through farm visits, herd management software, and conversations with the producer to understand the producer's goals. Understanding the goals of each operation created awareness of unique farm circumstances that influenced management decisions and data interpretation. For example, one farm sold a substantial number of lactating cows to other herds and these sales needed to be accounted for to calculate an unbiased herd turnover rate. We utilized 2020 data for milk production, reproduction, health, and other cow performance records, as that was the last full year of records when the study began. We identified some key data gaps on each farm, for which values were estimated during the analysis. Farms 1 and 3 did not have accurate DMI measures for either breed. Farms 2 and 3 did not have calf health records and farm 3 housed Holstein cows in a newer, better-ventilated barn compared to Jersey cows.

From PCDart and DairyComp305 herd management software, we determined the average annual milk, fat, and protein yields for each parity (1, 2, and 3+) by breed. Lactose content of 4.72% was used for Jersey cows and 4.85% for Holstein cows to calculate the SNFP sales (Lim et al., 2020). For farms 1 and 3, we utilized the formula of the National Academies of Sciences, Engineering, and Medicine (NASEM, 2021) to estimate DMI for each breed, whereas recorded DMI data were used for farm 2. Several factors impacted the DMI model; we utilized a parity factor of 0.67 to account for the age distribution in both herds, an average body condition score of 3, and estimated mature cow weights of 544 and 681 kg for Jersey and Holstein cows, respectively. Using the statistics from Table 3.1 to populate the equations, for farm 1 we computed a predicted DMI for Jersey cows of 21.8 kg/d and 26.3 kg/d for Holstein cows. For farm 3, the predicted DMI was 20.0 kg/d for Jersey cows and 25.9 kg/d for Holstein cows. The same formula was used to estimate dry cow DMI with the milk energy at 0 and BCS at 3.75. With these parameters, for farm 1, Jersey dry cows were estimated to consume 13.7 kg DM /d and Holstein dry cows 16.7 kg DM /d. The NASEM (2021) equation predicted farm 3 Jersey dry cows to consume 12.7 kg DM /d and Holstein dry cows 16.7 kg DM /d.

We also compared reproductive statistics and costs between breeds. On each farm, if Jersey and Holstein conception rates differed by less than 4% and services per conception differed by less than 0.5 services between breeds, reproductive efficiency was considered not sufficiently different to be included in the analysis. This decision was based in part on the uncertainty around these estimates and in part on the relative impact of small magnitude differences on overall profitability. Farm 3 was the only dairy determined to have different reproductive performance between the breeds. Farm 3 also used a heat detection (activity) system on Holstein cows but not Jersey cows. Reproduction was accounted for by adding the yearly per-cow cost for the activity monitoring system to the cost of a conception per Holstein cow. The cost per conception was calculated by multiplying services per conception by cost per service for each breed. Although reproduction costs were not included in the comparative budgets of farms 1 or 2, minor reproductive differences influenced calving interval, milk yield (affected by average days in milk), and age at first calving, which were factors in comparative budget calculations. Turnover rate is impacted by many factors including reproduction, and is not directly reflective of reproductive performance.

Cow and calf health were assessed separately. All 3 farms recorded milk fever, retained placenta, metritis, respiratory, ketosis, displaced abomasum, and mastitis cases, which were used to calculate total annual disease costs for each breed. Although case definitions were not uniform across dairies, uniform management within herds provides confidence for the disease incidence comparisons across breeds within herd. All health data were calculated on an annual risk basis (annual cases divided by steady-state number of cows, by breed) and multiplied by the disease's respective treatment cost (APHIS USDA, 2013; Liang et al., 2017). We had limited information for calf health and were only able to include calf health records for farm 1, including pneumonia and scours cases. The risk of pneumonia or scours was calculated by breed (annual cases divided by the total number of calves raised in that year). The costs associated with each disease were then used to calculate the total cost on a risk of a case for pneumonia and scours for Jersey and Holstein calves (Schneider et al., 2009; Mohd Nor et al., 2012). On this farm, 70 pneumonia and 44 scours cases were recorded for calves with no breed designation. Therefore, we utilized the breed proportion of the assigned cases of pneumonia and scours to distribute the unassigned events to breeds, providing a more representative total disease cost for the calves. Due to the lack of calf mortality records, we were not able to factor mortality into the analysis, but the producer indicated mortality rates were similar between breeds. Without calf health data on farms 2 and 3, we could not assess differences between breeds in calf loss or health costs for these farms.

Bringing all economic factors together, a comparative budget was constructed on a per-cow annual basis for each dairy. The revenues included protein, fat, and SNFP sales, cull cow sales, value of calves born, and milk bonuses. Expenses included milk transport, milk discounts, feed, manure handling, heifer raising, cow health, calf health, and reproduction costs. Labor was only included in reproduction and disease treatment costs, as other labor costs were assumed to be the same per cow across breeds. Bonuses for low SCC and other milk bonuses and charges were applied on a fluid milk basis whereas component sales are applied on a solids basis (per practices of milk cooperatives). Heifer raising was factored into the analysis on a risk of leaving the herd basis; for example, if a breed within a herd had a 30% turnover rate, cows in that breed were charged 30% of the cost of raising a heifer from birth to first calving. Cow and calf health costs were valued based on risk of cases annually. Costs or benefits that were not apparently different between the two breeds were not included within the comparative budget, as already mentioned for reproduction.

Due to the impact of the Covid-19 pandemic on the dairy markets in the U.S. in 2020, we utilized average 2021 prices for milk components, milk bonuses, feedstuffs, and animals, as it was a more representative year for dairy markets. We used average prices for the year 2021 from the Mideast Milk Marketing Order of $4.168/kg for fat, $6.091/kg for protein, and $0.852/kg for other solids to calculate milk value (USDA, 2022). Two different milk cooperatives were represented within the study and fluid milk bonuses and charges were determined from producer milk checks. A standard somatic cell count (SCC) bonus structure was used across all herds, with a bonus (all per kg fluid milk) of $0.004 for SCC from 180,000 to 200,000; $0.009 for SCC from 170,000 to 180,000; $0.013 for SCC from 160,000 to 170,000; $0.018 for SCC for 150,000 to 160,000; and $0.022 for SCC under 150,000. For the producer price differential (PPD), we used -$0.0013 per kg of fluid milk, which was the 2021 average from the Mideast Milk Marketing Order (USDA, 2021). A producer transport cost of $0.014 per kg was used for all farms. Bonuses, charges, and discounts applied on a fluid milk basis were collectively referred to as milk price adjustments. We valued an AI service at $39.60, which included farm costs of semen, labor, and synchronization program hormones, which came from the producers.

Farm-level feed ingredient costs were used in feed cost calculations. A standard value for calves and cull cows were used across farms based on market prices; Jersey and Holstein cull cows were valued at $450 and $750, respectively, whereas Jersey heifer and bull calves were valued at $100 and $25, respectively, and Holstein heifer and bull calves were valued at $150 and $125, respectively. Disease costs accounted for veterinary, treatment, discarded milk, and labor costs, as it was assumed that decreased milk production, culling, reproduction, and death were already accounted for within our comparative budget. Regardless of breed, the cost per case of milk fever was $97.84, retained placenta was $96.63, metritis was $140.92, respiratory disease was $28.60, ketosis was $64.20, displaced abomasum was $212.72, and mastitis was $154.71 (APHIS USDA, 2013; Liang et al., 2017). Disease costs per case were then multiplied by the risk of a case for each condition to determine annualized disease costs per cow for each breed. Calf scours and pneumonia treatment and labor were priced at $11.00 and $38.00 per case, respectively (Schneider et al., 2009; Mohd Nor et al., 2012).

RESULTS AND DISCUSSION

Results from comparative budgets revealed that Holstein cows are more profitable than Jersey cows on these 3 North Central U.S. dairies (Table 3.2). Within the comparative budget, component sales accounted for between $708 and $1,029 (or 72 to 86%) of the total revenue difference between the breeds, with Holstein cows producing an average of 367 ± 60 (SD) kg more milk solids than Jersey cows. After accounting for animal sales and fluid milk bonuses, Holstein cows generated an estimated $940 to $1,424 more total revenue than Jersey cows.

In total, Jersey cows had annual expenses of $517 to $740 less than Holstein cows. All expense categories showed an advantage for the Jersey breed. We hypothesized that the Jersey breed would have an advantage in heifer raising costs due to their smaller size and lesser feed requirements (Beecher et al., 2014). We indeed found that the total variable costs (excluding infrastructure) to raise a Jersey heifer ranged from $1,275 to $1,379, whereas Holstein heifer rearing costs ranged from $1,521 to $1,681. On farm 1, individual calf milk consumption data were available due to use of robotic calf feeders. We did not have starter intake data but utilized research from Terré et al. (2007) to estimate Holstein calf starter intake at 19.48 kg over the preweaning period. Milk intake data showed that Jersey calves consumed 80% of the milk that Holstein calves consumed, and this proportion was applied to predict starter intake for the Jersey calves (15.58 kg). On all 3 dairies, Jersey heifers were older at first calving than the Holstein heifers, diminishing the cost advantages of raising Jersey heifers. This could be partially attributed to producers noting more Jersey calf health events potentially disrupting growth. Furthermore, heifer raising costs were factored into the comparative budget based on the number of heifers needed to replace cows leaving the herd. Farm 1 had an annual turnover rate of 33.3% for Jersey cows and 27.9% for Holstein cows, resulting in annual costs of raising replacement heifers for a Jersey cow of $459 compared to $462 for a Holstein cow, giving just a $3 advantage to Jersey cows on this farm. Across farms, annual Jersey replacement costs ranged from -$203 to -$3 relative to Holstein.

The total profitability difference revealed that the reduced expenses for Jersey cows did not compensate for the revenue lost compared to Holstein cows. The net change in profitability for switching from Holstein to Jersey cows on these farms ranged from -$345 to -$601 per cow annually, a substantial net loss. To put this in context, a farm financial database including 414 dairies primarily in the North Central U.S. reported a median net profit of $18.85/cow for 2021 (FINBIN, 2023), meaning that the loss in profitability for a Jersey vs. Holstein cow would dwarf the small profit margin for a typical farm that year.

Prior to the study, we anticipated an advantage for Jersey cows in fluid milk bonuses and charges. On farm 1, Jersey cows had more consistent and lower SCC throughout the year but had a larger advantage in the summer. With this significant SCC gap in summer – consistent with reported heat stress resilience of the Jersey breed (Smith et al., 2013) – Jersey cows were able to capture an additional \$0.004/kg bonus in June and August and an additional \$0.013/kg in July compared to Holstein cows. However, because SCC bonuses are paid on a fluid milk basis, the net SCC bonus revenue was still greater for Holstein than Jersey cows in these months (due to greater fluid yield). This same seasonal SCC pattern was observed on farm 2 but not on farm 3, where lactating Jersey cows were housed in an older, less ventilated barn.

Sensitivity analysis was used to investigate factors that could potentially alter profitability conclusions. Jersey daily milk production, milk bonuses and discounts, and Jersey DMI were varied for this analysis, with all other factors held constant (Figure 3.1). The sensitivity analysis revealed that Jersey profitability would equal that of Holstein (assuming no changes in Holsteins) if any of the following changes occurred: Jersey milk production increased to between 29.5 kg/d and 32.6 kg/d (79-87% of Holstein production); milk price adjustments decreased from -\$0.008/kg fluid milk to between -\$0.10 and -\$0.12 per kg fluid milk; lactating cow TMR price increased from \$0.23 to \$0.29/kg DM to between \$0.40 and \$0.59/kg DM; Jersey DMI decreased from between 19 and 21 kg/d to between 13 and 17 kg/d; or the DMI NASEM (2021) formula overpredicted Jersey DMI by 20 to 34%. Although additional DMI would be required for increased Jersey milk production, this is accounted for in the productivity sensitivity analysis. The sensitivity analysis strengthened the conclusion that Holstein cows are more profitable than Jersey cows on these 3 North Central U.S. dairy farms; extreme changes would have to take place for Jersey cows to be more profitable on these farms.

CONCLUSIONS

The key takeaways are that greater fat and protein yields – despite lesser concentrations – put Holstein cows at a significant profitability advantage over Jersey cows. Because milk bonuses on these farms were greater than the discounts and charges applied on a fluid basis, the greater volume produced by Holstein cows added to their advantage. Although the differential between Jersey and Holstein cows varies with market conditions (Figure 3.1), greater Jersey productivity was the only factor considered in the sensitivity analysis that could plausibly change the outcome with current market structures.

There are some caveats in how these findings should be interpreted. First, these conclusions apply to a North Central U.S. climate and pricing environment. We also based the analysis on use of existing facilities; building new facilities may change our conclusions, as a given infrastructure investment could house more Jersey cows. The conclusions may be influenced by unique revenue streams on some farms (e.g. breeding animal sales). Lastly, we did not have data available to assess crossbred performance within herds.

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TABLES AND FIGURES

Table 3.1 *Characteristics of the 3 dairy farms used to evaluate profitability of Holstein and Jersey cows.*

	Farm 1		Farm 2		Farm 3	
Item[1]	Holstein	Jersey	Holstein	Jersey	Holstein	Jersey
Number of cows	867	448	3,035	189	651	208
Percent of herd (%)	66	34	94	6	76	24
Fat (%)	3.75	4.90	4.10	4.70	3.71	5.17
Protein (%)	3.12	3.74	3.36	3.69	3.03	3.73
Fluid milk yield (kg/yr)	13,489	9,782	11,684	8,777	13,232	8,376
Fat yield (kg/yr)	514	473	487	413	491	433
Protein yield (kg/yr)	424	367	399	324	401	312
SNFP yield (kg/yr)	757	529	666	475	742	453
Total component yield (kg/yr)	1,695	1,370	1,551	1,211	1,635	1,199
Turnover rate (%)	27.9	33.4	42.4	40.0	38.7	37.5
Mean DIM (d)	157	177	200	190	168	147
Lactating DMI (kg/d)	26.3	21.8	25.7	19.7	25.9	20.0
Calving interval (months)	13.6	13.5	13.0	12.9	13.4	12.8
21-day pregnancy rate (%)	29.2	26.7	22.9	23.0	31.6	43.0
Pregnancies per AI (%)	34.1	30.6	42.3	40.0	28.1	35.7

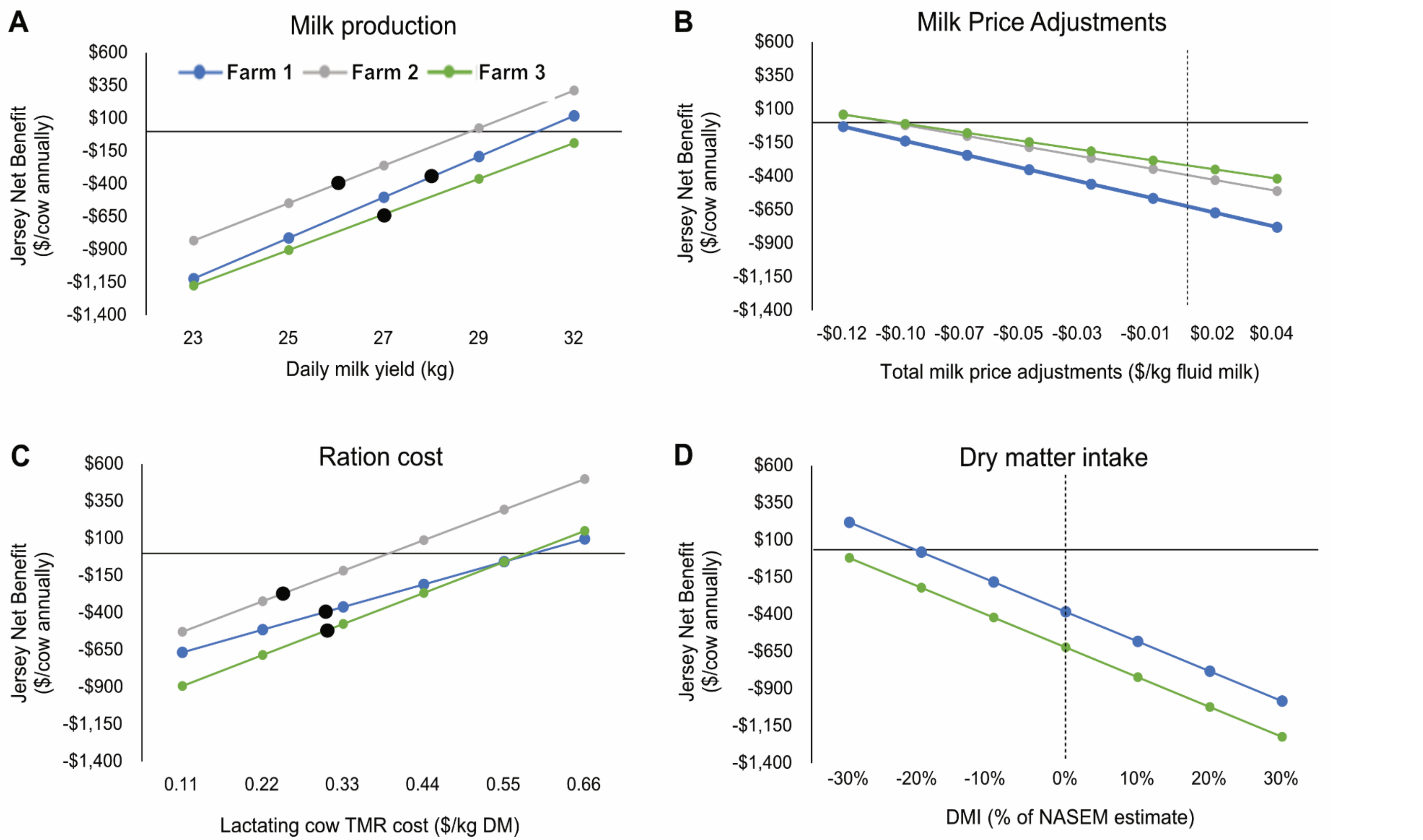
[1] SNFP = solids not fat and protein; DIM = days in milk; DMI = dry matter intake; AI = artificial insemination

Table 3.2 *Summary of the three farm comparative budgets with averages and standard deviations for the study.* The comparative budget was determined on a per cow annual basis. Changes were calculated through subtracting Holstein figures from Jersey figures.

	Revenue changes ($)						Expense changes ($)				
Revenue Factors	Farm 1	Farm 2	Farm 3	Mean	SD	Expense Factors	Farm 1	Farm 2	Farm 3	Mean	SD
Protein sales	(345)	(458)	(542)	(448)	99	Milk transport	(51)	(69)	(108)	(76)	29
Fat sales	(170)	(310)	(241)	(240)	70	Feed costs	(415)	(431)	(478)	(441)	33
SNFP sales[1]	(194)	(163)	(247)	(201)	42	Manure handling	(40)	(34)	(54)	(43)	10
Cull cow sales	(60)	(138)	(122)	(106)	41	Heifer raising	3	(203)	(100)	(102)	100
Calf value	(66)	(66)	(70)	(67)	3	Cow health	(10)	(4)	(20)	(11)	8
SCC bonus	(57)	92	(140)	(35)	117	Calf health	2	-	-	1	1
Milk bonuses	(49)	(40)	(64)	(51)	12	Reproduction	-	-	(64)	(21)	37
Total revenue change	(940)	(1,084)	(1,424)	(1,149)	249	Total expense change	(517)	(740)	(823)	(693)	158
Net change in profit (switching from Holstein to Jersey)							(422)	(345)	(601)	(456)	131

[1] SNFP = solids not fat and protein

Figure 3.1 *Sensitivity of profitability results to changes in key input variables.* Each panel shows the net profitability advantage of replacing a Holstein cow with a Jersey cow in response to varying A) Jersey daily milk production, B) total milk price adjustments, C) lactating cow TMR price, or D) Jersey DMI relative to NASEM (2021) DMI model estimates for the 2 farms without DMI data. For each sensitivity analysis, all other factors were held constant, with the exception that DMI was adjusted to align with increasing milk production for panel A. The black dots and dashed lines represent the scenarios evaluated in the study.



CHAPTER 4:

ASSESSMENT OF GREENHOUSE GAS FOOTPRINTS ON EXEMPLARY SMALL AND MID-SIZED U.S. DAIRY FARMS

ABSTRACT

Greenhouse gas (GHG) emissions from the dairy industry are receiving increased scrutiny as climate change concerns grow. Our objective was to estimate GHG footprints for 4 dairy farms (150 to 850 lactating cows; 89 to 353 ha) representing different regions of the U.S. using the Farm Environmental Stewardship (ES) and USDA Comet life cycle analysis models. Herds averaged 10,782 ± 2,037 kg/yr fat- and protein-corrected milk (FPCM; 4.0% fat, 3.3% protein) and 24 ± 2.8 kg/d dry matter intake during lactation. Data from 2021 were gathered from farm management software, producer interviews, and on-farm evaluations. Soil organic matter data for ≥ 7 yr were available on 3 of the farms. Emissions intensity was quantified as net CO_2 equivalents (CO_2e) emitted per unit of FPCM sold. Model output was compared to assess alignment across tools. Comet estimated greater GHG emissions compared to Farm ES on all farms. Mean GHG emissions for all farms were 0.97 ± 0.16 kg CO_2e/kg FPCM and 2.13 ± 5.05 kg CO_2e/kg FPCM in Farm ES and Comet, respectively. The Northeast dairy had the greatest FPCM/cow, yet the Southeast dairy had the least emissions intensity at 0.55 kg CO_2e/kg FPCM in Comet; in Farm ES, the Northwest dairy had the least at 0.73 kg CO_2e/kg FPCM. In both models, methane accounted for the largest share of GHG emissions on all farms. Comet estimated that manure accounted for 69 ± 29% of farms' total GHG emissions, whereas Farm ES attributed only 28 ± 9% to manure. Two farms that utilized manure separation had an average footprint 0.20 kg CO_2e/kg FPCM less than farms that did not (Farm ES). Average annual soil carbon sequestration rates ranged from -0.82 to 3.52 Mg carbon/ha. Farms which produced more

FPCM/cow had lesser GHG emissions per unit of milk. Manure management and cropping strategies also impacted emissions estimates. In conclusion, productivity, manure management, and cropping systems are important determinants of the GHG emissions intensity of milk produced on a given farm. Additionally, Comet emission estimates are highly variable, especially from manure, and misalign with published dairy farm GHG benchmarks.

Key words: emissions, life cycle analysis, sustainability

INTRODUCTION

Greenhouse gas (GHG) emissions are produced by nearly every industry. About 8 to 11% of the total GHG emitted globally are attributed to animal agriculture, while only 1.9% of U.S. GHG emissions are charged to the dairy industry (O'Mara, 2011; EPA, 2022a). Enteric methane emissions, methane and nitrous oxide emissions from manure management, and carbon dioxide and nitrous oxide emissions from feed crop production are the 3 primary sources of emissions on U.S. dairy farms (EPA, 2022a).

Strategies for decreasing enteric methane production are under intense research. Studies have estimated that 33 to 50% of a dairy farm's GHG emissions come from enteric methane (Mc Geough et al., 2012; EPA, 2022a). Although enteric methane production will likely never be eliminated, the dairy industry has opportunities to alter feeding methods to improve feed efficiency and reduce enteric emissions. To reduce this source of methane on dairy farms, scientists have investigated potential genetic improvements and feed additive options. Dry matter intake (DMI) is directly related to a dairy cow's methane emissions and is a heritable trait (Pickering et al., 2015). Yet reducing DMI has a negative impact on milk production, making this an economically unsustainable option for dairy producers. Genomics may provide an opportunity to reduce DMI and methane emissions while maintaining or improving milk production. Producers currently can select to improve feed efficiency in dairy cattle through the "feed saved" trait (Lu et al., 2018). Furthermore, plant extracts have been investigated as dietary supplements for dairy cattle to reduce enteric methane emissions while maintaining milk yield (Kolling et al., 2018). *Asparagopsis armata*, a type of seaweed, reduced enteric methane emissions by 26% and 67% when fed at 0.5 and 1% of the ration, respectively (Roque et al., 2019). However, the 1% dose decreased milk production by 11.6% due to significant reductions in DMI, although the 0.5% dose had no apparent impact on productivity (Roque et al., 2019). The compound 3-nitrooxypropanol (3-NOP) has also been researched to target methane production enzymes. 3-NOP inhibits the enzyme methyl-coenzyme M reductase (MCR), which is the key enzyme for methane production among many of the most common archaea in the rumen (Duin et al., 2016; Lu et al., 2018). Although there are many feed additives being researched, the challenge in the industry remains determining ways to reduce enteric methane while maintaining or improving milk and component production with these feed additives.

A significant amount of methane and nitrous oxide emissions on dairy farms come from manure, whereas more of the carbon dioxide and nitrous oxide are emitted through the production of feeds (EPA, 2022a). Estimated crop nitrous oxide emissions represent 26% of the total GHG emissions whereas manure methane and manure nitrous oxide represent 8% and 7%, respectively (Mc Geough et al., 2012). Manure that is stored in anaerobic conditions has been found to have the greatest rate of methane emissions compared to other manure storage methods (De and Il Ver, 2014).

Cropping emissions arise from carbon dioxide produced from equipment usage and nitrous oxide emissions from fertilizer application. Emphasis has been placed on the use of cover crops throughout the dairy industry to reduce erosion while improving soil health and sequestering carbon (Fronning et al., 2008). Manure sampling to determine soil nutrient concentrations allows producers to apply nutrients more precisely to crops and reduces the chances of over-applying nutrients. By focusing efforts on the cows, manure management, and feed production as the primary emission sources that contribute to the dairy GHG footprint, the industry may reduce the environmental impact from milk production.

Much of the emissions data available for the dairy industry targeting “net zero” farms are products of research focused on large dairy operations utilizing anaerobic digesters. Previous investigations have estimated GHG emissions from both large and small dairies, yet limited research has simultaneously evaluated GHG emissions and soil carbon sequestration (Belflower et al., 2012; Geough et al., 2012; Stuart et al., 2013; Thoma et al., 2013b; Arndt et al., 2015; Bacenetti et al., 2016; Lorenz et al., 2019; Liebe et al., 2020; Rotz et al., 2020, 2021). Careful assessment of GHG emissions from selected dairy operations can help to determine achievable GHG targets and highlight practices that are feasible for small farms to minimize GHG emissions. Therefore, the primary objective of this work was to quantify GHG footprints for 4 commercial dairy farms recognized as sustainability leaders by dairy cooperatives throughout the U.S. using the Farm ES and USDA Comet LCA models. Additionally, longitudinal soil organic matter data were used to determine how soil carbon sequestration may influence the GHG footprint estimates for farms.

MATERIALS AND METHODS

Four small to mid-sized commercial dairy farms were selected in 4 regions of the U.S. Farms were selected by regional dairy cooperatives; selected farms were viewed as excellent environmental stewards by their cooperative and regional dairy checkoff partners. Selection was based on use of environmental sustainability practices and herd size of < 1,000 lactating cows.

Table 4.1 describes the farms and highlights key management factors. The herd sizes ranged from 156 to 835 lactating cows. Milking systems varied across farms and included traditional parlor operations and robotic milking systems. Pasture and free stall dairies were represented in this study with various manure handling and storage systems, including under-barn pit storage, lagoons, and gravity flow manure separation systems. Farm visits were conducted in Michigan (MI), Georgia (GA), Pennsylvania (PA), and Washington (WA) between July and October 2022. Each visit consisted of a day on the farm gathering data and understanding the management process for the dairy operation. The goal was to understand the operation comprehensively to better determine how to incorporate practices into the models, particularly cropping practices, crop rotations, manure handling, and manure and fertilizer applications on all fields.

To reduce the potential accounting variation between farms, data were collected from consistent sources for all farms to the extent possible. All data were from the 2021 calendar year. Annual milk yield, herd inventory, and reproduction data were taken from herd management software. Not all farms were enrolled in DHIA testing, and therefore milk processor data was used to gather daily milk component data. All farms referred to 2021 monthly invoices to estimate energy use. Fuel used for livestock and manure management was estimated but fuel used for cropping was excluded to avoid double accounting within Farm ES.

Cropping information was acquired from the farm's comprehensive nutrient management plan (CNMP) and discussed with the producer. Farm ES did not require crop management information as it utilizes regional mean emissions estimates for each crop (USDA, 2008a; b). Following each farm visit, data were compiled and inputted into the Farm ES (Asselin-Balençon et al., 2013) and Comet (Paustian et al., 2018) modeling programs. Outputs from these programs were transferred into a spreadsheet built to compare emissions across farms and software programs.

The current owners of the WA dairy bought the dairy in 2012. Therefore, we could not verify the cropping and tillage practices taking place on the farm from 2000-2011, which were required Comet inputs. Based on the knowledge of the current owners, we assumed that the previous owners had similar cropping practices and these assumptions were used for Comet inputs.

Comet estimates soil carbon sequestration, but Farm ES does not. Therefore, longitudinal soil organic matter data were gathered from MI, PA, and WA to analyze soil carbon data. Soil data ranged from 2010 to 2023. All samples were taken by the farms or agronomic service providers, sampling the top 30.5 cm of soil. Chemical analysis of soil organic matter (OM) was carried out according to AOAC Official Method 942.05 for each sample (Thiex et al., 2012). The annual rate of soil OM change was determined by least-squares regression over the time range available for an individual farm ($\geq$ 7 years). At least 90 data points were available over time for each farm to determine average annual rate of soil OM change. Change in soil organic carbon (SOC) was calculated by multiplying the change in soil OM by 58% (Pribyl, 2010). The USDA soil survey website was utilized to estimate soil bulk density (USDA, 2023), which was then used with the longitudinal soil OM data to determine mean annual carbon sequestration per ha according to *Equation 1*.

Equation 1. Annual carbon sequestration per ha

$$= 3{,}048\text{m}^3 * \text{bulk density } (\text{Mg/m}^3) * \Delta \text{ SOC/year}$$

The annual carbon sequestration per ha was further converted into metric T CO_2 equivalent units by dividing by 0.27 (Brander, 2012). The CO_2 equivalent units were used when identifying the impact of carbon sequestration on GHG emission intensities.

RESULTS AND DISCUSSION

Greenhouse gas footprint and emissions intensity estimates for farms were compared to assess impacts of management practices. Additionally, results from Farm ES were compared with USDA Comet outputs to evaluate model agreement.

Models Used: Farm ES and Comet

To compare across programs, all output values were converted to equivalent emissions intensity units, kg CO2e/kg FPCM. Table 4.2 compares the 2 programs across the different components of a farm's GHG footprint. Carbon sequestration estimates from Comet were excluded because Farm ES does not incorporate this factor. Overall, Comet generated far greater GHG footprint estimates than Farm ES for 2 of the dairies, primarily due to vastly greater estimated emissions from on-site manure for the MI and WA dairies. On the other hand, both programs had similar total emissions estimates for the GA and PA dairies, with Comet's footprint on average 0.37 kg CO_2e/kg FPCM lesser for these dairies, which could at least in part be attributed to Comet not estimating emissions for energy used beyond cropping.

Table 4.3 compares emissions intensity estimates generated by direct measurements and 4 different LCA models. These data reveal that Comet's estimates for 2 of our farms are higher than published findings from intensive dairy systems globally, which are uniformly less than 2 kg CO_2e/kg FPCM. Comet emissions estimates per cow were implausibly variable across farms for manure methane, in particular. The Farm ES GHG emissions intensity estimates in this study more closely align with past estimates from other models. Therefore, we determined that farm-to-farm comparisons were more reliable with Farm ES, although we retained Comet's carbon sequestration estimates for comparison to measured changes.

Farm to Farm Comparisons

Figure 4.1 provides the estimated GHG emissions breakdown for the 4 farms. The average GHG emissions intensity across the 4 farms was 0.97 kg $\pm$ 0.16 CO_2e/kg FPCM. Asselin-Balençon et al. (2013) reported a median total GHG emissions intensity of 1.14 kg CO_2e/kg FPCM across 531 U.S. farms. The MI farm was the only site in our cohort with an emissions intensity greater than this median from 10 yr ago, whereas other farms were 18 to 27% less. This may be due in part to our selection of exemplary farms, but it is also consistent with remarkable reductions in GHG emissions intensity of milk over the past 10-15 yr (Capper and Cady, 2020). Comparing the data from the 4 farms confirmed that farms (specifically MI) with the greatest DMI/FPCM ratio (poorer feed efficiency) had the greatest total GHG intensity (Asselin-Balençon et al., 2013).

Methane accounted for the largest share of GHG on all 4 farms (Figure 4.2). Carbon dioxide accounted for approximately the same proportion of GHG on all the farms, and nitrous oxide, the most potent GHG, was the most variable across the farms. The PA dairy's nitrous oxide emissions made up a greater proportion of their farm emissions compared to the other 3 farms; this is likely due to the use of compost-bedded packs for their dry and late-lactation cows, as the composting manure generates far more nitrous oxide than other manure storage systems (Hao et al., 2002; De Boer and Wiersma, 2021). The PA dairy can reduce nitrous oxide emissions by reducing the number of active mixed bedded packs used throughout their farm (Hatfield et al., 2006).

The largest component of the GHG footprint was enteric methane, contributing 0.40 ± 0.03 kg CO_2e/kg FPCM. There was little variation in the contribution of enteric methane emissions across farms, equating to 42 ± 6% of total emissions. Feed supplements that are currently under investigation are areas of opportunity to reduce these enteric emissions (Kinley et al., 2020; Pitta et al., 2022), but highly effective methane inhibition tools (reducing enteric methane production by more than 20%) are not commercially available in the U.S. today.

The average manure footprint was 28 ± 9% of the GHG footprint and was the most variable component of the footprint across farms. Table 4.1 identifies differences in manure handling systems across farms. The MI dairy did not utilize manure separation technology, which led to a similar manure footprint as the PA dairy, the only other dairy within the cohort not separating manure. These farms had, on average, 0.20 kg CO_2e/kg FPCM greater GHG emissions intensities compared to WA and GA farms, which both utilized manure separation. In other terms, farms utilizing separation technology had a 50% lesser manure footprint compared to the farms not separating manure solids. These reductions in GHG emissions for farms separating manure aligns with previously reported environmental benefits of such technologies (Sefeedpari et al., 2019).

The third largest portion of the footprint on all these dairies comes from feed production (Figure 4.1), consistent with previous analyses in the literature (Asselin-Balençon et al., 2013) at 24 ± 5% of the GHG footprint. Georgia had the greatest proportion of purchased feeds at 32%, likely due to the quantity of pellets fed in the automated milking system. The MI, PA, and WA farms utilized 18%, 17%, and 17% purchased feeds, respectively. The PA farm had the smallest feed production emissions intensity while farming the least land per cow (0.39 ha/cow), resulting in lesser carbon dioxide release from equipment use. In contrast, variability in proportion of purchased feed does not greatly influence the feed production footprint, as emissions from purchased feeds are estimated based on cropping systems by region (Asselin-Balençon et al., 2013).

The 4 farms had an average on-site energy use intensity of 0.06 ± 0.05 kg CO_2e/kg FPCM, which was 6 ± 4% of the GHG footprint. None of the farms in the project generated any form of renewable energy. On 2 of the farms, electricity use may be inaccurate for the following reasons. The MI farm utilized 2 electric heaters for a viewing room to allow visitors to watch the milking robots, slightly biasing on-site energy use for this farm. On the other hand, the electricity use reported for the GA farm seemed unrealistically low for that region; all other farms in the study utilized more than 100,000 kWh of electricity, compared to 22,250 kWh reported for this farm. We anticipated that the GA dairy would have greater electricity use per cow, given the fans needed to cool cows for much of the year.

Comet's focus on cropping and agroforestry allowed us to look more closely at these areas. Within Comet, pastures are included in cropping inputs, allowing the carbon sequestration advantages of perennial forage systems to be accounted for. Comet predicted an average annual carbon sequestration rate of 3.37 ± 2.8 Mg / ha across the 4 farms. The WA farm was predicted to sequester the most carbon at 7.52 Mg carbon/ha per yr, likely due to a no-till cropping system based primarily on perennial grasses. The GA and PA farms had riparian buffers or wooded lots, and Comet estimated that an average of 10.32 ± 11.66 Mg carbon/ha were sequestered in these parcels annually. Agroforestry sequestration is dependent on the age of the forest. Mature forests often contain larger trees that can store and absorb more carbon each year compared younger trees (Lorenz and Lal, 2010); however, mature forests reach a point of soil carbon saturation, as a balance between decomposition of plant material and new growth results in a steady state, with no net C sequestered (Carey et al., 2001). The GA farm estimate included 18.56 Mg C/ha sequestered annually over 63 ha of mature woods. Given the maturity of this forest plot, additional data would be warranted to verify the plausibility of this C sequestration estimate.

Longitudinal Soil Carbon Data

Soil OM data was collected from the 3 farms that had longitudinal data available: MI, PA, and WA. On all 3 farms, the data used to analyze soil OM was from shallow carbon storage, the top 30.5 cm of soil. Figure 4.3 shows the OM for all the soil sample data across farms. Longitudinal data from the PA farm point to soil C accumulation at greater rates than the MI farm, which showed accumulation of only 0.02% per year. The very high OM content and slightly negative linear slope for longitudinal samples from the WA farm suggest that the soil on this farm may have reached the upper soil carbon capacity limit (Stewart et al., 2007). Although the shallow carbon soil data suggested carbon saturation, we did not have deep soil OM data, and it is possible that the perennial grass system employed on the WA farm is promoting accumulation of deep soil C stocks, which are more stable (Button et al., 2022).

To determine the amount of carbon sequestered per ha annually from the soil OM data, we assumed that soil OM was 58% C (Edwards, 2021). Although none of the farms had soil bulk density data, we utilized the USDA Web Soil Survey to estimate average soil bulk densities for each farm (USDA, 2023). The USDA soil bulk density estimates may not be entirely representative of the individual farmland due to variation in soil management techniques. As shown in Table 4.4, these calculations suggest that the PA farm is sequestering the most C per ha at 3.52 Mg/ha annually. Comparing the quantity of carbon sequestered based on the soil samples to the predicted carbon sequestered in Comet, Figure 4.5 shows that all 4 farms were predicted to sequester carbon. Comet predicted the WA farm to sequester the most carbon per ha and PA the least, which was the opposite of findings from soil sampling data. Data from PA suggest that C sequestration is occurring at a rate 1.41 Mg/ha per yr greater than Comet's prediction. Despite the conditions being right for soil C accumulation on the WA dairy (hence the high estimate from Comet), soil C saturation likely prevented further accumulation. Comet does not model a point of soil carbon saturation and continues to predict increases in soil carbon sequestration based on field management practices.

Farm ES does not attempt to account for carbon sequestration. Therefore, we utilized the carbon sequestration estimates based on soil data, in combination with Farm ES estimates for other emissions components, to assess the impact of accounting for soil C sequestration on GHG emissions intensity estimates. Figure 4.5 indicates that 2 farms, MI and PA, approach net GHG neutrality after accounting for accumulation of soil C, with opportunities to achieve this goal. Although the WA farm appears to have relatively static soil C stores, this study did not include data on deep soil C storage, which could decrease the estimated GHG emissions intensity of this farm (Fowler et al., 2023). As previously stated, manure separation has the potential to reduce a farm's manure footprint by an average of 50%. If this technology was adopted on the MI and PA dairies, reducing their manure footprint, their estimated GHG emissions intensities would be reduced to 1.01 and 0.76 kg CO_2e/kg FPCM, respectively. If we account for carbon sequestration, estimated GHG intensities reduce to 0.92 and 0.54 kg CO_2e/kg FPCM for MI and PA, respectively. If these farms were to adopt manure separation, an expected 50% reduction in manure intensities would result in farm intensity values of 0.74 and 0.36 kg CO_2e/kg FPCM in MI and PA; only 62 and 38% of their original estimated intensities, respectively. Nonetheless, although the farms are not quite there yet, the data from MI and PA farms suggests that some small and mid-sized dairies may be approaching a point where they are sequestering more CO_2e than is being emitted based on the soil OM calculations.

Further research is needed to confirm soil sequestration findings. Although Farm ES does not attempt to account for carbon sequestration, it is vitally important when addressing agricultural GHG neutrality (Bispo et al., 2017). O'Brien et al. (2014) found that including carbon sequestration reduced GHG emissions intensities of energy-corrected milk for US confined dairy systems and Irish pasture-based dairy systems by 12% and 22%, respectively. A Dutch study also revealed that including carbon sequestration within dairy farm GHG assessments results in a 37% decrease in net GHG emissions (Schils et al., 2005). Therefore, the dairy industry should focus more research and adoption efforts on quantification of soil C sequestration and strategies that are most effective at promoting soil C repletion.

Based in part on research demonstrating reductions in manure GHG emissions and on financial incentives for farms and businesses (EPA, 2022b), anerobic digester utilization has been increasing on dairy farms, especially in the Western U.S. (Holly et al., 2017; Rocha, 2020). Although large farms are benefitting from the financial incentives of these digester projects and in turn, reducing their emissions and carbon footprints, small producers do not have the manure volume to justify the large capital investment in an anaerobic digester. Yet, research indicates that 69% of consumers' desire food to be sustainably sourced (Wells, 2017), leading major food companies to invest in ensuring sustainability measures are met on supplying farms (Burstein, 2021). Despite the lack of anaerobic digestors on most small dairies, our findings suggest that they still have the opportunity to approach GHG neutrality through soil carbon sequestration in combination with best practices in animal and manure management.

Limitations

There were several limitations that could alter the accuracy of the emissions estimates. First, actual measurement of GHG coming from a farm is an incredibly difficult task, meaning much research on GHG footprinting relies on prediction models, which themselves rely on many assumptions. Better measurement tools and techniques are needed to solidify estimated GHG emissions from farms of all types to ensure model accuracy. Further, model outputs are only as good as the data that was collected on farm, emphasizing the importance of accurate record keeping on dairies in order to yield a footprint with greatest confidence. Additionally, neither Farm ES nor Comet considered manure application method, which could have a large impact on the nitrogen loss as nitrous oxide and what is available to the crop (Ketterings et al., 2005). Lastly, this study did not have access to deep soil carbon analysis, which would have provided a more meaningful estimate of true soil carbon sequestration rates.

CONCLUSIONS

Despite not utilizing anaerobic digesters, exemplary small dairy farms may be nearing GHG neutrality after accounting for soil carbon sequestration. Comet and soil data collected over years provided unique insights into the benefits of accounting for agroforestry and perennial forages. The carbon sequestered on this land impacts whole-farm footprint estimates and emission intensity estimates. Furthermore, manure separation plays an important role in reducing manure footprints. On the 2 dairies that utilized manure separation systems, the manure component of GHG emissions intensity was reduced by roughly 50% compared to the 2 dairies that did not separate manure, reducing total GHG emissions intensity by approximately 19%. Additionally, emissions resulting from feed production remain an opportunity to reduce a farm's carbon footprint. Farms can invest in precision agriculture tools to apply manure and fertilizer more accurately to fields, reducing the nitrous oxide losses. Lastly, productivity is an important determinant of farm emission intensities. Improving production efficiencies will further reduce farm GHG emissions intensities throughout the industry. Dairy farms of any size can implement sustainable management practices for manure management and feed production to reduce their carbon footprint, which may result in net GHG-neutral dairy production.

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TABLES AND FIGURES

Table 4.1 *Farm information for the 4 regions.*

Item	MI	GA	PA	WA
Annual milk production (kg)	1,299,888	4,527,256	3,015,256	7,605,905
Daily milk per cow (kg)	28.54	38.62	39.99	29.02
Milk fat (%)	4.10	3.90	3.80	4.55
Milk protein (%)	3.20	3.20	3.10	3.48
FPCM (kg/cow per yr)	8,371	12,156	12,753	9,851
Lactating herd	156	365	227	835
Dry cows (% of herd)	20	12	14	14
Average young stock raised on farm	115	410	191	40
Average young stock raised off farm	0	0	0	400
Lactating cow DMI (kg/day)	21.28	27.28	26.11	22.90
Total ha farmed	162	210	89	353
Hectares per cow	1.04	0.57	0.39	0.42
Milking System	Robot	Robot	Parlor	Parlor
Feeding System	Grazing and robot pellets	PMR (26% CS) and robot pellets	TMR (36% CS)	TMR (40% grass silage)
Primary manure storage system	Pasture deposit, UAL	Solids separation; UAL, composting	Under barn pits, composting	Solids separation; aerobic treatment, NC slurry
Years of soil OM data	15	1	10	7

[1] FPCM = fat and protein corrected milk; DMI = dry matter intake; CS = corn silage; UAL = uncovered anaerobic lagoon; NC = natural crust; TMR = total mixed ration; PMR = partial mixed ration

Table 4.2 *Greenhouse gas emissions intensity estimate comparison between Comet (Paustian et al., 2018) and Farm ES (Asselin-Balençon et al., 2013) LCA models.* These emissions intensity [kg carbon dioxide equivalent (CO2e)/kg fat and protein corrected milk [FPCM]) estimates do not include soil carbon sequestration for either program.

	MI		GA		PA		WA		Average	
Emission	Farm ES	Comet	Farm ES	Comet	Farm ES	Comet	Farm ES	Comet	Farm ES	Comet
Feed production footprint	0.26	0.33	0.27	0.13	0.18	0.08	0.22	0.17	0.23	0.18
Manure footprint	0.36	10.29	0.21	0.17	0.37	0.35	0.15	2.80	0.27	3.40
Energy use footprint	0.14	--	0.02	--	0.04	--	0.04	--	0.06	--
Enteric footprint	0.44	0.32	0.40	0.23	0.36	0.14	0.41	0.16	0.40	0.21
Total footprint	1.19	10.94	0.90	0.54	0.94	0.56	0.83	3.12	0.97	3.79

Table 4.3 *Model emission intensity comparison from past research.*

	Uddin et al., 2021	Flysjö et al., 2011	Little et al., 2017	Del Prado et al., 2011	Henriksson et al., 2011
Model	-	-	Holos	SIM Dairy	Swedish National Model
Number of farms	1 (259 dairy cattle)	2	1 (60 dairy cattle)	5	1051
Region/location	Wisconsin, USA	New Zealand and Sweden	Quebec, Canada	United Kingdom	Sweden
Emission intensity	1.43 kg CO_2e/kg FPCM	1.08 kg CO_2e/kg FPCM	1.25 kg CO_2e/kg FPCM	1.07 kg CO_2e/kg Milk	1.13 kg CO_2e/kg FPCM

Table 4.4 *Carbon sequestration estimates based on longitudinal soil sample data and Comet modeling.*

State	OM % Change per year	Average bulk density[1] (Mg/m^3)	Carbon Sequestration (Mg carbon/yr) Per ha based on soil samples	Carbon Sequestration (Mg carbon/yr) Per ha based on Comet
MI	0.02	1.62	0.60	2.50
PA	0.14	1.41	3.52	2.11
WA	-0.03	1.47	-0.82	7.52
GA	--	1.43	--	1.37

[1] Bulk density was estimated for each farm using the USDA Soil Survey program (USDA, 2023).

Figure 4.1 *GHG emissions by source and farm location based on the Farm ES model.*

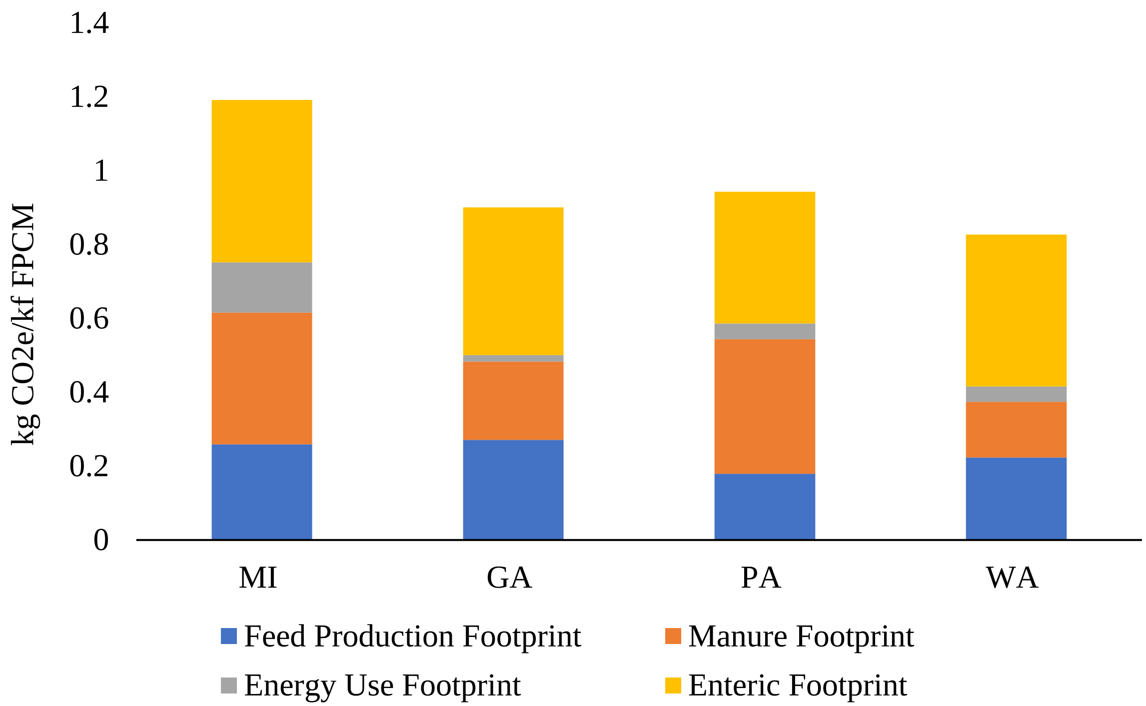


Figure 4.2 *GHG type breakdown by percent of total farm emissions from the Farm ES model.*

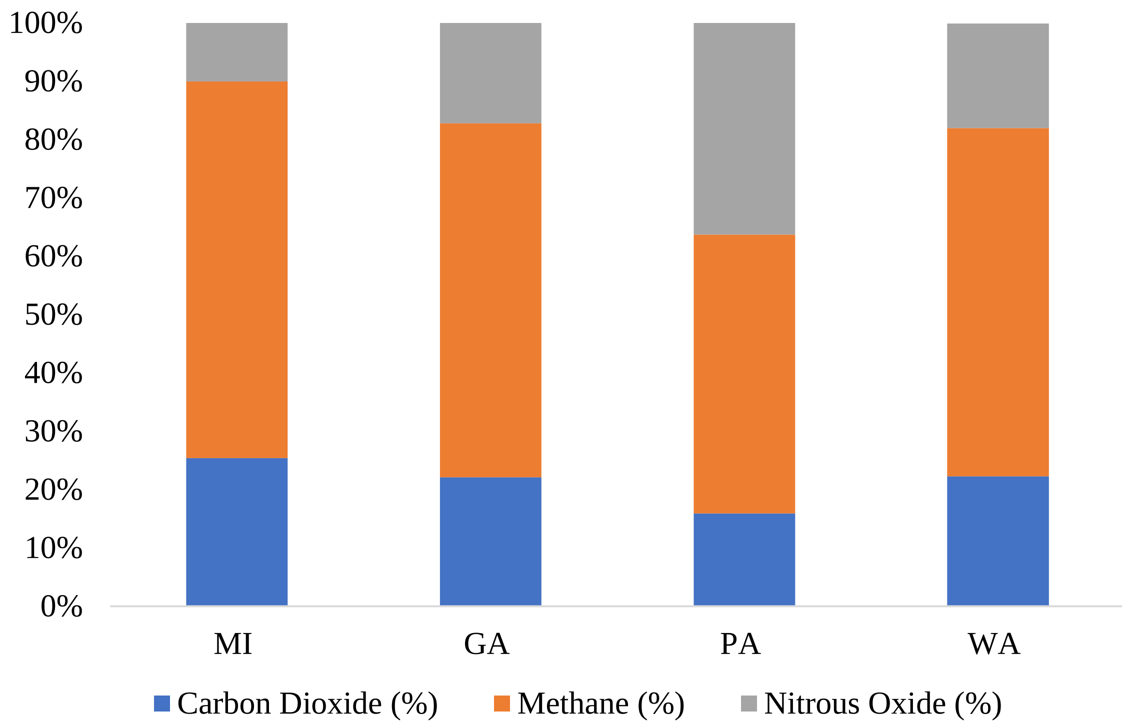


Figure 4.3 *Plotting longitudinal organic matter from soil samples.* The MI data accounts for 181 samples, PA 164 samples, WA 90 samples, and GA has 18 samples from only the year 2023. Georgia's mean OM was 2.88%.

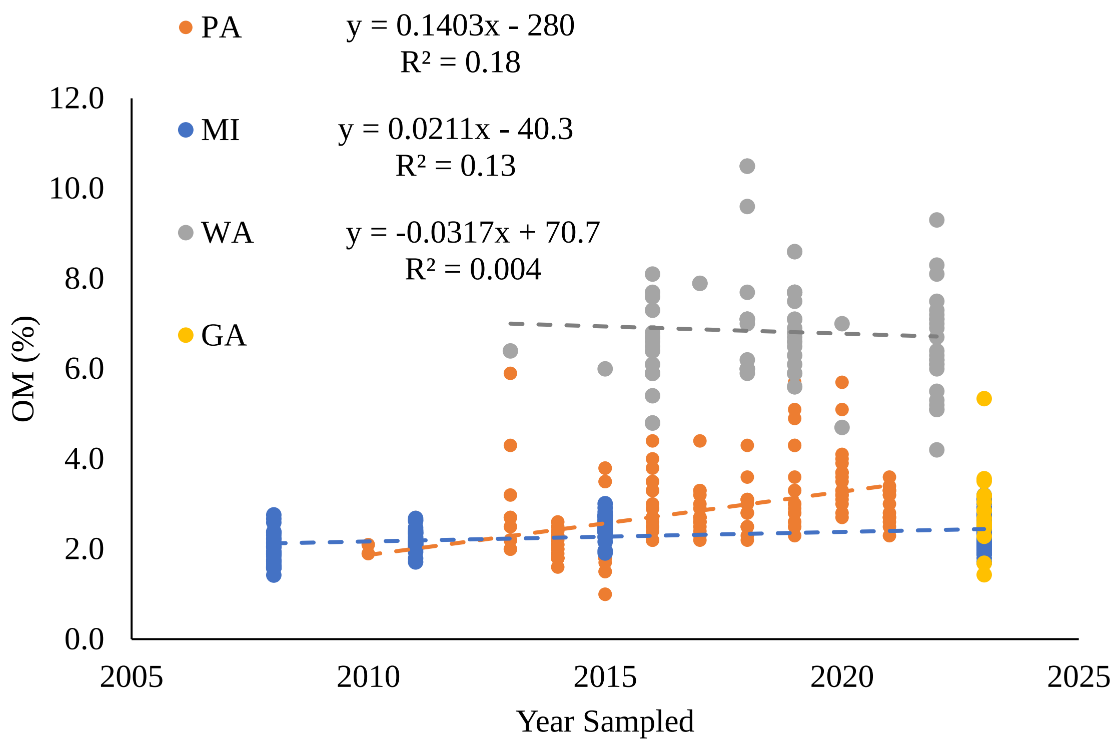


Figure 4.4 *Comparing carbon sequestration rate based on soil sample organic matter and Comet model predictions.* The data was measured in Mg carbon/ha for both the soil samples and Comet.

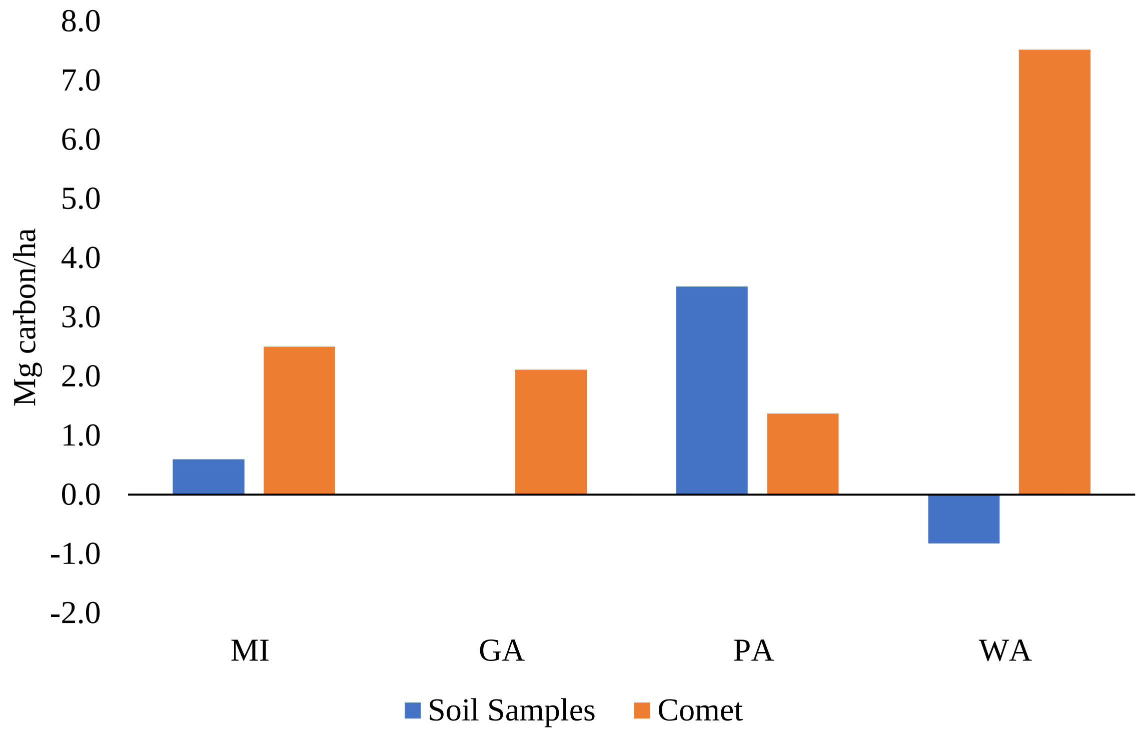
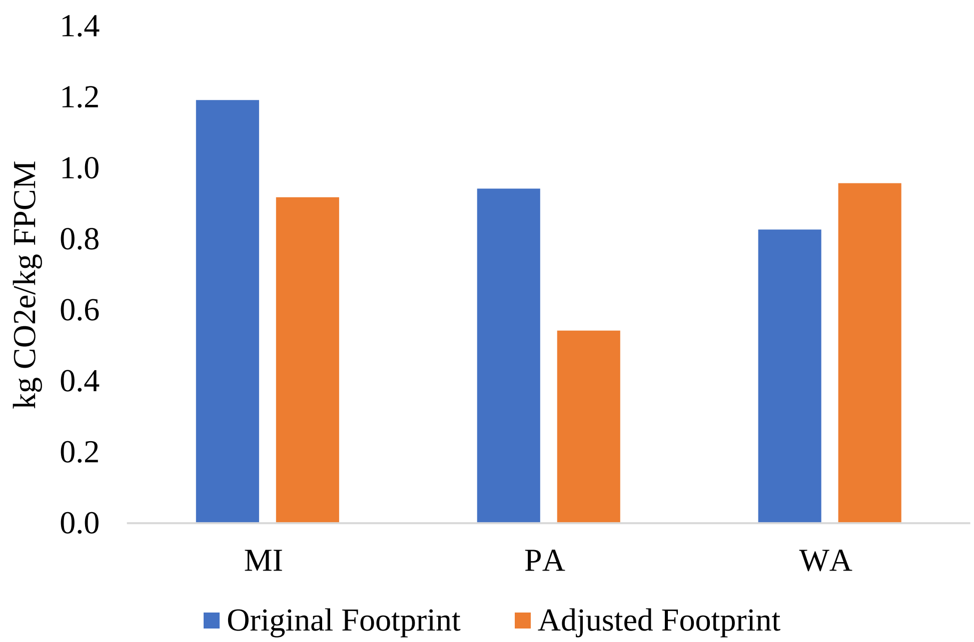


Figure 4.5 *Comparing farm GHG footprints based on soil sample carbon sequestration and estimated Farm ES footprint emissions.* The carbon sequestered was converted into CO_2e before factored into emissions estimations using the adjusted footprint.



CHAPTER 5:

OVERALL CONCLUSIONS

Sustainability is driven through the combined investment in economic, environmental, and social wellbeing. Dairy producers who make decisions based on these 3 components set their farms up to achieve sustainability and longevity for their businesses. This thesis focused primarily on 2 major questions in the dairy industry related to economic and environmental sustainability, and discovered answers that may aid producers in making more sustainable decisions in the future.

The never-ending industry debate over whether Jersey or Holstein dairy cattle are more profitable is one that is important for economic sustainability of dairy farms. In a North Central U.S. climate, although Jersey cows produced milk with greater component concentrations, Holstein cows had an advantage in profitability due to greater milk component yields. Sensitivity analysis revealed that the most plausible way for Jersey cows to overcome the profitability disadvantage would be through increasing milk production by over 10% while maintaining current component concentrations. In the relatively cool North Central climate, we did not find evidence to support the perceived fertility or health advantages of Jersey cows that may be apparent in warmer regions of the U.S. Further research should be conducted in warmer regions of the U.S. to aid dairy producers in determining the most profitable breed for their region while also considering the economic performance of crossbred cows.

Our second study sought to provide some data around a topic receiving much attention but limited analysis. We assessed GHG footprints of 4 small to mid-size dairy farms throughout the U.S. to better document the current status of dairies of this scale and to identify the most impactful practices for reducing GHG emissions. It is important to recognize that what may be environmentally sustainable for large dairy producers is not always economically sustainable for small dairy producers. Through this study we were able to determine differences in management practices that lead to reduced carbon footprints and can be both environmentally and economically sustainable for small producers. We concluded that exemplary small dairy farms are approaching GHG neutrality when accounting for soil carbon sequestration within models. Manure management and manure separation technologies play a large role in reducing dairy farm GHG footprint. Significant carbon sequestration benefits were attributed to agroforestry, perennial forages, cover cropping, and reduced tillage practices. Lastly, productivity is an important determinant of the GHG emissions intensity of milk produced on a given farm.

In conclusion, although these projects evaluated very different dairy management questions, both provide answers that dairy producers can implement on their farms today to achieve a more sustainable future. Finding the sweet spot among all three aspects of sustainability remains the goal of many members across the dairy industry as we identify solutions for producers.

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